Concept Design and Thermal-hydraulic Analysis for Helium-cooled ADS

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ABSTRACT

The Accelerator Driven Subcritical Reactor System (ADS) is a kind of nuclear reactor which can burn minor actinide waste products produced from conventional reactors with inherent safety features. In this paper, a concept design of 10MW helium-cooled experimental ADS with prismatic reactor core and solid target is presented.

The subcritical core is divided into a fast neutron zone and a thermal neutron zone. There is only one kind of hexagonal prism fuel assembly in the fast neutron zone, and the coated fuel particles disperse in these assemblies. And there are three kinds of hexagonal prism pin-in block type fuel assembly which contains hexagonal graphite block and annular fuel rods in thermal neutron zone. Because of the characteristics of a subcritical reaction process, the fission chain reaction is maintained by additional neutrons generated in spallation target induced by proton beams. Tungsten is chosen as the spallation target material and is modeled into the honeycomb structure. The high pressure helium is used as coolant for both the core and the spallation target.

The thermal-hydraulic model and corresponding code for ADS was built, in which the solid domain was simulated with three-dimensional heat conduction model and the fluid domain was simulated with the one-dimensional quasi-static model. The results indicate that the peak temperature in core and target is lower than the limiting values under operating state.

KEYWORDS

ADS, Helium-cooled, Prismatic block core, Solid target

1. INTRODUCTION

With the large-scale application and development of nuclear energy, post processing of spent nuclear fuel became a subject of much attention, because of the radioactivity of fission products (FPs) and minor actinides (MAs), as well as the low utilization of fuel. Recently the Accelerator Driven System [1,2] (ADS) is introduced for transmutation of spent nuclear fuel. In ADS, a high-energy proton beam strikes a heavy element target [2,3], which yields copious neutrons by (p, x n) spallation reaction, and the target drives fission chains in a subcritical core.

The liquid-metal-cooled ADS [4,5,6] attracts the most attention in the field of ADS, in this framework the liquid-metal spallation targets (such as window target and windowless target) [7,8] are the scheme most talked about. Meanwhile, with the established technologies and the inherent thermal safety of High Temperature Reactors (HTR), the gas-cooled ADS [9,10] which we adopted is also a promising scheme. As for the spallation target, liquid-metal target and gas-cooled solid target are all the candidates. In view of neutron economy and the simplification of cooling system and auxiliary system, helium-cooled solid target is a scheme worthy of exploration. The water-cooled tungsten-tantalum target is widely used in spallation neutron source, but there are rare reports about gas cooled solid target used for ADS. Then a concept design of helium-cooled tungsten target will be presented.

The structure of the paper is as follows. Section 2 gives a description of the spallation target design and the subcritical core design. Section 3 introduces the calculation of deposition heat distribution in target and core. And the thermal-hydraulic model of the system is presented in Section 4. Finally, the results of steady condition in Section 5 demonstrate the effectiveness of the model and the feasibility of design.

2. CONCEPT DESIGN FOR ADS

2.1. Reactor Core

The annular reactor core [11] similar to High Temperature Engineering Test Reactor (HTTR) [12] in Japan is shown in Figure 1. The subcritical core can be divided into the fast neutron zone, thermal neutron zone, permanent reflector block and replaceable reflector block. The spallation target which produces neutrons for the subcritical core is located in the center of core. With the action of cavity cooling panels surrounding the reactor pressure vessel, the decay heat will be transferred radially through the fuel regions, side reflector blocks and reactor pressure vessel to the cooling panel by heat conduction, radiation and convection without any active cooling system.

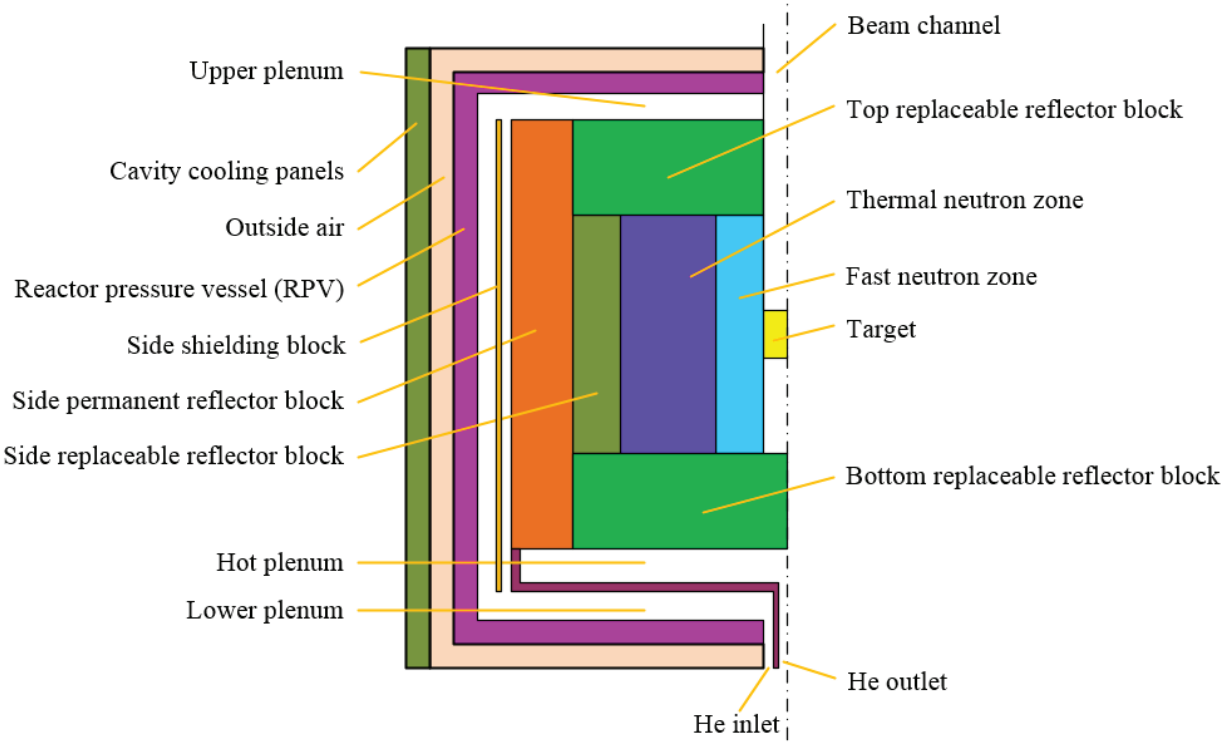


Figure 1. Configuration of reactor core

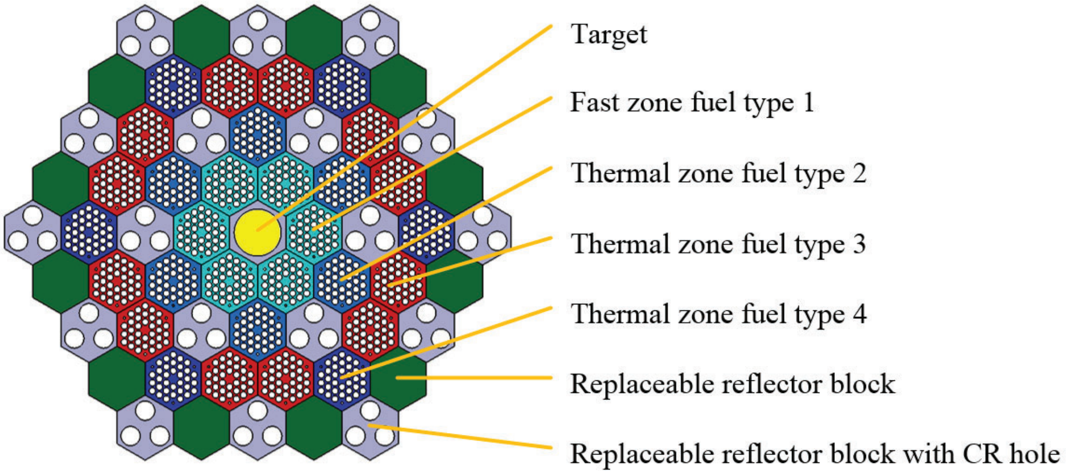


Figure 2. Fuel arrangement and top view of core

As shown in Figure 2, there is only one kind of hexagonal prism fuel assembly (type 1) in the fast neutron zone, and the TRISO fuel particles disperse in these assemblies. There are three kinds of hexagonal prism pin-in block type fuel assembly (type 2, type 3, type 4) in the thermal neutron zone, the assembly contains hexagonal graphite block and annular fuels rods. The main parameters of the core are listed in Table I.

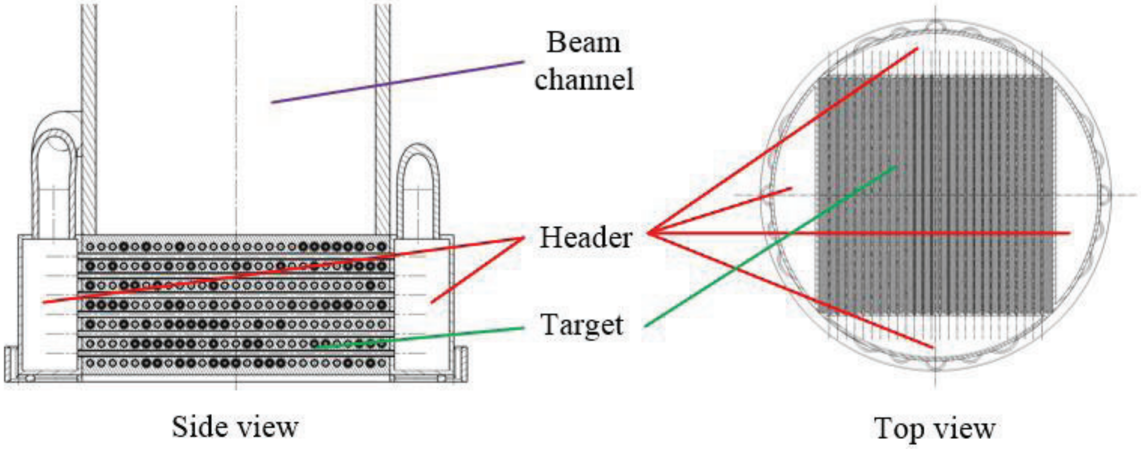
Table I. Main parameters of core

General	
thermal power	10 MW
form of fuel	TRISO
coolant	He
mass flow	5 kg/s
pressure	4 MPa
inlet temperature	480 K
outlet temperature	864 K
Geometry	
layer number of fuel assembly	5
assembly number at each layer (fast/thermal)	30(6/24)
height of assembly	400 mm
assembly spacing	360 mm
gap between adjacent assemblies	2 mm
diameter of coolant hole	41 mm
coolant hole spacing	51.5 mm
form of fuel	TRISO
Fast zone	
fuel composition	$(U,MA)O_2$
enrichment	(U:15%, MA:40%)

base material	SiC
volume fraction of TRISO fuel	25%
form of dispersion	in block
number of coolant holes	33
Thermal zone	
fuel composition	UO_2
enrichment	(2#:6%, 3#:6%, 4#:7.5%)
base material	graphite
volume fraction of TRISO fuel	8.16%
form of dispersion	in rod
number of coolant holes	37
material of reflector	graphite

2.2. Spallation Target

In ADS a spallation target as a source of neutrons can drive fission chains in a subcritical core. The configuration of the spallation target is schematically illustrated in Figure 2. As shown in Figure 3 and Table II, the target is a cuboid with intensive interlacing round channels, which increase the heat transfer area. The proton beam is injected in -z-direction, while high pressure helium flows in honeycomb holes in x-direction and y-direction. Tungsten is chosen as the spallation material for the target due to its high neutron production rate, low neutron absorption, high melting temperature, good heat conductivity and mechanical strength.



Side view

Top view

Figure 3. Configuration of spallation target

Table II. Parameters of target

Geometry	
length	216 mm
width	216 mm
height	104 mm
number of channel	27×13
channel pitch	8 mm
channel diameter	5 mm
Operating condition	
proton energy	250 MeV
current intensity	4 mA
beam diameter	200 mm
pressure	4 MPa
inlet temperature	500 K
inlet velocity	30 m•s^{-1}
outlet temperature	711 K

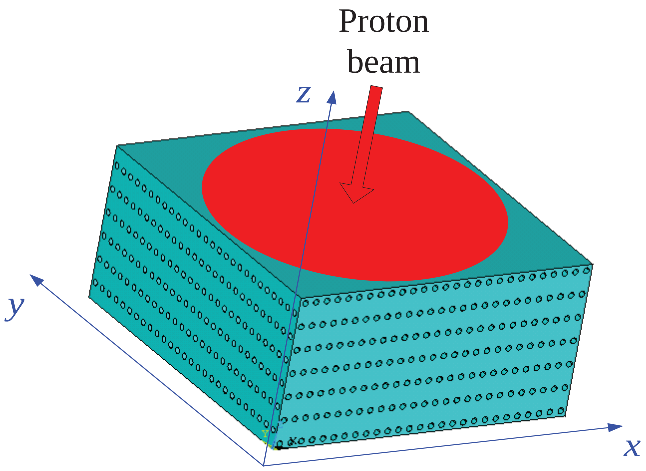


Figure 4. Geometry of target

3. CALCULATION OF DEPOSITION HEAT

When the high energy protons generated by the accelerator hit upon the target, neutrons are generated and the deposition heat is released into the target. In the direction of radius, the flux of injection proton is distributed as the parabolic function. Driven by the neutrons from the target, the fission reaction happens, and heat is generated in the fuel.

MCNPX code is used to calculate the deposition heat distribution in the target and core. The deposition heat distribution of the target and core is given in Figure 5 and Figure 6 respectively. The total thermal power of target and core is 0.863 MW and 9.988 MW respectively.

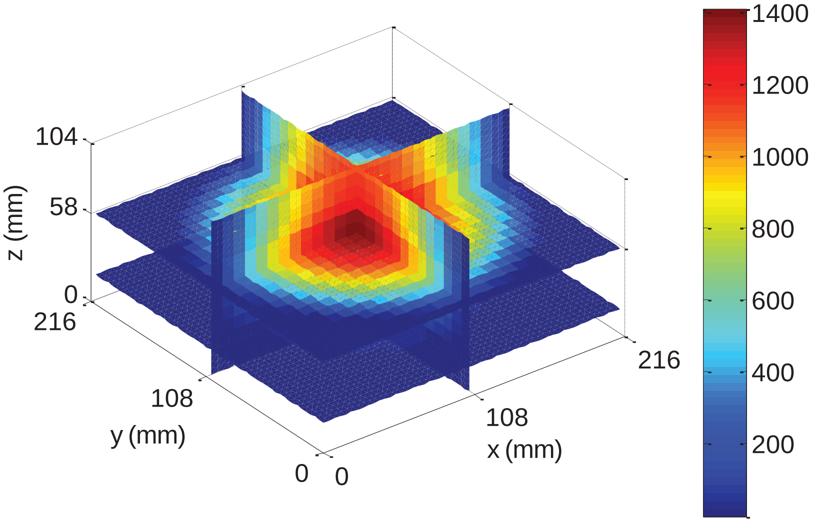


Figure 5 Deposition heat distribution (W·cm^{-3})

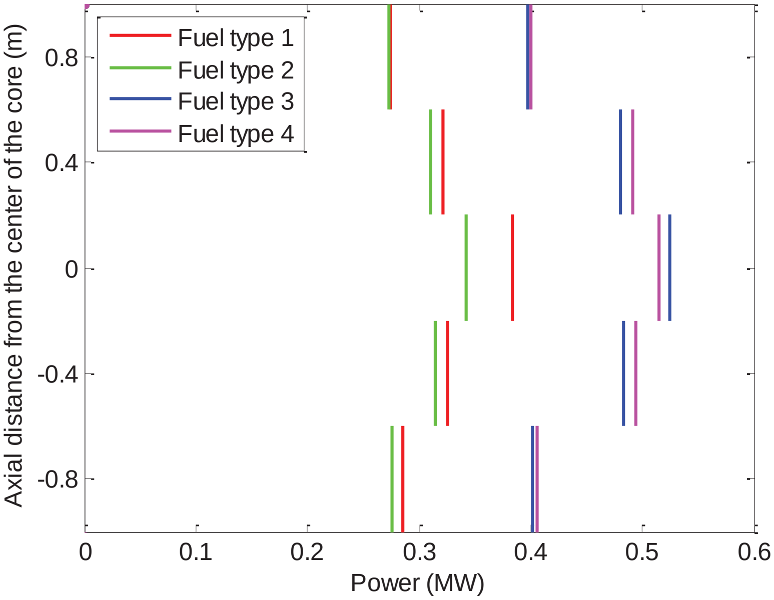


Figure 6. Thermal power distribution

4. THERMAL-HYDRAULIC MODEL

Thermal analysis of this complex core and target geometry using a CFD code would require a large amount of computing time. Thus, a simple model was developed to solve the heat transfer problem in ADS, as shown in Figure 7.

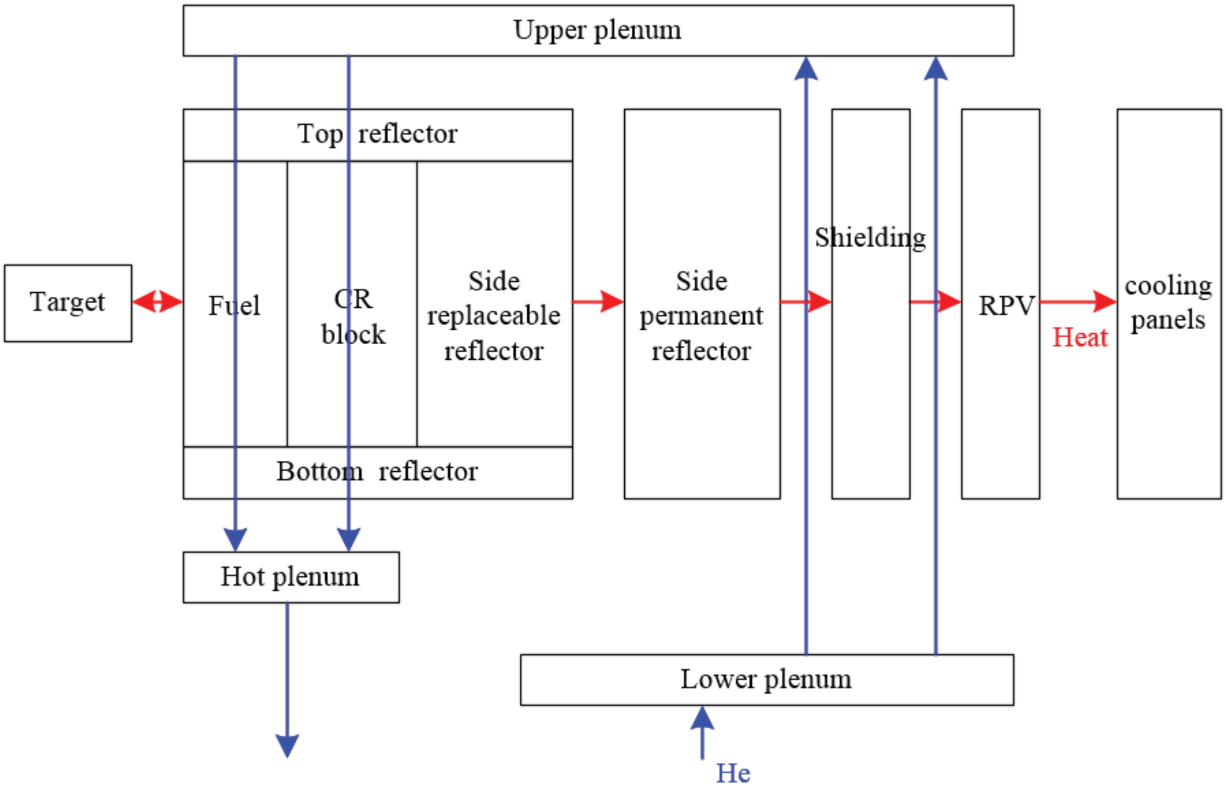


Figure 7. Heat transfer model

In the heat transfer problem of ADS, the temperature distribution is the main concern. Thus, we analyze the solid zone with a three-dimensional heat conduction model. For helium in the channels, what we concerned only with the ability to carry the heat, rather than the detailed distribution of the flow field. The L/D of channels is 44.0, and so a one dimensional model is accurate enough to simulate the flow and convection heat transfer; and the inertia force and thermal capacity of helium are negligible, then the quasi-static model is used [13].

For the subcritical reactor, the 1/6th of core can represent the whole core because of the rotational symmetry. Then the 1/6 core is recognized as the computational domain. In the vertical direction, the computational domain is divided into 9 layers related to the assemblies; in the horizontal direction, the computational domain is divided into 26 nodes, as shown in Figure 8. To simplify the analysis, cross flow and bypass flow have been neglected in preliminary calculations [14].

The target is divided into 75816 orthogonal 4mm×4mm×4mm grids, shown in Figure 9; Helium channels are divided to 18954 4mm long cylinders which match the solid grids, shown in Figure 10. To simplify the calculation, radiation in the channels is ignored, which is conservative.

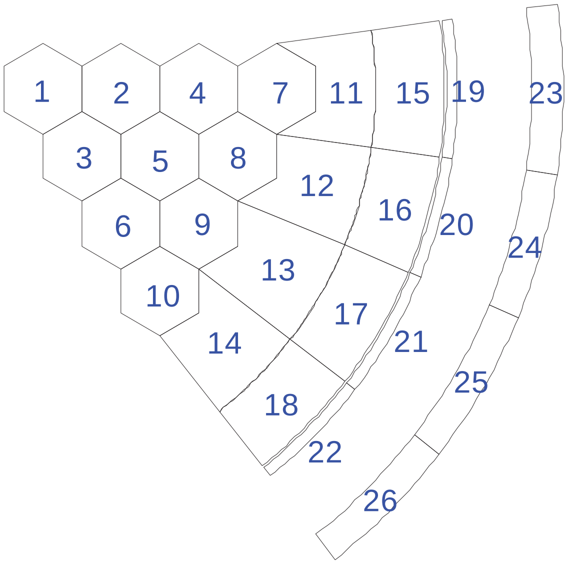


Figure8. Core nodes of solid domain (top view)

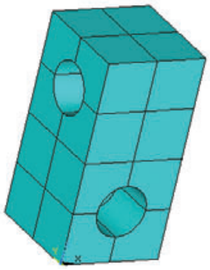


Figure9. Target grids of solid domain (partial)

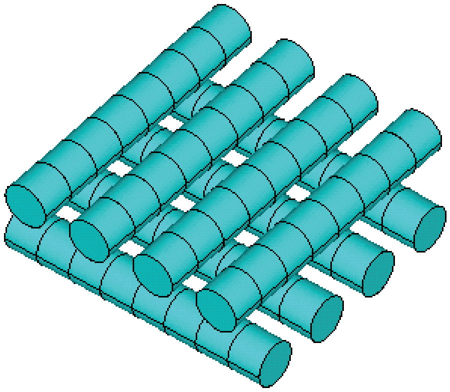


Figure 10. Target grids of fluid domain (partial)

The three-dimensional transient heat conduction equation of solid zone can be discretized as follows:

$$\rho C\Delta V\frac{T-T_0}{\Delta t}=\sum_i \lambda\frac{A_i}{\Delta l_i}\left(T-T_i\right)+\lambda\frac{A_{z+}}{\Delta z}\left(T-T_{z+}\right)+\lambda\frac{A_{z-}}{\Delta z}\left(T-T_{z-}\right)+S_{\mathrm{v}}\Delta V-\left(Q_c+Q_r\right) \tag{1}$$

$$Q_c=\int_V h\left(T_{\mathrm{w}}-T_{\mathrm{f}}\right)\mathrm{d}A \tag{2}$$

$$Q_r=\sum_i\left[\frac{\sigma\left(T^4-T_i^4\right)}{\frac{1}{\varepsilon A_r}+\frac{1}{\varepsilon_i-1}\frac{1}{A_i}}\right] \tag{3}$$

The governing equations of fluid domain are as follows[14]:

Mass conservation equation:

$$\frac{\partial M}{\partial l} = 0 \tag{4}$$

Momentum conservation equation:

$$\frac{\partial\left(M^2/\rho_\mathrm{f}\right)}{\partial x} + \frac{\partial p}{\partial l} + f = 0 \tag{5}$$

The formula[14,15] used to calculate the friction coefficient in channels is as below.

$$f = \begin{cases} 64Re^{-1} & Re < 2300 \\ 0.3164Re^{-0.25} & Re \geq 2300,\ \text{circular} \\ 0.376Re^{-0.25} & Re \geq 2300,\ \text{annular} \end{cases} \tag{6}$$

Energy conservation equation

$$\frac{\partial\left(MCpT_\mathrm{f}\right)}{\partial l} = q_\mathrm{l} \tag{7}$$

$$q_\mathrm{l} = h\left(T_\mathrm{w} - T_\mathrm{f}\right)\frac{\mathrm{d}A}{\mathrm{d}l} \tag{8}$$

$$h = \frac{\lambda_\mathrm{f}}{d} Nu \tag{9}$$

The correlation[14,15] used to calculate Nusselt number is as below.

$$Nu = \begin{cases} \left(3.66^3 + 1.66^3 RePr\dfrac{d}{l}\right)^{1/3} & Re < 2300 \\ 0.0214\left(Re^{0.8} - 100\right)Pr^{0.4}\left(1 + \left(\dfrac{d}{l}\right)^{2/3}\right) & Re \geq 2300,\ \text{circular} \\ 0.0215Re^{0.8}Pr^{0.4} & Re \geq 2300,\ \text{annular} \end{cases} \tag{10}$$

5. RESULTS OF STEADY CONDITION

With the boundary conditions for the cooling panels (70℃) and outside air (30℃), the results of rated condition are obtained. Figure 11, Figure 12 and Figure 13 show the temperature distribution of blocks and fuel rods in steady-state operation, Figure 14 shows the temperature distribution of the target.

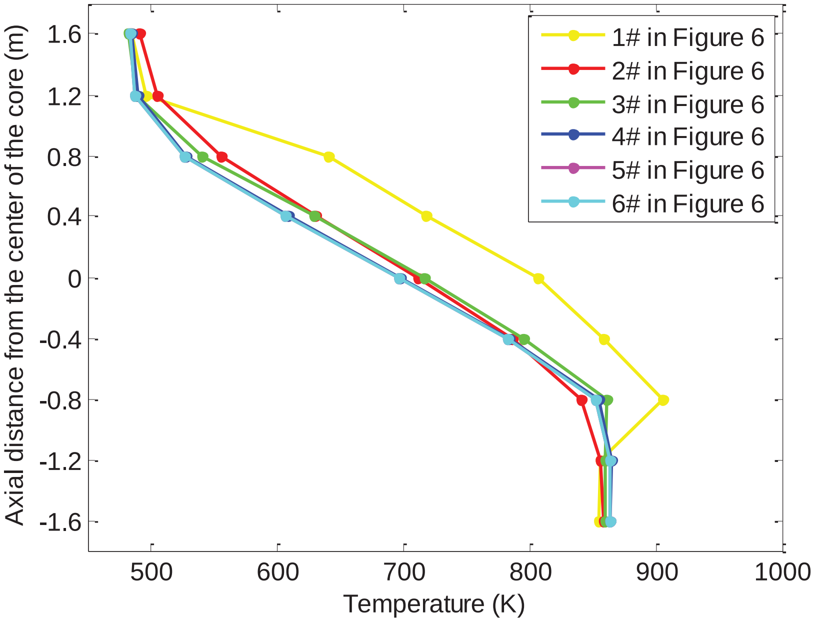


Figure 11. Blocks temperature distribution

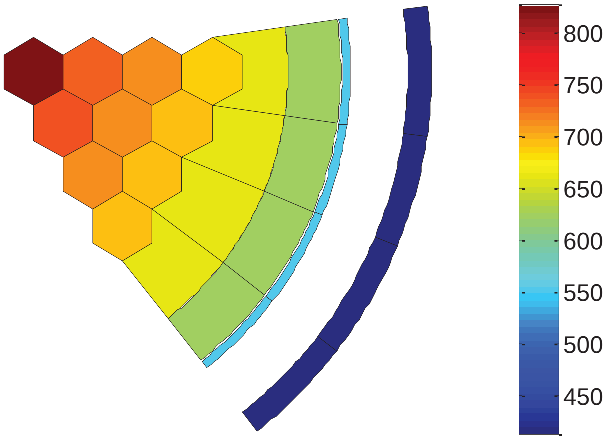


Figure 12. Blocks temperature horizontal distribution (the center section of core)

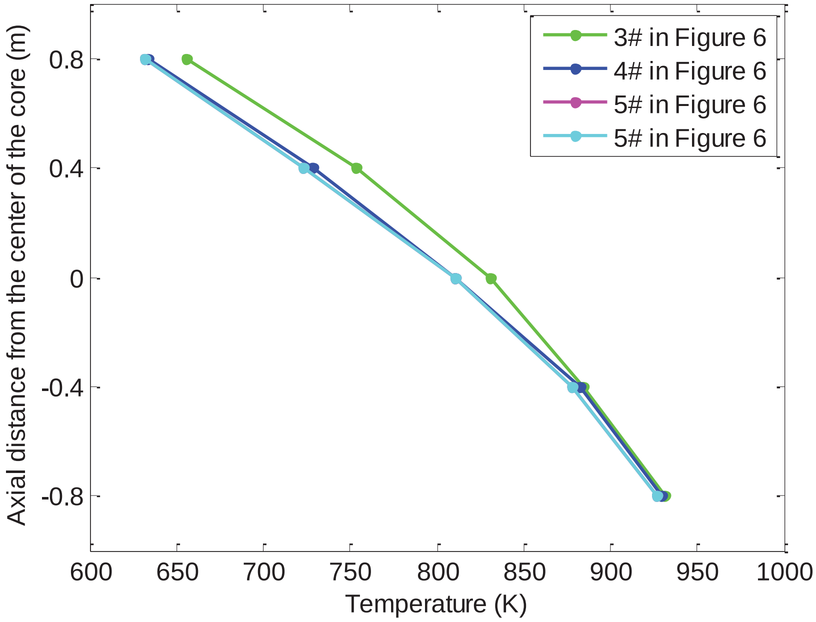


Figure 13. Fuel rod temperature distribution

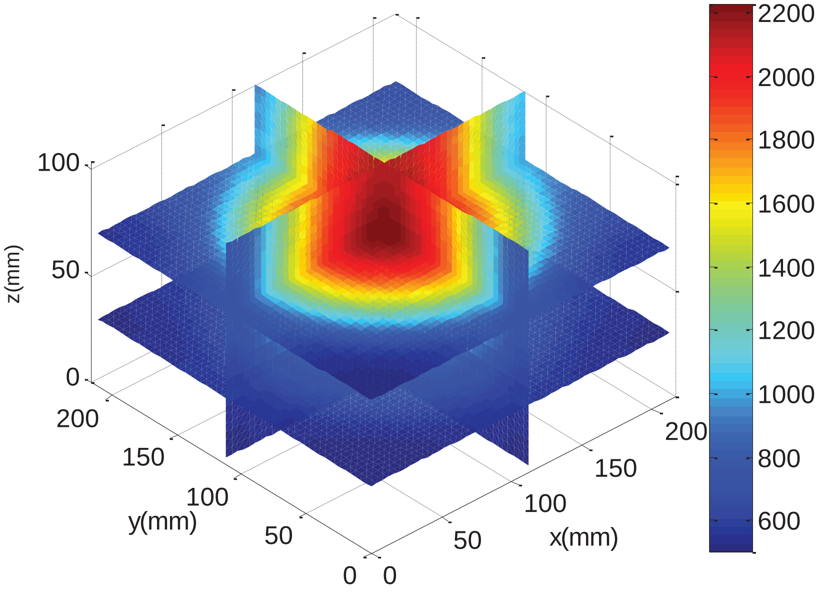


Figure 14. Target temperature distribution of solid (K)

The maximum temperature of fuel is 931 K, substantially below the limiting value of 1533 K[16]. And the peak target temperature is located at (114 mm, 114 mm, 70 mm), with the temperature of 2223 K, also below the melting point of tungsten 3673 K. So, the design of ADS might be feasible.

6. CONCLUSIONS

The thermal-hydraulic analysis is an essential part in the R&D of ADS. A helium-cooled prism core and target conceptual design was presented in this article. The thermal-hydraulic model for ADS is built, in which the solid domain is simulated with a three-dimensional heat conduction model and the fluid domain is simulated with a one-dimensional quasi-static model. The results demonstrate the effectiveness of the model and the feasibility of the thermal design preliminarily.

NOMENCLATURE

A	area of convection wall (m^2)
A_r	area of radiation wall (m^2)
C	specific heat of tungsten (J•kg^{-1}•K^{-1})
Cp	specific heat of helium (J•kg^{-1}•K^{-1})
d	diameter of channel (m)
f	friction coefficient in channels
h	convection coefficient of wall (W•K^{-1}•m^{-2})
M	mass flow rate of helium (kg•s^{-3})
Nu	Nusselt number of helium
l	length of channel (m)
p	pressure of helium (Pa)
Pr	Prandtl number of helium
Q_c	Wall heat flux of convection (W)
Q_r	Wall heat flux of radiation (W)
q_l	heat flow of helium per unit length (W/m)
Re	Reynolds number of helium
S_v	density of the heat source (W•m^{-3})
t	time (s)
T	average temperature of solid element (K)
T_f	temperature of helium (K)
T_w	temperature of wall (K)
V	volume of solid element (m^3)

Greek letters

λ	thermal conductivity of tungsten (W•m^{-1}•K^{-1})
λ_f	thermal conductivity of helium (W•m^{-1}•K^{-1})
ρ	density of tungsten (kg•m^{-3})
ρ_f	density of helium (kg•m^{-3})

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