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Nuclear-thermal-coupled optimization code for the fusion breeding blanket conceptual design

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HIGHLIGHTS

- A nuclear-thermal-coupled predesign code has been developed for optimizing the radial build arrangement of fusion breeding blanket.
- Coupling module aims at speeding up the efficiency of design progress by coupling the neutronics calculation code with the thermal-hydraulic analysis code.
- Radial build optimization algorithm aims at optimal arrangement of breeding blanket considering one or multiple specified objectives subject to the design criteria such as material temperature limit and available TBR.

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ABSTRACT

Fusion breeding blanket as one of the key in-vessel components performs the functions of breeding the tritium, removing the nuclear heat and heat flux from plasma chamber as well as acting as part of shielding system. The radial build design which determines the arrangement of function zones and material properties on the radial direction is the basis of the detailed design of fusion breeding blanket. For facilitating the radial build design, this study aims for developing a pre-design code to optimize the radial build of blanket with considering the performance of nuclear and thermal-hydraulic simultaneously. Two main features of this code are: (1) Coupling of the neutronics analysis with the thermal-hydraulic analysis to speed up the analysis progress; (2) preliminary optimization algorithm using one or multiple specified objectives subject to the design criteria in the form of constrains imposed on design variables and performance parameters within the possible engineering ranges. This pre-design code has been applied to the conceptual design of water-cooled ceramic breeding blanket in project of China fusion engineering testing reactor (CFETR).

1. Introduction

Development and optimization of design of blanket is a logical progression based on initial results obtained with one and two dimensional scoping and parametric analyses followed by detailed 3D design and analyses. A set of critical parameters such as functional zones arrangement, composition of materials and coolant parameters (pressure, temperature and velocity) were expected to change and expanded as the evaluations and studies proceeded and as they provided feedback into the iterative design process [1]. Multi-disciplines are involved in the blanket design progress such as neutronics, thermal-hydraulics and mechanical load analysis those are depended on the different analysis codes as well as the individual parameter format [2]. It is time/force consuming progress for the blanket design.

Therefore a comprehensive design tool is needed to be capable of considering all these variables to define the optimum blanket design and satisfying all the design constraints for the adopted figure of merit and the blanket design criteria. Be different from the existing blanket design tools [3–5], this contribution aimed at optimizing the radial build design including optimization materials components, arrangement of cooling plates and breeder/multiplier zones those are parallel to first wall. The optimizing objective is to achieve the best nuclear and thermal-hydraulic performance for the breeding blanket. A Nuclear-thermal-coupled Optimization Code (NTOC) has been developed and been applied to the conceptual design of a kind of water cooling solid blanket whose radial

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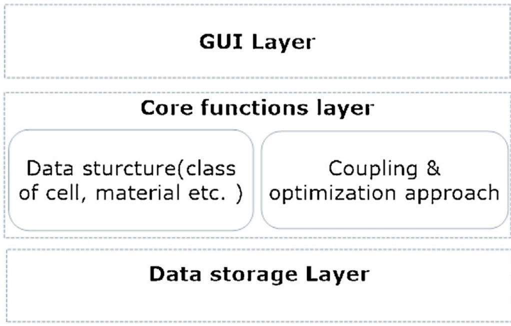


Fig. 1. Framework of NTOC.

build arrangement is parallel to the first wall. This paper discusses in details on the coupling, optimization approaches and implementations of this code.

2. Design principle of NTOC

2.1. Framework and GUI of NTOC

NTOC adopts the object-oriented and modularization design pattern which is benefit to improve the robustness and extendibility of code. The code has been developed on the Visual Studio 2010 platform. Fig. 1 shows the layering framework of NTOC consisting of graphical user interface (GUI) layer, core functions layer and data stored layer. User-friendly GUI aimed at making blanket design progress easier and more efficient. Fig. 2 (left) shows the main GUI which contains the radial build list view, functional buttons and option setting. Fig. 2 (right) shows the function of configuration which provides the blanket parameters setting and option of normalization factor which is the important parameter to estimate the nuclear response variations such as neutron flux and nuclear heating. Two options neutron wall load (NWL) and fusion power have been provided as normalization factor. Core functions layer includes the reasonable data structure and the approach of coupling and optimization. For the radial build optimization problem, each blanket function zone is designed as a cell class consisting of geometry data, materials and thermal parameters etc. Material as property of a cell class, it is also an independent class which encapsulated not only compositions and density of material but also operations of material such as adding and removing a composition from a material. Various cells are organized as a list array from which is convenient to insert and remove an instance of cell class. The approach of coupling and optimization calculation is introduced in detail in Section 2.2. For the data storage layer, it is data base for the default configuration parameters and material compositions.

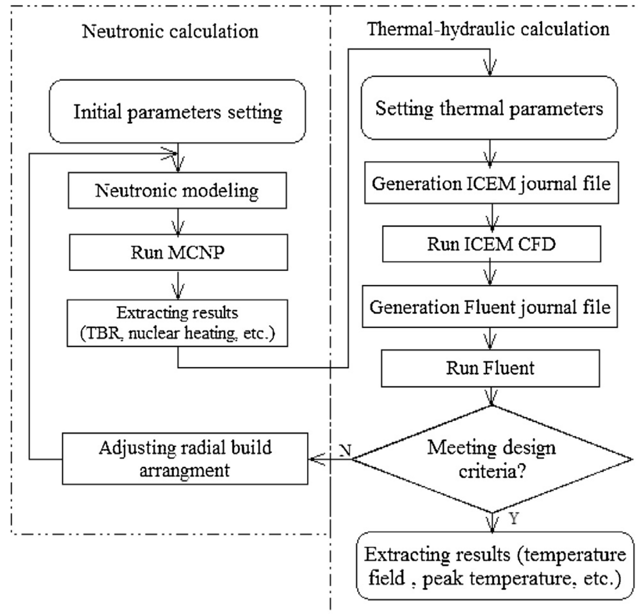


Fig. 3. Flowchart of coupling module of NTOC.

2.2. Approach of coupling and optimization

The design objective of NTOC is to achieve the best/proper nuclear-thermal performance by optimizing the radial build of blanket. To fulfill this objective, under the specific optimization strategy, the iterative optimizing progress would be carried out automatically by the coupling calculation interface. Fig. 3 shows the workflow chart of the coupling module. The key issue for coupling approach is to ensure that geometry dimension and properties of calculation models are consistent between neutronics calculation and thermal-hydraulic calculation. For this radial build optimization problem, one dimensional cylinder neutronics model and two-dimensional thermal calculation model have been developed respectively and they share the identical geome-

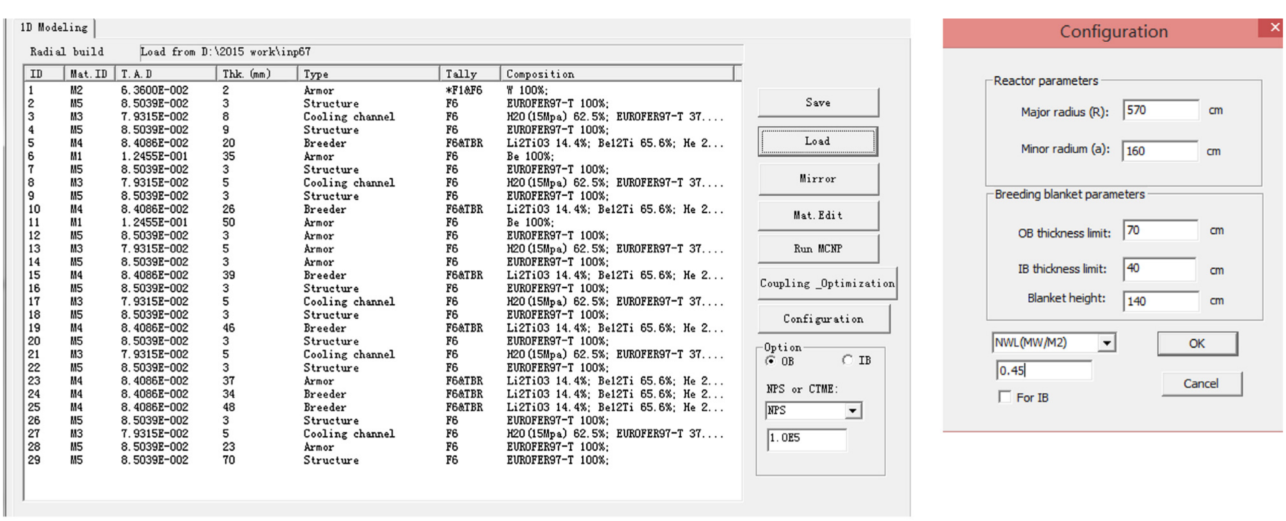


Fig. 2. Main window (left) and Configuration window (right) of NTOC.

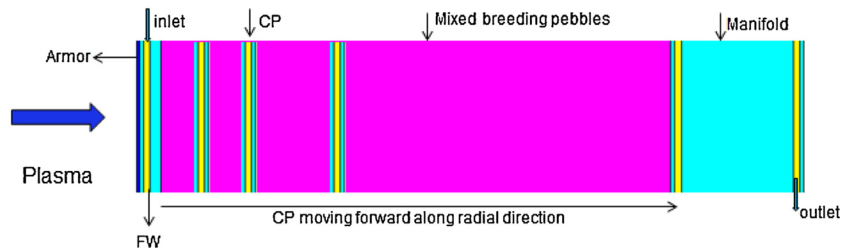


Fig. 4. Radial builds of optimized breeding blanket model.

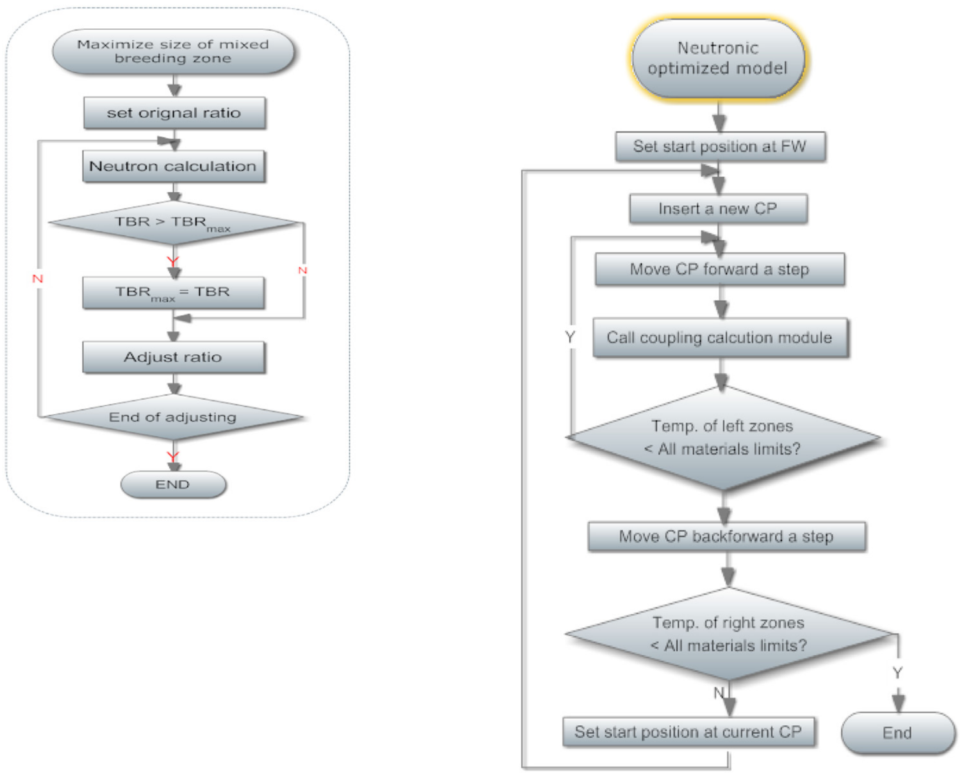
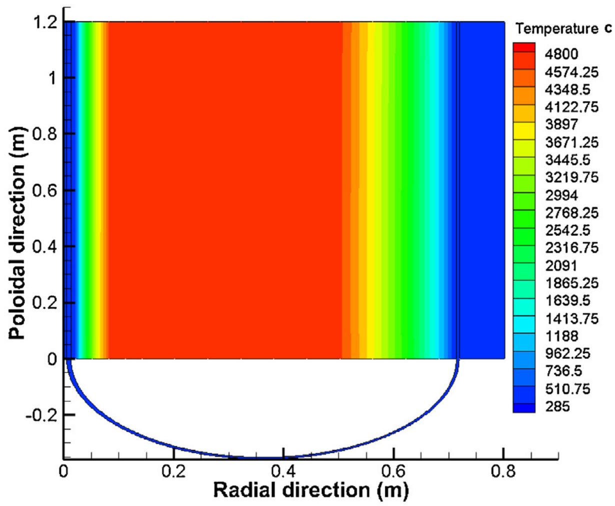


Fig. 5. (a) (left) Algorithm of neutronic optimization. (b) (right) Algorithm of thermal optimization.

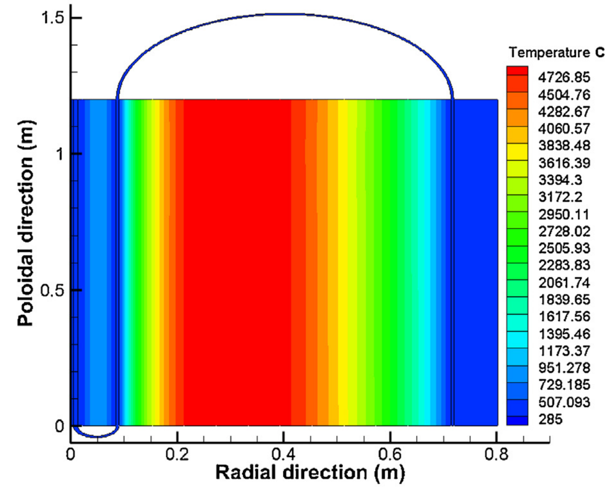
try dimension, material properties and nuclear heating deposition on the radial direction. On the poloidal direction the nuclear heating deposition is approximated to homogenization because this is a one-dimensional design optimization problem. For the neutronics calculation, MCNP [8] is used as neutrionic calculation code. Neutron source adopts isotropic volume distribution and source energy definition employs a Gaussian fusion spectrum. Nuclear responses are normalized according to NWL. The convergence criterion of neurtionic calculation is statistical relative error less than 5%. Thermal hydraulic calculation is carried out by using FLUENT code [9] and its convergence criteria are that the continuous and momentum equations should be less than 10e-04, and the energy equation should be less than 10e–05 [2]. More details such as boundary conditions and turbulence model used in CFD simulation would refer to our previous paper [2].

The radial build optimizing strategy is to satisfy following two design requirements simultaneously. The first requirement is to make tritium breeding ratio (TBR) of the whole breeding blanket as high as possible; the second one is to make the temperature of each breeding blanket function zone as high as possible for meeting the tritium releasing requirement in condition of the peak temperature of each function zone less than material temperature limit.

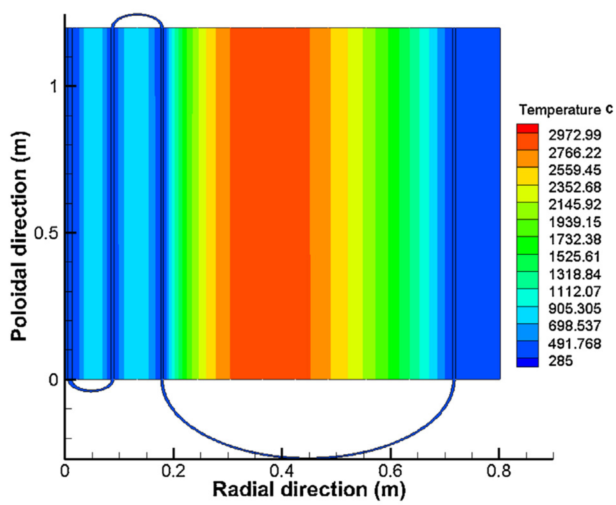
The optimization progress initializes from a cylinder neutronics model which just contains armor, first wall (FW), mixed breeder pebbles and manifold. Firstly, neutronics optimization shown in Fig. 5 (left) is carried out to achieve as high as possible TBR. Then thermal optimization shown in Fig. 5 (right) is carried out with help of coupling module. The cooling plane (CP) is inserted into breeder pebbles on the radial direction from the FW to manifold one by one until the peak temperature of each function zone all satisfy the temperature limits of materials. Once inserting a CP, the coupling module would be called to analyze the neutronics and thermal-hydraulic performance. If the peak temperature of left (front) function zones defined as zones from FW to the last inserted CP is below material temperature limit, the last inserted CP would be moved forward a step, otherwise it would be moved back forward a step. The default distance of moving step is 2 cm. Then temperature of right (back) functional zones which is defined as zones from the last inserted CP to manifold is calculated to judge whether their peak temperature exceeds the material temperature limit. If it is, these right functional zones are considered as the new left functional zones, and above progress of inserting a CP is repeated, otherwise the progress of thermal optimization is end. Fig. 4 illustrates an optimized arrangement of blanket radial build.



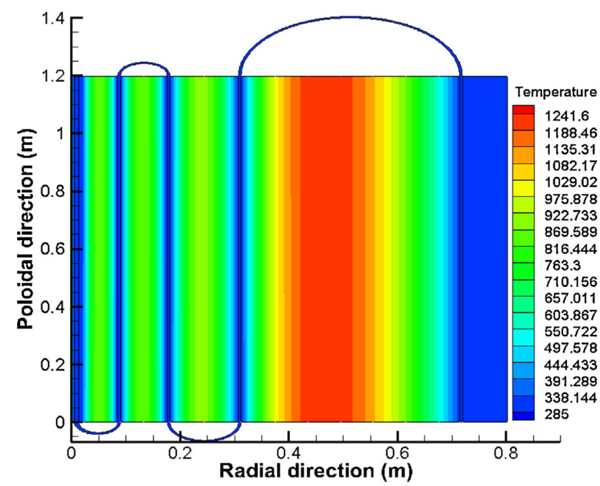
(a) Without CP in the breeder (TBR=1.489)



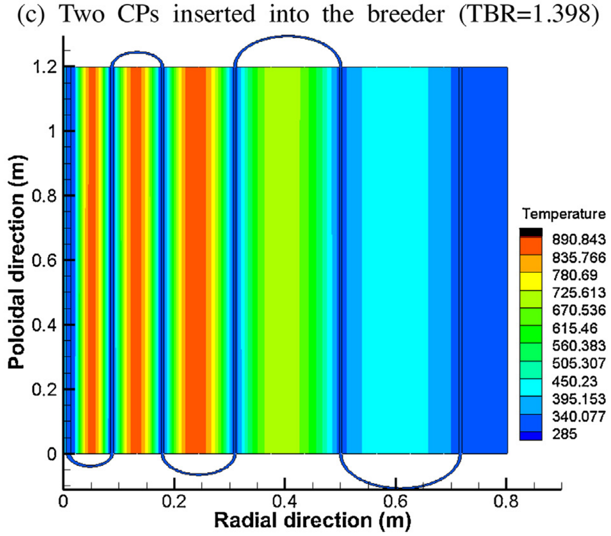
(b) One CP inserted into the breeder (TBR=1.434)



(c) Two CPs inserted into the breeder (TBR=1.398)



(d) Three CPs inserted into the breeder (TBR=1.391)



(e) Four CPs inserted into the breeder (TBR=1.390)

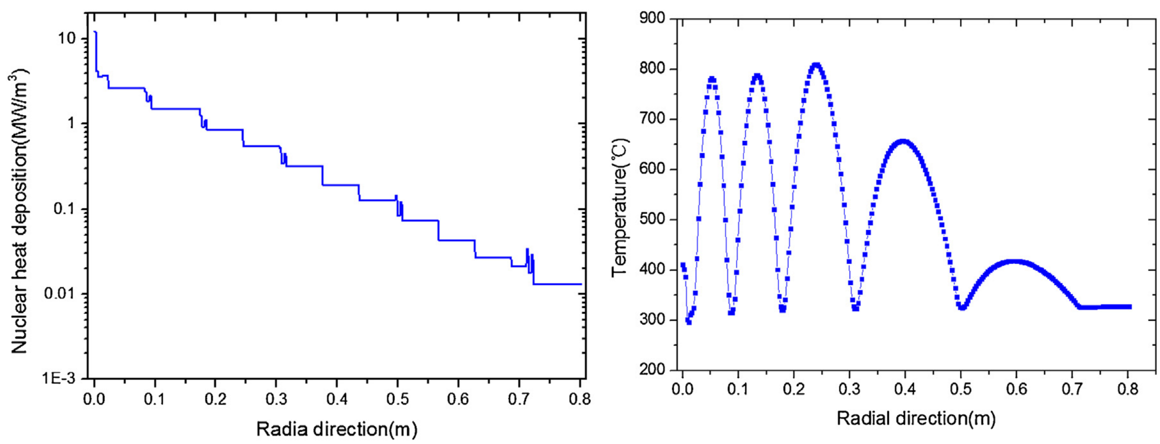
Fig. 6. The procedure of the radial build optimization.

3. Application and results

NTOC has been applied to the conceptual design of the water-cooled ceramic breeding blanket for Chinese Fusion Engineering Test Reactor (CFETR) [6]. Here is a radial build optimization example for the equatorial outboard blanket design. The design parameters, material temperature limit and thermal physical parameters

Table 1
Design parameters and thermal physical parameters of a water-cooled breeding blanket.

Design parameters [6]		
Heat flux density of first wall (MW/m^2)	0.5	
Coolant (water) input/output temperature(°C)	285/325	
Operation pressure (MPa)	15.5	
Average neutron wall loading (MW/m2)	0.454	
Materials	Temp. limit(°C)	Thermal physical parameters
Tungsten [10]	1300	$\lambda_{tungsten} = 207.98 - 0.136T + 5.649T^2 - 7.835 \times 10^{-9}T^3$
Be pebble beds [11,12]	1300	$\lambda_{Beryllium\,\text{pebble bed}} = 10.897 + 0.0016T - 5.265 \times 10^{-6}T^2$
RAFM [13]	550	$\lambda_{RAFM} = 32.5$
Breeder pebble beds [14]	900	$\lambda_{mixed\,\text{pebble bed}} = 1.68215 + 0.0013T - 1.894 \times 10^{-7}T^2$
Water [15]		$\lambda_{Water} = 1.587 - 0.0018T c_{pWater} = -7733 + 23T$
		$\mu_{Water} = 0.000314706 - 3.95055 \times 10^{-7}T$
		$\rho_{Water} = 1902.14 - 2.054(T + 273)$



(a) Nuclear heat deposition on the radial direction (b) Temperature variation on the radial direction

Fig. 7. Results of the final optimized radial build.

of this pressured water-cooled blanket are listed as Table 1. In the formula of thermal physical parameters, λ is thermal conductivity (w/(m k)); C_p is specific heat capacity (j/(kg k)); ρis mass density (kg/m^3); μis the coolant dynamic viscosity (Pa s); T is the temperature, °C.

To optimize the radial build arrangement. The first step is setting blanket parameters in the configuration window shown in Fig. 3. As one of important configuration parameters, the NWL is set to use as a normalization factor for calculation nuclear heat deposition. The initial geometry and material property of blanket model could be set in the main window. Then the radial build optimization would be carried out automatically by clicking the coupling optimization button, and the whole optimizing procedure spends only a few minutes without extra manual intervention. Fig. 6(a)–(e) shows the radial build optimization progress. Fig. 6(a) shows the temperature distribution of initial model which has no CP inserted in the mixed breeder pebbles. It is noted that the peak temperature in breeder pebbles reaches to more than 4000° because no coolant removes the heat away effectively. The TBR is as high as 1.489 with the optimized ratio of mixture breeder which is 14.4% of Li_2TiO_3, 65.6% of $Be_{12}Ti$ and 20% of Helium. Then the CP is inserted into the mixed breeder pebbles one by one to transfer heating as well as to ensure the temperature of breeder high enough for meeting tritium releasing requirement. Fig. 6(b)–(e) show that with inserting the CPs, the temperature of breeder pebbles bed decreased to safety temperature range from FW to manifold. When four CPs are inserted into the mixed breeding zone, the peak temperature of whole breeding blanket has decreased to 890 °C which is safe temperature of breeder pebbles. The final optimized results of nuclear-thermal performance have been shown in Fig. 7(a) and (b) which satisfy the entire design requirements and materials temperature limit.

To compare the differences of nuclear and thermal performance between 1D model optimized by NTOC and 3D model, a 3D blanket model has been developed according to radial build arrangement of 1D model. Thermal-hydraulic analysis on the whole module of water cooled ceramic breeder blanket (WCCB) has been carried out [7]. The comparison results show a good agreement of nuclear heating deposition along the radial direction, except that high relative error occurred in the front zone of blanket, namely 33% for tungsten armor and 17% for the first breeder zone, as shown in Fig. 8.

4. Summary and future work

A nuclear-thermal-coupled code (NTOC) has been developed to optimize the radial build of breeding blanket. It facilitates the pre-design progress of fusion breeding blanket and saves times and manual works for models developing and parameters passing between nuclear and thermal analysis codes. The functions of NTOC have been validated by the preliminary application for the conceptual design of WCCB which has a paralleling radial build arrangement to FW. The main features of NTOC are concluded as following:

1) Friendly GUI facilitates design configuration and parameters setting.
2) Efficiently coupling calculation provides the nuclear & thermal results simultaneously.

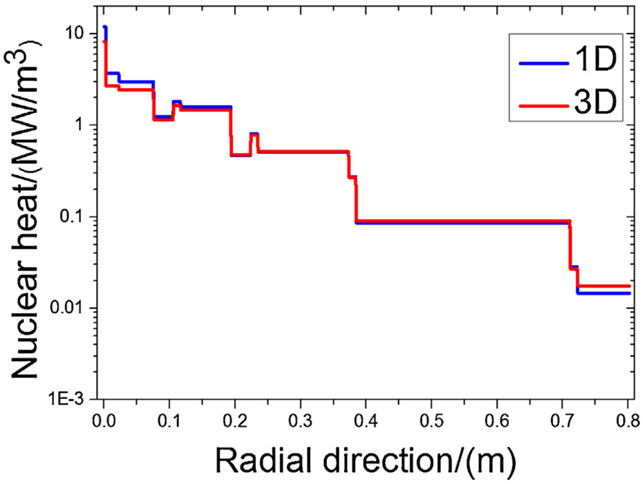


Fig. 8. Comparison nuclear heating deposition of 1D model and 3D mode.

3) Automatically optimization provides the proper/best radial build arrangement based on the nuclear-thermal coupling calculation results.

In the future work, additional functions would be integrated into NTOC: adding the shielding design function and providing several variance reduction (VR) techniques; expanding the parallel arrangement of radial build to other patterns of arrangement optimization etc.

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