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Further Development of the CIAMA Nodal Method for Kinetic Applications

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1. Introduction

Recently, a new nodal method using Channel-wise Intrinsic Axial Mesh Adaptation (CIAMA) has been developed by the authors [1]. The uniqueness of the method lies in its way to handle the intra-nodal axial heterogeneity introduced by partially-inserted control rods and/or stationary fuel grids. Unlike today's common practices of using coupled iterations of 3D whole core coarse-mesh nodal solution and axially 1D local channel-wise fine-mesh solution to treat the intra-nodal axial heterogeneity, the CIAMA nodal method handles the issue at the fundamental level of nodal equation formulation by removing the precondition of conventional nodal methods, i.e, the node must be homogeneous. For a given transverse (radial) leakage, along each axial channel a rigorous sub-node heterogeneous calculation is performed with the explicit axial heterogeneity within each coarse axial node. However, the transverse leakage between the axial channels is still calculated on the basis of coarse axial nodes, using the axially averaged radial current in each coarse axial node. Since the coupling between the axial channels is through the coarse axial nodes, it is not necessary to match the boundaries of the axial sub-nodes of neighboring axial channels in order to incorporate the axial sub-node calculation as an intrinsic part of the whole core global calculation. Therefore in the CIAMA nodal method, each axial channel is allowed to have its own sub-nodes adapting to its own axial heterogeneity variation, which gives the method excellent flexibility and also computational efficiency to handle various intra-nodal axial heterogeneities. The method fully eliminates the need of constructing a separate auxiliary 1D fine-mesh heterogeneous model. Moreover, since there is no online axial nodal re-homogenization at all, the method fully eliminates the subtleties of generating and using axial nodal discontinuity factors as well.

The CIAMA nodal method has been implemented in NuStar's 3D steady-state core analysis code EGRET and extensively qualified in the process of EGRET verification and validation. Its performance has been confirmed to be rather satisfying [1,2]. Recently, in order to develop a code suite for Dynamic Rod Worth Measurement (DRWM) [3], EGRET has been extended to 3D core neutron kinetic applications and a corresponding kinetic version, EGRET-K, has been developed and qualified. This paper is about the further method development related to the extension of the CIAMA nodal kernel for kinetic applications.

2. Issues and Solutions

The implementation of the CIAMA nodal method in both EGRET and EGRET-K codes is based on the multigroup semi-analytic nodal method (SANM)[4]. Since the necessary details on method implementation for steady state has already been given in Ref. [1], only the kinetic application-specific issues of the method are addressed in this paper.

2.1 Issues

The basic idea of the CIAMA nodal method is applicable for both static and kinetic problems, however, as will be discussed below, further method development is still needed to extend the method for kinetic applications.

Eq.(1) gives the group-wise transversely-integrated neutron kinetic equation for a homogeneous node at a given moment t_{j+1}

$$-D_{j+1}\frac{d^2\varphi_{j+1}(u)}{du^2}+\Sigma_{j+1}\varphi_{j+1}(u)=S_{j+1}(u)-L_{j+1}(u)+Q_j(u) \qquad (1)$$

where the original time derivative term appearing in the neutron flux equation has been discretized by the fully-implicit difference method and all the delayed neutron precursor equations have been analytically solved with the assumption that the nodal fission rate varies linearly over one time step. It should also be noted that all the parameters relating to the previous moment t_j are included in the term Q_j. It acts as an additional neutron source for the current moment.

One may notice that except for this additional neutron source Q_j, Eq.(1) is in the same form as that of the 1D steady state neutron diffusion equation. Therefore, all the CIAMA technologies [1] are applicable to the solution of this equation. However, due to the inherent floating sub-node meshing scheme of the CIAMA method, this source term poses an additional difficulty for the application of the method.

As illustrated in Fig.1, when the method is applied for a core transient introduced by control rods insertion, the coarse node division scheme that couples all fuel channels together is generated once for all, it does not vary with time, however, for the sub-node division scheme that adapts to the axial heterogeneity for each channel, it does alter from moment to moment. As shown in Fig.1, at moment t_{j-1}, there is no sub-node at all within the coarse node *K*, however, with the continuously insertion of control rod, in order to explicitly represent the rodded and unrodded zones within the node, the sub-node division schemes for the subsequent two moments t_j and t_{j+1} keep varying.

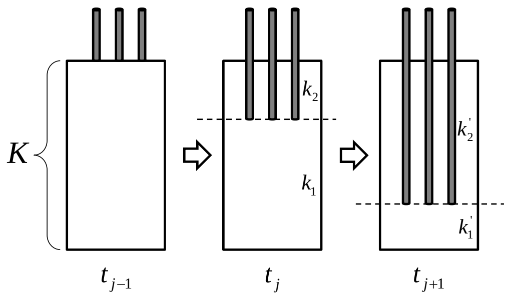

Fig. 1 the time-varying sub-node division scheme within one coarse node.

As mentioned earlier, axially each sub-node is taken as a regular node in the CIAMA method, therefore for the case illustrated in Fig.1, for both sub-nodes k_1' and k_2' for moment t_{j+1}, there should be a corresponding extra neutron source coming from moment t_j. However, since the neutron kinetic equation is solved at a different set of sub-nodes at moment t_j, one cannot readily derive the physical parameters needed to calculate this extra neutron source. This poses a challenge when the CIAMA nodal method is extended to kinetic applications.

2.2 Solutions

Like most of today's advanced nodal codes, EGRET applies the weighted-residual method to determine the unknown coefficients of the 1D semi-analytic flux expansion. When applying the weighted-residual method to Eq.(1), obviously, the weighted integration also applies to the extra neutron source Q_j at the right hand side. Once this weighted integration is known, and then Eq.(1) can be solved straightforwardly by following the solution method developed for steady state. Therefore, the key issue one needs to resolve is how to derive the weighted integration of Q_j.

Taking the solution of problem for sub-node k_2' illustrated in Fig.2 as an example, the weighted integration has the form as

$$I_n = \int_{-1}^{1} \omega_n(z) Q_j(z) dz, \quad n = 0,1,2 \qquad (2)$$

where z is the normalized axial position parameter of sub-node k_2'.

As can be seen from Fig.2, the above integration can be separated into two parts, one part integrates over part of the height of sub-node k_1 and the other integrates over the whole height of sub-node k_2 (as shown in Eq.(3)). Since the two integrands are now known functions, they can both be pre-calculated before solving Eq.(1) for the current moment. And once this issue is resolved, the neutron kinetic problem can be solved moment by moment by applying the CIAMA nodal method as that for the steady state.

$$I_n = \int_{-1}^{z'} \omega_n(z) Q_j(z) dz + \int_{z'}^{1} \omega_n(z) Q_j(z) dz. \quad (3)$$

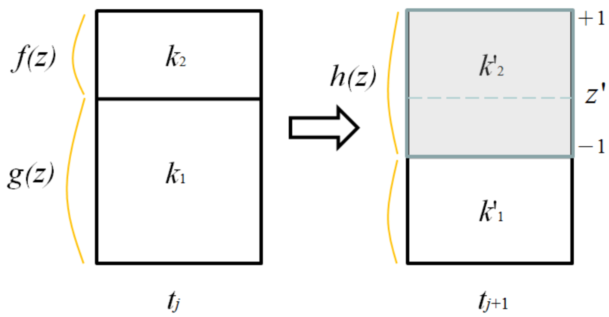

Fig. 2 Generating contributions from previous time moment as an extra source for the current moment.

3. Verification Results

The 3D LMW benchmark problem [5] is used to verify the extended capability of the CIAMA nodal method. Since the primary intended use of EGRET-K code is for DRWM application, where all the physical tests are performed at hot zero power condition, only the case without thermal-hydraulic feedback is analyzed.

The case simulates an operational transient of a PWR core involving control rod movement. The transient sequence is initiated by withdrawing one group of rods initially inserted at the mid-plane with a constant speed until they are fully withdrawn. At 7.5s, the rod group 2, which initially stays out of the core, starts to move in with the same speed of rod group 1 withdrawn for a period of 40s. The whole transient defined in the benchmark lasts 60s.

The benchmark problem is solved by the EGRET-K code for both CIAMA nodal method and the simplest volume weighted method (VWM). In order to demonstrate how well the CIAMA nodal method resolves the control rod cusping issue and how stable its performance is, a set of three axial coarse node sizes (10, 20 and 40cm) are used for both CIAMA and VWM calculations, the obtained results are compared against the reference one obtained by VWM with 5cm axial node size. Since it is not in the radial direction that exists the intra-nodal material heterogeneity, a fixed coarse node size of 20cm × 20cm is used in radial direction for all the EGRET-K calculations. Moreover, since it is not the point of the paper to discuss the time step size effect, a fixed 250 ms time step size is used for both CIAMA and VWM calculations.

The results are compared in Fig.3 and the accompanying Table 1 and Table 2. The Fig.3 is focused on the comparison of the performance of resolving the control rod cusping effect, where relative power errors for the whole transient are shown for both CIAMA and VWM methods. It can be concluded that the performance of the CIAMA nodal method for resolving the control rod cusping effect is excellent. Actually, it can be seen that the control rod cusping effect can basically be eliminated by the method when a normal axial nodal size is employed. Although as expected its performance deteriorates slightly as the axial nodal size becomes larger, its performance is still good even when an extremely large axial nodal size of 40cm is used. From the error comparison given in Table 1 and Table 2, one may see that for VWM, as the axial nodal size goes larger, the results deteriorate quickly, while for CIAMA, the performance is quite stable, even the axial nodal size is as large as 40cm, there is still no significant accuracy deterioration.

These comparisons demonstrate that the extension of the CIAMA nodal method to kinetic applications is successful, the excellent performance of the method, which has been demonstrated for previous steady state applications, has now been restored for kinetic applications.

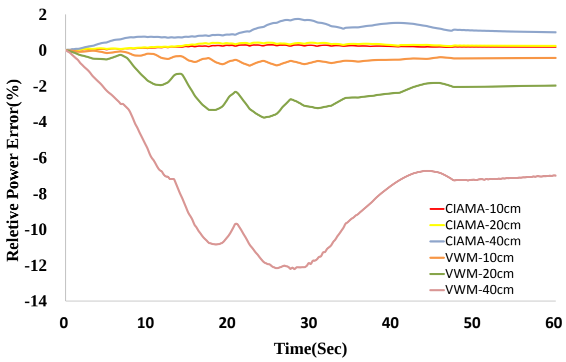

Fig. 3 Relative power errors for VWM and CIAMA results obtained with different axial nodal sizes.

Table 1. Axial nodal size effect of the volume weighted method.

Time /s	Reference power	Relative power deviation for the results obtained with different axial coarse node sizes /%		
		10cm	20cm	40cm
5	1.128	-0.16	-0.52	-2.35
10	1.342	-0.19	-1.72	-5.81
20	1.709	-0.62	-2.60	-10.47
30	1.365	-0.70	-3.17	-11.81
40	0.806	-0.53	-2.41	-7.39
50	0.501	-0.45	-2.05	-7.24
60	0.385	-0.43	-1.97	-7.04

Table 2. Axial nodal size effect of the CIAMA nodal method.

Time /s	Reference power	Relative power deviation for the results obtained with different axial coarse node sizes /%		
		10cm	20cm	40cm
5	1.128	-0.12	-0.09	0.28
10	1.342	-0.16	-0.12	0.47
20	1.709	0.06	0.17	0.66
30	1.365	0.40	0.54	1.79
40	0.806	0.38	0.45	1.69
50	0.501	0.23	0.29	1.14
60	0.385	0.17	0.22	0.99

Besides the above comparisons, the EGRET-K CIAMA results with 20cm axial nodal size are also compared against results reported in literatures. Table 3 summarizes the comparisons. It can be seen that although different code uses different nodal method, different meshing scheme for both static and kinetic calculations and the time step size for kinetic calculation may also be different, EGRET-K and other modern nodal codes produce a very close eigenvalue for the initial steady state and also comparable reactor power during the whole transient. Considering that the axial nodal size adopted by EGRET-K is the coarsest, its good performance is once again confirmed.

Table 3. Intercomparison for the results of LMW benchmark problem

Code	QUANDRY[6]	PANTHER[7]	SPANDEX[8]	AETNT[9,10]	EGRET-K
Mesh Structure	6x6x20	11x11x40	22x22x80	11x11x40	6x6x10
Eigenvalue	0.99974	—	0.99964	0.99971	0.99965
Time step /ms	250.0	250.0	375.0	250.0	250.0
Time	Reactor power				
0.0	150.0	150.0	150.0	150.0	150.0
5.0	169.1	—	—	167.7	169.0
10.0	202.0	202.1	201.1	198.7	200.7
20.0	262.2	258.9	256.9	253.4	255.1
30.0	210.8	207.3	205.9	203.9	203.8
40.0	123.0	122.0	121.4	120.7	120.1
50.0	75.7	75.7	75.4	75.0	74.7
60.0	57.9	58.1	58.2	57.5	57.4

* The PANTHER and SPANDEX results are quoted from Ref.[11].

6. Conclusions

The CIAMA nodal method previously developed for steady state applications has been successfully extended to kinetic applications. Issues exclusively related to handling the time-varying sub-node scheme for kinetic calculations have been resolved. Numerical results verified against the volume-weighted method for the 3D LMW benchmark problem demonstrate that for kinetic problems involving control rod movement, the CIAMA method is very effective to resolve the control rod cusping issue and its performance is quite stable as the axial nodal size becomes larger. The CIAMA nodal method thus possesses excellent performance for both static and kinetic applications.

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