Impact of Photon Transport in STREAM on VERA 5 2D Problem

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1. Introduction

The energy of photon is usually incorporated into the Kappa values and the explicit calculation of photon distribution is neglected in the calculation chain to reduce the computational burden [1]. However, photons can move to other regions from its birth places, resulting in changes of the power distribution and affect other dependent calculations such as depletion or thermal hydraulics (TH) feedback in which the power distribution is needed.

STREAM developed by the Computational Reactor Physics and Experiment Laboratory (CORE) at the Ulsan National Institute of Science and Technology (UNIST) is a deterministic neutron-transport code specialized for the analysis of two-dimensional and three-dimensional reactor cores [2]. Recently, effort has been taken to implement a photon transport module in STREAM to extend the code's calculation capabilities to improve the power distribution accuracy. The impacts of explicit photon transport in STREAM on pin power distributions during depletion with TH feedback for a simple 2D VERA 5 core [3] are presented in this paper.

2. Method and Results

2.1. Photon transport and the energy deposition model in STREAM

Photon transport module in STREAM employs a photon library based on the ENDF/B-VII.1 library [4], generated with by NJOY code [5]. Generation of the multi-group photon library for STREAM is detailed in reference [6]. The photon fixed source solver in STREAM was implemented based on the adaptation of the MOC solver already present for the neutron calculation. The implementation and verification of this module was detailed in references [7].

The energy release per fission, Kappa, is applied to obtain the pin power. The current Kappa in STREAM [8] is based on the On-The-Fly Energy Release per Fission Model (OTFK). The Kappa values in OTFK method is computed via Equation (1)

$$\kappa_i \approx ER_i(0) + 1.157\overline{E}_i - 8.07[\overline{\nu}_i - \nu_i(0)] + \overline{Q}_c \qquad (1)$$

where, *$ER_i(0)$* is the total energy released per fission excluding the neutrino energy from Evaluated Nuclear Data File (ENDF), the second and third term is a correction term for contribution of delayed photon, delayed beta and prompt neutron emission induced by incident neutron energy $\overline{E}_i$ and the last term $\overline{Q}_c$ is the average energy from neutron capture reactions released per neutron fission, obtained by diving the total energy of photon from neutron capture, Q_c in a system by the number of fissions in that system.

The energy deposition is calculated by the production of the fission rate with the Kappa values. All energy is placed in the fuel regions and the energy deposition in coolant is approximated by the energy of neutron capture reactions in coolant.

When photon transport is turned on in STREAM, the value of Kappa from OTFK method is modified. In short, if a nuclide is available in STREAM photon library, the fission gamma energy contribution in the *$ER_i(0)$* term of that nuclide will be removed. The value of $\overline{Q}_c$ is also left out. The energy obtained from the OTFK method (production of fission rate and modified Kappa values) now gives the recoverable energy of fission products, betas, kinetic energy of fission neutrons. All these energies are placed in the fuel regions. The photon transport is performed and provides the explicit photon energy deposition in all material regions. The energy deposited in the fuel is then equal to the sum of the deposited photon energy and the recoverable energy obtained with the modified Kappa as mentioned previously. The energy deposited in the coolant now has the contribution of photon arrived from other regions.

2.2. VERA 5 2D problem and the TH model

VERA 5 2D problem is provided in the VERA Benchmark [3]. The configuration of the core is shown in Figure 1.

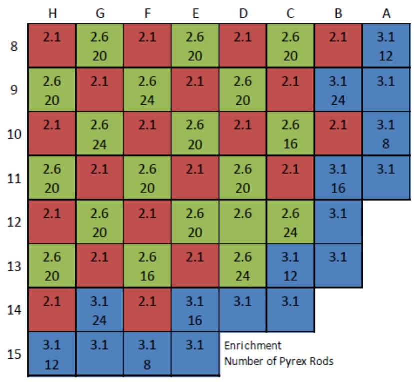


Figure 1. Layout of VERA 5 2D core (copied from reference [3])

The core baffle, barrel and vessel are modelled explicitly in STREAM. No control rod insertion is considered. The depletion mode is turned on with

Critical Boron Concentration (CBC) search and Equilibrium Xenon Calculation (EQXE). TH feedback is also turned on using simple TH1D model. The VERA 5 2D core is run with photon transport (modified OTFK) and with OTFK method (no photon transport). Results of pin-wise power and temperature between these two runs is compared to analyze the impact of photon transport in STREAM.

It is noted that the simple TH1D model is slightly modified when photon transport is used. The heat source in the cladding is considered when photon transport is used. The temperature in the cladding with the presence of heat source from gamma heating can be found in reference [9] that the temperature of cladding at radius *r* can be obtained via Equation:

$$T(r) = -\frac{q'''r^2}{4k} + Aln(r) + B \quad (2)$$

$$A = \frac{q_i''R_i}{k} + \frac{2q'''R_i^2}{4k}$$

$$B = T_s + \frac{q'''R_o^2}{4k} - Aln(R_o)$$

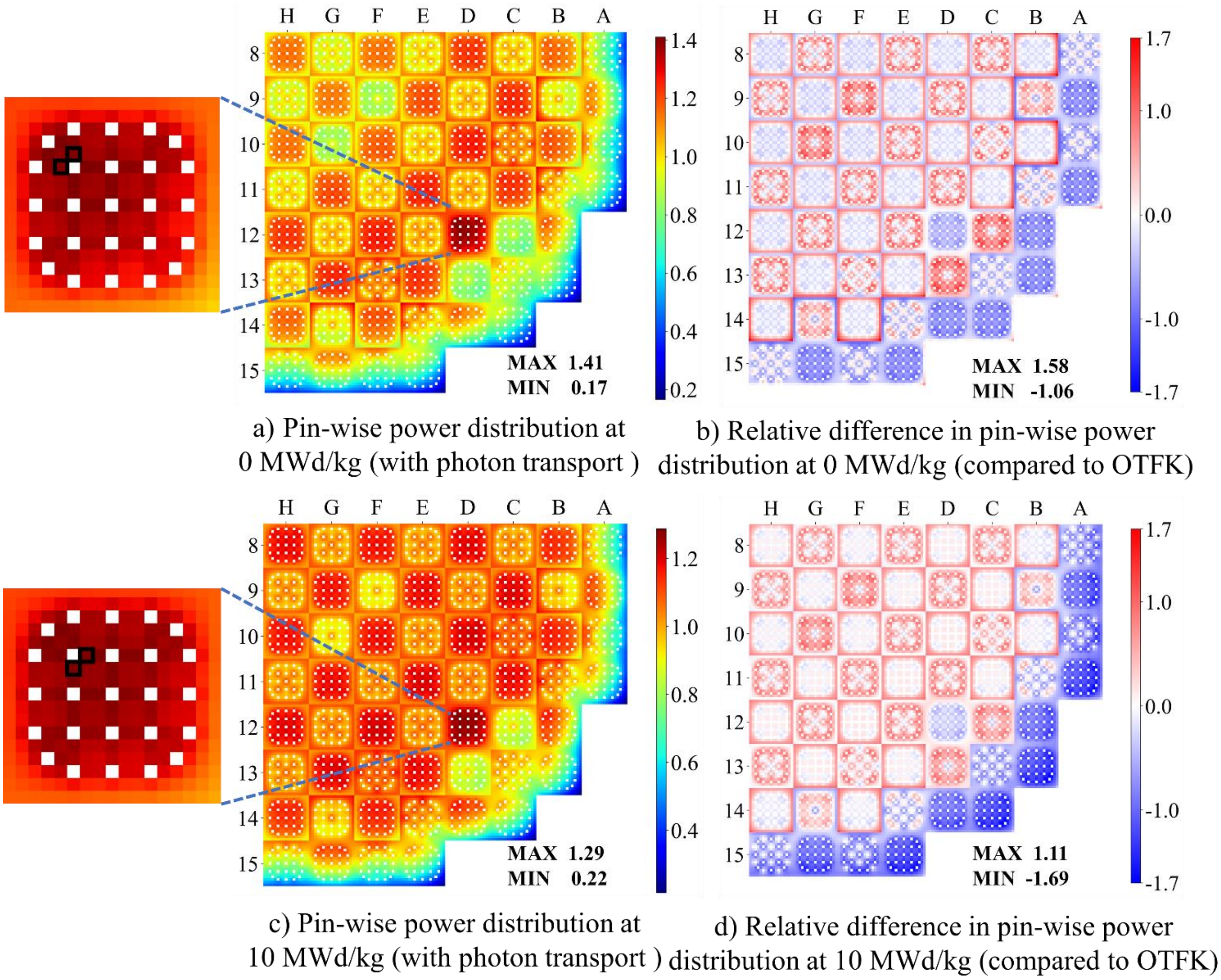
where q''' is the heat source in the cladding, q_i'' is the heat flux at the cladding inner surface, based on power generated only in the fuel, R_o and R_i are cladding outer and inner radius, respectively, and T_s is cladding surface temperature.

2.3. Results for pin power and temperature distribution

The CBC turns negative after 10 MWd/kg in both photon transport mode and OTFK mode. The results of pin-wise power distribution at 0 MWd/kg and 10 MWd/kg are shown in Figure 2. The relative difference (*Rel.Diff*) between results obtained with photon transport and with OTFK is defined as:

$$Rel.Diff. = \left(\frac{Photon\ transport}{OTFK} - 1\right) \times 100\% \quad (3)$$

Position of assemblies housing Pyrex rods are indicated in Figure 1 and as can be seen in Figure 2, pin close to the Pyrex rods have higher power, up to 1.5%



a) Pin-wise power distribution at 0 MWd/kg (with photon transport)

b) Relative difference in pin-wise power distribution at 0 MWd/kg (compared to OTFK)

c) Pin-wise power distribution at 10 MWd/kg (with photon transport)

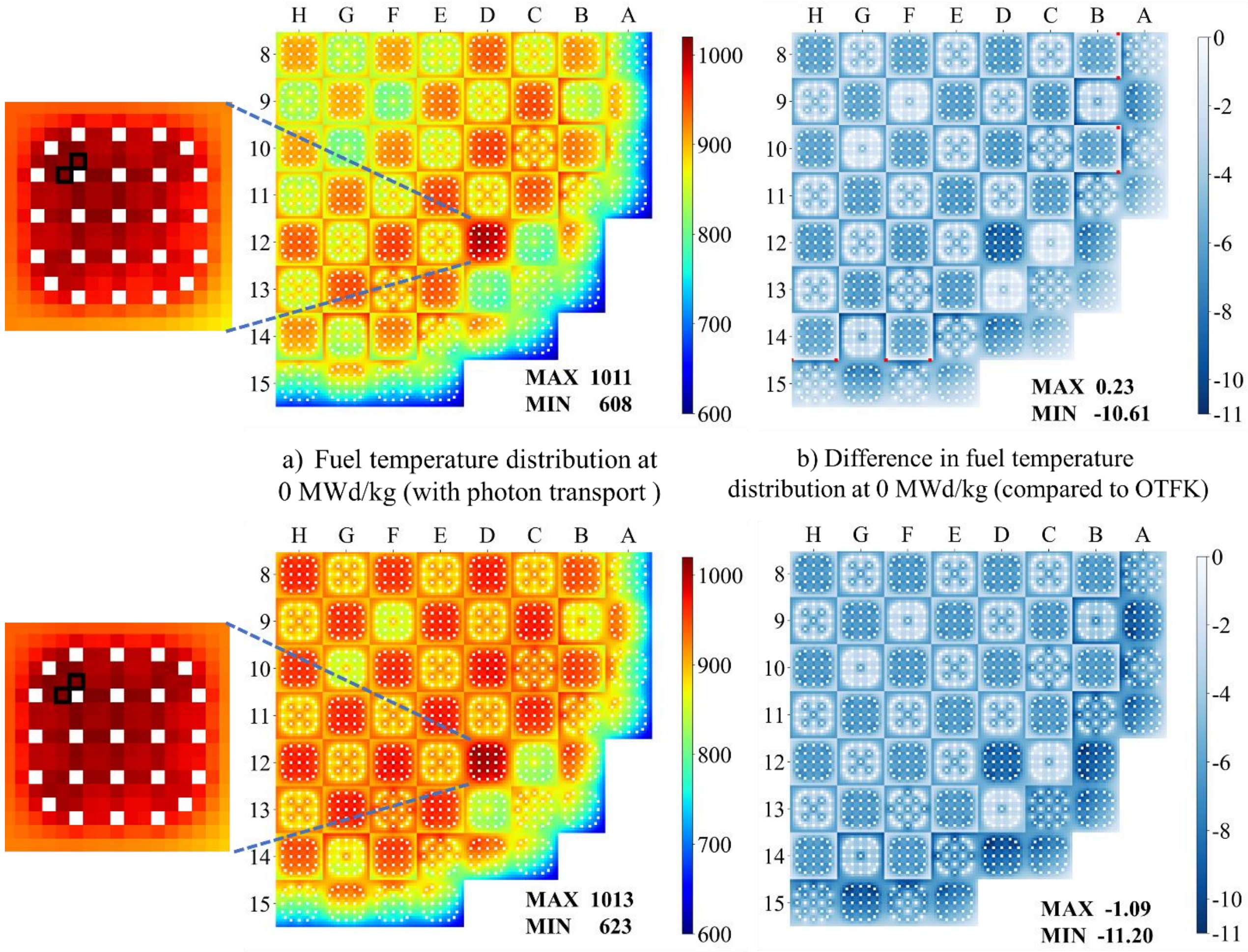
d) Relative difference in pin-wise power distribution at 10 MWd/kg (compared to OTFK)

Figure 2. Normalized pin-wise power distribution with photon transport and relative difference (unit: %) compared to OTFK method (hot-spots marked by black squares).

compared to those from OTFK. B_4C in Pyrex contain B^{10} which is a strong neutron absorber, emitting 0.45 MeV gamma and these gammas can travel and get absorbed in nearby pins. The pins at the periphery of assemblies without Pyrex rods show higher power compared to those from OTFK, around 1%. In contrast, pin at the periphery of assemblies with Pyrex rods show lower power with photon transport, where a -0.5% to -1% relative difference is found when compared to the power obtained with OTFK.
It is observed in Figure 2b that the pin power at the edge of the core adjacent to the baffle have lower power when photon transport is turn on. The difference is more noticeable at later burn up as seen in Figure 2d where approximately -1.7% in the relative difference is found. It can be explained that the OTFK method does not transport photons, but the energy of photon is locally deposited and incorporated into the Kappa. Gamma generated in pins at the core edge, however, has more change to escape due to higher leakage at these positions. The power map is more accurate with photon transport.

The fuel temperature distribution is presented is Figure 3. The difference in temperature is equal to the temperature with photon transport minus those from OTFK.

At 0 MWd/kg, photon transport reduces the fuel temperature in virtually all the pins and the temperature can be dropped by 10 K. Only few pins have slightly higher fuel temperature when photon transport is on (marked by red dot in Figure 3b), but just by 0.2 K. The pins of assemblies at core edge show more temperature drop with increased burnup. As shown in Figure 2d, these pins show a lower power with photon transport compared to OTFK, leading to lower fuel temperature. Though pins close to Pyrex has higher power, but the fuel temperature of these pins are still lower with photon transport. It has been checked that the energy deposition in the fuel regions of such pin is smaller with photon transport while the energy deposition in non-fuel regions such as cladding and coolant is higher, resulting in higher pin power but lower fuel temperature of pins close to Pyrex. It is also noted that with OTFK, the hotspots in power distribution remain at the same pins at 0 and 10 MWd/kg



a) Fuel temperature distribution at 0 MWd/kg (with photon transport)

b) Difference in fuel temperature distribution at 0 MWd/kg (compared to OTFK)

c) Fuel temperature distribution at 10 MWd/kg (with photon transport)

d) Difference in fuel temperature distribution at 10 MWd/kg (compared to OTFK)

Figure 3. Fuel temperature distribution (unit: K) with photon transport and difference (unit: K) compared to OTFK (hottest spots marked by black squares).

while these spots are changed when photon transport is on. However, the hot spot for fuel temperature does not change for both OTFK and photon transport mode during depletion. The same issue occurred as explained previously that higher energy depositions in non-fuel materials led to higher pin power, making the shift of power hotspots but not temperature hotspots.

With photon transport, the maximum fuel center line temperature can drop by 18.31 K (1337.54 K vs 1355.85 K) and 18.01 K (1366.57 K vs 1348.56 K) at 0 MWd/kg and 10 MWd/kg, respectively. On the average, the fuel temperature drops by 4 to 5 K with the photon transport compared to those from OTFK. The change in other core parameters such as CBC, Fq is trivial when photon transport is on.

3. Conclusion

A photon transport module based on the present MOC neutron solver has been implemented in STREAM code. The energy deposition model based on the OTFK method has been modified to work with the photon energy deposition provided from the explicit photon calculation and the impact on a simple VERA 5 2D core has been present.

Compared to OTFK, photon transport can introduce a better power map for depletion and TH calculation. Pin-wise power can show a difference within ±1.7% compared to results derived with OTFK. The fuel temperature, in general, is reduced with photon transport since the generated gamma in fuel has been transported out of its birthplaces instead of deposit its energy locally. Only a few pins show higher fuel temperature at 0 MWd/kg but the difference is trivial (just 0.2 K). The maximum fuel center line temperature can be reduced by 18 K with photon transport. Other core parameters do not show any noticeable difference between calculations employed photon transport or OTFK.

Future study will focus on the analysis of the 3D problems, especially when Gadolinia is introduced in the core and compare to measurement data. The explicit calculation for energy deposition from neutron slowing down will also be implemented.

Acknowledgement

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