Original Article

Design and evaluation of an innovative LWR fuel combined dual-cooled annular geometry and SiC cladding materials

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A B S T R A C T

Dual-cooled annular fuel allows a significant increase in power density while maintaining or improving safety margins. However, the dual-cooled design brings much higher Zircaloy charge in reactor core, which could cause a great threat of hydrogen explosion during severe accidents. Hence, an innovative fuel combined dual-cooled annular geometry and SiC cladding was proposed for the first time in this study. Capabilities of fuel design and behavior simulation were developed for this new fuel by the upgrade of FROBA-ANNULAR code. Considering characteristics of both SiC cladding and dual-cooled annular geometry, the basic fuel design was proposed and preliminary proved to be feasible. After that, a design optimization study was conducted, and the optimal values of as-fabricated plenum pressure and gas gap sizes were obtained. Finally, the performance simulation of the new fuel was carried out with the full consideration of realistic operation conditions. Results indicate that in addition to possessing advantages of both dual-cooled annular fuel and accident tolerant cladding at the same time, this innovative fuel could overcome the brittle failure issue of SiC induced by pellet-cladding interaction.

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1. Introduction

Towards higher economy and security of Light Water Reactors (LWRs), the concept of annular fuel with internal and external cooling channels was proposed by Massachusetts Institute of Technology (MIT) [1]. Benefit from the innovative geometry, this fuel allows a 30-50% increase in power density while maintaining or even improving safety margins [2]. Hence, the dual-cooled annular fuel element aroused wide attention, and was developed as a promising fuel design for LWRs by Westinghouse Electric Corporation [1], Korea Atomic Energy Research Institute [3] and China Institute of Atomic Energy [4]. Much work has been done and great progresses have been made, including fuel design [5,6], manufacture technology [7], thermal-hydraulic analysis [8–11] and fuel performance analysis [12,13], as well as the optimization towards addressing the concern of blockage of internal channel [14]. However, there is one concern that might hinder the final application of dual-cooled annular fuel in LWRs. The annular geometry brings larger cooling area, but also means much higher Zircaloy charge in reactor core, which is a great concern to LWRs under severe accident conditions.

One of the direct and effective way to solve this issue is replacing the Zircaloy cladding by Accident Tolerant Fuel (ATF) claddings. ATF claddings could be divided into three categories: the coated Zircaloy, other metal claddings and ceramic claddings [15]. The coated Zircaloy could mitigate or delay the oxidation and hydrogen generation, but could not completely avoid them under extreme circumstances. For other metal claddings, take FeCrAl for example, the higher neutron absorption cross section [15] could be unacceptable for the annular fuel due to its much higher cladding-fuel volume ratio. As to ceramic cladding, take SiC cladding for example, could provide 3–4 orders of magnitude higher oxidation resistance and has even better neutron economic performance than Zircaloy [16], seems to be a promising option for dual-cooled annular fuel. In addition, the annular geometry could address some concerns of SiC cladding. In specific, because of the presence of outward swelling and the absence of inward creep down of SiC cladding, the fuel temperature and Fission Gas Release (FGR) could be substantially higher than those in conventional UO2-Zr fuels. However, this issue could be perfectly solved by annular fuel with larger heat transfer.

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area and shorter heat conduction conductive path. Therefore, the combination of dual-cooled annular geometry and SiC cladding seems to be an attractive nuclear fuel design for LWRs.

Aiming to verify the feasibility of above suppose and derive initial insights into UO₂-SiC annular fuel, preliminary design, optimization and performance evaluation of this innovative fuel concept were conducted in this study. The preliminary findings of this research could inform future fuel testing and development of dual-cooled annular fuel.

2. Upgrade of FROBA-ANNULAR and its validation

2.1. Modeling for SiC properties

There are two category of SiC materials: monolithic SiC (generally fabricated by Chemical Vapor Deposited method, CVD for short) and composite SiC (SiC/SiC Ceramic Matrix Composite, CMC for short) [16]. It should be noted that properties vary greatly with different manufacturing technologies for CMC, the CMC refers to the HNLS/ML-F [17] CMC in this study.

(a) Irradiation swelling. Different with Zircaloy, SiC presents significant irradiation swelling. According to reference [18], there was obvious saturation effect on SiC swelling and no substantial difference was found between CVD and CMC. The saturated swelling was temperature dependent and can be calculated with Eq. (1):

$$\frac{\Delta V}{V_0} = 4.82 - 0.00617 \cdot T + 2.17 \times 10^{-6} \cdot T^2$$  

where \(\frac{\Delta V}{V_0}\) is the saturation swelling volume in %; \(T\) represents the temperature in K. Carpenter [19] further established the transient swelling model of SiC, given in Eq. (2):

$$\left(\frac{\Delta V}{V_0}\right)_{sat} = \left(\frac{\Delta V}{V_0}\right)_{sat} \cdot \left[1 - \exp\left(-\frac{6 \gamma}{\gamma_{sat}}\right)\right]$$  

where \(\frac{\Delta V}{V_0}\) means the swelling volume in % at certain moment; \(\gamma\) is the irradiation dose in dpa; \(\gamma_{sat}\) represents the saturation dose and is suggested as 1 dpa for SiC.

(b) Thermal conductivity. High-purity CVD has a high thermal conductivity, but it can be significantly reduced due to radiation defects. In general, the thermal conductivity of CVD is given as a function of temperature and irradiation swelling [18]:

$$\frac{1}{K_{CVD}^{irr}} = \frac{1}{K_0} + \frac{1}{K_{irr}}$$

where \(K_{CVD}^{irr}\) represents the thermal conductivity of CVD in W m⁻¹ K⁻¹ after irradiation, without irradiation and with saturated irradiation, respectively, and the last two can be calculated by Eq. (5) [16]. Fig. 1 shows thermal conductivities of CVD and CMC obtained by this study and General Atomics [20]. Conductivities of CMC present a relevant large difference, which might be caused by different manufacturing technologies.

(c) Thermal expansion. According to the experiment [21], the influence of radiation on thermal expansion rate of SiC can be neglected, and no difference was found between CVD and CMC. The following equation was suggested for SiC expansion calculation:

$$\alpha = 10^{-6}(0.7765 + 1.435 \times 10^{-2}T - 1.2209 \times 10^{-5}T^2 + 3.8289 \times 10^{-9}T^3)$$  

where \(\alpha\) is the coefficient of thermal expansion in K⁻¹.

(d) Elastic/pseudo-plastic properties. The elastic modulus of CVD decreases slightly with the radiation, and can be calculated with Eq. (7):
where \( E_{\text{non-irr}}^{\text{CVD}} \) and \( E_{\text{irr}}^{\text{CVD}} \) represent Young’s modulus of CVD in Pa before and after irradiation, respectively; \( V_f \) means the dimensionless porosity. The Poisson’s ratio of CVD is generally regarded as a constant of 0.21. Since CVD is a typical ceramic material, there is no plastic or pseudo-plastic deformation.

For CMC, the mechanical deformation is more complicated because of its pseudo-plastic deformation. The mechanical calculation of CMC in this study was performed based on the stress-strain curve of CMC, as shown in Fig. 2 [22]. Firstly, CMC presents elastic behavior before the load exceeds the Proportional Limit (PLS), because the load is globally shared by the matrix and elastic behavior before the load exceeds the Proportional Limit strain curve of CMC, as shown in Fig. 2[22]. Firstly, CMC presents elastic behavior before the load exceeds the Proportional Limit (PLS), because the load is globally shared by the matrix and fibers. After that, the load is transferred to SiC fibers, and the fiber realignment and slippage results in a pseudo-ductile behavior. Since the nonlinear deformation after PLS will not be retained during the unload process, it is termed as the so-called “pseudo-plastic” rather than the real plastic. Finally, CMC experiences the “plastic” deformation. The mechanical calculation could be found in reference [22].

(e) Creep. Many studies [18,22] have shown that no substantial creep could be found if the temperature is lower than 1673 K. Hence, the creep of SiC was neglected in this study.

2.2. Modeling for multi-layer mechanical simulation

In this study, each cladding layer was regarded as non-rigid body. Hooke’s law without shear stress written as Eq. (8), compatibility equation of cylindrical body written as Eq. (9) and the assumption of uniform axial strain written as Eq. (10) forms a mechanical system of equations.

\[
\begin{align*}
E_{\text{non-irr}}^{\text{CVD}} &= 460 \times 10^9 \cdot \exp(-3.57V_f) - 0.04 \cdot \exp(-962/T) \\
E_{\text{irr}}^{\text{CVD}} &= E_{\text{non-irr}}^{\text{CVD}} \cdot \left[1 - 0.15 \times \left(\frac{\Delta V}{V_0}\right)\right]
\end{align*}
\]

(7)

where \( E_{\text{non-irr}}^{\text{CVD}} \) and \( E_{\text{irr}}^{\text{CVD}} \) represent Yong’s modulus of CVD in Pa before and after irradiation, respectively; \( V_f \) means the dimensionless porosity. The Poisson’s ratio of CVD is generally regarded as a constant of 0.21. Since CVD is a typical ceramic material, there is no plastic or pseudo-plastic deformation.

Additionally, there might be three type of mechanical boundary conditions. First, the radial stress equals to the surface pressure (coolant or gas pressure) at the free boundary, written as Eq. (11). Second, the cladding surface radius equals to the pellet surface radius at the contact surface if PCMI occurred, written as Eq. (12). Lastly, mechanical parameters should meet self-consistent requirements at the junction of different layers, written as Eq. (13).

\[
\begin{align*}
\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} &= 0 \\
\frac{dx_\theta}{dr} + \frac{2\varepsilon_\theta - \varepsilon_r}{r} &= 0
\end{align*}
\]

(9)

\[
\sigma_r = P_{\text{surface}}
\]

(11)

where \( P_{\text{surface}} \) means the surface pressure in Pa.

\[
r_{c,\text{contact}} = r_{f,\text{contact}}
\]

(12)

where \( r_{c,\text{contact}} \) and \( r_{f,\text{contact}} \) are cladding and fuel radius in m at the contact surface, respectively.

\[
\begin{align*}
\sigma_r^{\text{layer1}} &= \sigma_r^{\text{layer2}} \\
\sigma_\theta^{\text{layer1}} &= \sigma_\theta^{\text{layer2}} \\
F_z &= \int \sigma_z dA
\end{align*}
\]

(13)

where \( \sigma_r^{\text{layer1}} \) and \( \sigma_r^{\text{layer2}} \) represent the radial stress in Pa of layer 1 and layer 2, respectively; \( r_{\text{contact}}^{\text{layer1}} \) and \( r_{\text{contact}}^{\text{layer2}} \) are after-deformation radius in m of layer 1 and layer 2 at the junction, respectively; \( A \) represents the total area in m² of axial cross section of all layers; \( F_z \) means the total net axial force in N act on all layers.

All the equations and boundary conditions forms a closed system of equations, and the numerical solution could be obtained. More details about numerical methods and validation of above models could be found in Ref. [23].

2.3. Upgrade of relocation model

Relocation means pellet-cladding gap reduction caused by fuel cracking and relocation recovery is the phenomenon of crack closure due to the contact with cladding. Relocation and recovery

![Fig. 2. Stress-strain curve of CMC.](Image)
generally is modeled as the relocation strain to the fuel. In FROBA-ANNULAR, the relocation model in Ref. [5] was adopted. In this model, there is an assumption that cracked fuel fragments could move inward and outward freely, so Pellet-Cladding Mechanical Interaction (PCMI) only exists when both inner and outer gap were closed. However, if only external gap was closed, the fuel pellet might move inward to some extent but obviously cannot make the inner gap closed, since the real average pellet inner radius cannot be decreased. Therefore, a new relocation and recovery model was developed. The new relocation model was developed based on a model [24] of solid fuel. Because the annular pellet has a much larger radius and lower temperature gradient than those of the solid fuel, the relocation strain should be significantly smaller than that in solid rods. Hence, a geometry factor was proposed to modify this model for annular fuel, as shown in Eq. (14). As for the relocation recovery, if the recovery was induced by contact with internal cladding, the relocation recovery could be 100% and the cracked fuel could move out freely, which means no PCMI occurs until the external gap closed. If the recovery was induced by the contact with external cladding, the cracked fuel could not move totally in free and the peak relocation recovery fraction was assumed to be 20% [25].

\[
\begin{align*}
\{ e_{\text{relocation}} & = f_{\text{geometry}} e_{\text{relocation solid annular}} \\
 f_{\text{geometry}} & = (r_{\text{out}} - r_{\text{in}}) / r_{\text{out}}
\end{align*}
\]  

(14)

where \( e_{\text{relocation}} \) and \( e_{\text{relocation solid annular}} \) represent relocation strain in annular and solid fuel, respectively; \( f_{\text{geometry}} \) means the geometry factor; \( r_{\text{out}} \) and \( r_{\text{in}} \) with the unit meter are the external and internal radius of annular pellet.

2.4. Modeling for power radial profile

Because of more \(^{238}\text{U}\) resonance capture of epithermal neutrons at the regions close to the coolant, the buildup of \(^{239}\text{Pu}\) and power density is much higher at the peripheral regions, which is the so-called rim effect. In this research, a rim effect calculation model for dual-cooled annular fuel elements was developed by solving the neutron diffusion equation and burnup equations simultaneously. The dimensional neutron diffusion equation and burnup equations are presented as Eq. (15) and Eq. (16) respectively.

\[
\frac{1}{\nu} \frac{\partial \phi(r, t)}{\partial t} = S(r, t) + D \frac{\partial^2 \phi(r, t)}{\partial r^2} - \Sigma_a \phi(r, t)
\]  

(15)

\[
\begin{align*}
\frac{dN_{235}(r)}{dt} & = -\sigma_a^{235}\text{Pu} N_{235}\phi(r) \\
\frac{dN_{238}(r)}{dt} & = -\sigma_a^{238}\text{Pu} N_{238}\phi(r) \\
\frac{dN_j(r)}{dt} & = -\sigma_{ij}\phi(r) + \sigma_{j,i-1} N_j(r)
\end{align*}
\]  

(16)

where \( \phi \) means neutron flux in m\(^{-2}\) s\(^{-1}\); \( r \) is radial position in m; \( t \) is time in s; \( S \) is neutron source in m\(^{-3}\) s\(^{-1}\); \( D \) is the diffusion coefficient; \( \Sigma \) is the macroscopic cross-section in m\(^{-1}\); \( N \) means the isotope concentration in m\(^{-3}\); \( \sigma \) is the cross-section in m\(^{2}\); \( \sigma_a \) and \( \sigma_c \) means absorption and capture, respectively; the subscripts \( j \) means \( ^{239}\text{Pu}, ^{240}\text{Pu}, ^{241}\text{Pu}, \) and \( ^{242}\text{Pu} \). An empirical shape function, reflecting probabilities of \(^{239}\text{Pu} \) production at different positions, was fitted by MCNP to revise the cross section of \(^{238}\text{U} \) absorption. This empirical fit is presented as a function [5] of local position, the inner radius \( r_i \) and outer radius \( r_o \), as shown in Eq. (17).

\[
f(r) = 1.5e^{-8.2(r-r_i)/r_o} + 1.74e^{-7.3(r-r_o)/r_o} + 0.26 \cos \left( \frac{r - (r_o + r_i)/2}{r_o - r_i} \right)
\]  

(17)

2.5. Validation of upgraded FROBA-ANNULAR

The capability of design and performance analysis for UO2-SiC dual-cooled annular fuel was developed based on the FROBA-ANNULAR [13], which is a steady-state thermo-mechanical analysis code for dual-cooled annular fuel with Zircaloy cladding. Since the thermo-mechanical simulation capability of FROBA-ANNULAR has been validated in our previous study [13], the goal of validation in this research is to demonstrate calculation functions for SiC cladding.

The upgraded code was benchmarked against a finite element analysis software ADINA. In this benchmark case [16,22], a two-layer SiC cladding tube (inner radius 4.0 mm, outer radius 4.8 mm, CVD-CMC from inside out, both layer thicknesses are 0.4 mm) with full saturation swelling was simulated under thermomechanical loads (inner surface heat flux 500 kW m\(^{-2}\), outer surface temperature 600 K, inner surface pressure 5.0 MPa, outer surface pressure 15.0 MPa). As shown in Fig. 3, results by two codes agree well with each other, which proves that the upgraded code is correct and reliable for SiC cladding.

3. Fuel design and optimization

3.1. Multi-layer cladding design

As a pure ceramic material, CVD can provide enough hermeticity and oxidation resistance, but has the natural weakness of brittleness. CMC is the fiber reinforced composite material, formed by infiltrating single-phase SiC matrix into braided SiC fiber bundles. CMC composite presents pseudo-plastic deformation ability and could overcome the brittleness of single-phase SiC to some extent. However, the composite might be permeable as fabricated or its initial hermeticity could be easily damaged. Therefore, the SiC cladding generally has multi-layer design with both CVD and CMC. According to previous studies [22,26,27], the two-layer design with CVD exposed to the coolant could reduce oxidation and protect the brittle CVD from stress-induced failure during shutdown. As a comprehensive result, the geometry and material designs proposed initially in this study is shown in Fig. 4. Considering for the compatibility with assembly design of UO2–Zr annular fuel, the cladding radius and thickness keep unchanged. It should be noted that the external cladding is obviously thicker than the internal cladding because a thin CVD layer could guarantee the hermeticity while the CMC layer couldn’t be too thin due to current manufacture technology [16].

For SiC cladding, it is significant to reduce the stress-induced failure risk. To verify the cladding design, a thermo-mechanical simulation with the consideration of swelling effect was conducted under both normal operation and shutdown. Table 1 shows parameters of simulation cases. It should be noted that parameter of Case I was proposed based on the initial plenum pressure of 15.0 MPa. As shown in Fig. 3, results by two codes agree well with each other, which proves that the upgraded code is correct and reliable for SiC cladding.
300 MPa (might reach the ultimate tensile strength [16]), and the failure risk of CMC could not be ignored. What's more, the compressive stress of CVD in external cladding amazingly exceeded 500 MPa. It is still unknown whether so large compressive stress will cause failure, although ceramic materials could undertake large compressive stress. Since increasing the plenum pressure can make the stress of internal cladding decreased and the stress of external cladding increased. The two concerns of Case I might be mitigated by increase the as-fabricated plenum pressure. By sensitive study, this measure was proved useful and the optimal as-fabricated plenum pressure was 6 MPa (Case II). As shown in Fig. 6, the peak CMC tensile stress and the peak CVD compressive stress in Case II were reduced to about 200 MPa and 400 MPa, respectively. It should be noted that the initial plenum pressure should be limited to avoid the outward creep at high burnup stage for Zircaloy, but there is no such concern since the creep rate of SiC is so small.

3.2. Fuel rod design

Obviously different with Zircaloy cladding, SiC cladding experiences significant swelling rather than creep down, resulting in totally different gap size variation. Therefore, it is necessary to redesign the as-fabricated internal and external gap sizes. In the annular fuel design with SiC cladding, two points should be noted. First, both the cladding and pellet deforms outward in total, so gap sizes could be relevant smaller than those in UO2-Zr system (with both cladding creep down). In addition, the initial external gap size should be larger than the internal gap size, because pellet will experience long-term outward swelling. According to these two points and the annular fuel design of UO2-Zr [4], several designs were proposed, as shown in Table 2. To figure out the optimal one, the sensitive study was carried out. To quantitatively compare performances of different designs, several indexes were proposed. Table 3 presents the definition and significance of each index.

Results of sensitivity study are illustrated in Fig. 7, and the following conclusion could be drawn: (a) PCMI occurred in Design 1 and 8, resulting in strong PCMI pressure and large tensile CVD stress, which is unacceptable for SiC cladding. Among all designs, external gaps of these two were smallest, that means the external gaps should be larger than 55 mm. (b) In Design 2 and 7, external gap sizes were a bit larger than Design 1 and 8 and no PCMI happened. However, mechanical gaps were so small, indicating that the PCMI margins were small and there might be potential stress-induced failure risks. (c) For Design 3 to 6, they have similar mechanical performances. As for thermal performance, Design 6 has the lowest fuel temperature, but it presents significantly higher heat-coolant split unbalance, inducing obviously lower DNBR. (d) For the rest designs, all the indexes were similar and under acceptable extent. According to results of fuel design and

![Fig. 4. Cladding design of dual-cooled annular fuel. r1 = 4.120; r2 = 4.275; r3 = 4.690; r4 = 6.890; r5 = 7.400; r6 = 7.630; unit = mm.](image)

![Fig. 3. Benchmark between upgraded FROBA-ANNULAR and ADINA.](image)

**Table 1**

Parameters of simulation cases for SiC cladding design verification.

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat flux of clad surface (W m⁻²)</th>
<th>Normal operation</th>
<th>Shutdown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coolant pressure (MPa)</td>
<td>Plenum pressure (MPa)</td>
<td>Expansion Swelling</td>
</tr>
<tr>
<td>I</td>
<td>500000</td>
<td>15.50</td>
<td>7.00</td>
</tr>
<tr>
<td>II</td>
<td>500000</td>
<td>15.50</td>
<td>18.00</td>
</tr>
</tbody>
</table>
optimization, the final fuel design parameters were summarized in Table 4. It should be noted that the original annular fuel design of UO₂-Zr system is from the research by China Institute of Atomic Energy for the potential application in Qinshan II nuclear power plants. In addition to the geometry change, the fuel enrichment increased from 4.45% in solid rods to 7.00% in annular rods. In the annular fuel design with SiC cladding, the rod sizes, cladding thicknesses and annular pellet thickness were kept the same with those in UO₂-Zr system. As for the thickness design of each SiC layer, it was obtained based on the comprehensive considerations: a) reduce the thickness of CVD to lower down the brittle failure risk, and make sure the thickness of CVD is enough (generally larger than 150 μm) to provide enough resistance to oxidation; b) a sensitive study from the view of CVD-CMC stress profile [20,22].

4. Fuel performance evaluation

The fuel design and optimization need iterative computations and sensitivity study, so many hypothetical boundaries or conditions were used for fuel performance simulation in Section 3. In order to verify the fuel design and gain deeper insight into the new fuel concept, the fuel performance analysis under realistic conditions should be conducted. Fig. 8 illustrates linear power histories of a solid fuel and an annular fuel. The power history of solid fuel was from the pin with the highest discharge burnup in a typical pressurized water reactor obtained by previous reactor physics simulations [16]. The power history of annular fuel was obtained correspondingly based on the assumption of 30% uprate of reactor power with 13 × 13 assembly design [4]. The axial power profile was assumed to be of a chopped-cosine shape with the peak-to-average ratio about 1.2.

4.1. Thermo-hydraulic performance

Fig. 9 illustrates the fuel temperature variation of dual-cooled annular fuel. Both the peak fuel temperature and average fuel temperature in annular fuel with SiC cladding were obviously higher than those in annular fuel with Zircaloy cladding. It was because the thermal conductivity of both CMC and CVD after irradiation was significantly lower than that of Zircaloy. In addition, the gap size of UO₂-Zr system might be smaller than the gap of annular rod with SiC cladding due to the creep down, also resulting in lower fuel temperature. Anyway, benefit from the innovative geometry design, the fuel temperature of UO₂-two-layer-SiC system was still dramatically lower than the temperature of solid fuel. Because of low fuel temperature in annular fuel, there was almost only athernal FGR caused by strong kinetic energy and atomic impact at the periphery region of fuel, which has no association with fuel temperature [28]. Hence, there was almost no difference of FGR fraction between UO₂-two-layer-SiC system and UO₂-Zr system, as shown in Fig. 10. The internal gas pressure in UO₂-two-layer-SiC system was significantly higher than that in UO₂-Zr system, which was the result of higher as-fabricated plenum pressure. It should be note that the peak gas pressure in UO₂-two-layer-SiC system exceeded the coolant pressure, but it is acceptable for SiC cladding.

Heat split, coolant split and the matching degree between them are unique and significant phenomena in dual-cooled annular fuel, which could affect the DNBR margin significantly [9,10]. Fig. 11 shows the internal channel fraction of heat split and coolant split. Coolant splits of both UO₂-Zr system and UO₂-two-layer-SiC system almost remained unchanged during the whole operation. Unlike coolant split, the variation of heat split versus operation time could be dramatic due to the complicated variation of internal and external gas gap sizes. In internal channel of UO₂-Zr system, the heat flux fraction was much lower than the coolant flux fraction, and the peak gap was about 10%. This was because the internal gas gap was significant larger than the external gap (as shown in Fig. 14), which hindering the heat flow to the inner channel to some extent. In UO₂-two-layer-SiC system, the situation was different. The heat flux fraction of internal channel was higher than the coolant fraction with the peak gap of about 5%. This was because the internal gas gap was smaller than that of external gap during

### Table 2

<table>
<thead>
<tr>
<th>Design No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clad sizes</td>
<td>As shown in Fig. 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal gap/μm</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>30</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>External gap/μm</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>70</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>Other inputs</td>
<td>Average linear power: 50 kW m⁻²; Axial power profile: chopped-cosine with peak-power factor of 1.2; Operation time: 1500 day; Inlet temperature: 556.15 K; Mass flow rate: 0.68 kg s⁻¹; Active length: 3.675 m; Plenum length: 0.25 m; As-fabricated plenum pressure: 6 MPa; Enrichment: 7%; Fuel density: 95%TD.</td>
<td></td>
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</table>
most of the operation (as shown in Fig. 14). The variation of gap size will be discussed in Section 4.2. Overall, it seems that the heat/coolant split was more balanced in annular fuel with SiC than that of Zircaloy. DNBR variation versus time is illustrated in Fig. 12. DNBRs of internal and external channels in UO2-two-layer-SiC system deviated more than that in UO2-Zr system, resulting in lower MDNBR of the rod itself. This was because the internal channel has much smaller surface, but it exported more heat than the coolant in it (heat flux fraction was larger than the coolant flux fraction). Anyway, the MDNBR of UO2-two-layer-SiC system was still larger than 5, indicating it was under good conditions of thermal-hydraulic safety.

### 4.2. Mechanical performance

Fig. 13 presents the deformation of dual-cooled annular fuel. Different with Zircaloy claddings, both the internal and external SiC claddings moved outward rapidly due to irradiation swelling and then almost remained unchanged after the SiC swelling saturated. As a result, no contact occurred in UO2-two-layer-SiC system, which could protect the CVD from brittle failure. Fig. 14 shows the gap size variation of both thermal and mechanical. The thermal gap, used in the gap heat transfer calculation, means the real gap between cladding and fuel. However, because relocation recovery could provide a degree of offset for pellet growth, even if the thermal gap

<table>
<thead>
<tr>
<th>Index</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel temperature</td>
<td>Including peak temperature and average temperature. The index represents the thermal performance. The index value of desired design should be low.</td>
</tr>
<tr>
<td>Heat transfer unbalance degree</td>
<td>In annular fuel, heat split and coolant split between two channels could not be consistent. The index was defined as the fraction difference (time-averaged, in %) between heat and coolant split. The index value of desired design should be low.</td>
</tr>
<tr>
<td>DNBR</td>
<td>It means the minimum Departure from Nucleate Boiling Ratio (DNBR) of the rod itself. It represents the thermal safety margin and the desired value should be high.</td>
</tr>
<tr>
<td>Minimum mechanic gap</td>
<td>PCMI should be avoided for SiC cladding. The index represents the margin of PCMI. To some extent, the index value should be high.</td>
</tr>
<tr>
<td>Peak PCMI pressure</td>
<td>The index means the peak contact pressure in PCMI. It represents the strength of mechanical interaction of fuel and clad and the desired value should be low.</td>
</tr>
<tr>
<td>Peak CVD stress</td>
<td>It is significant to reduce the tensile stress of brittle CVD. The index reflects mechanical safety conditions of cladding and the desired value should be low.</td>
</tr>
</tbody>
</table>
closed, there might be no real mechanical action, which is the so-called “soft” contact [5]. To evaluate PCMI, a virtual gap was defined as the sum of thermal gap and the space of relocation recovery, which is so-called mechanical gap. There will be real PCMI only after the mechanical gap closed. Hence, the “soft” contact (thermal gap closure) occurred before the “hard” contact (mechanical gap closure).

Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UO₂-Zr system</th>
<th>UO₂-two-layer-SiC system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Stack Length</td>
<td>3.657 m</td>
<td>3.657 m</td>
</tr>
<tr>
<td>Plenum length</td>
<td>0.25 m</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Pitch</td>
<td>16.42 mm</td>
<td>16.42 mm</td>
</tr>
<tr>
<td>Rod inner radius</td>
<td>4.12 mm</td>
<td>4.12 mm</td>
</tr>
<tr>
<td>Rod outer radius</td>
<td>7.63 mm</td>
<td>7.63 mm</td>
</tr>
<tr>
<td>Inner gap thickness</td>
<td>55 μm</td>
<td>35–45 μm (35 μm in this paper)</td>
</tr>
<tr>
<td>Outer gap thickness</td>
<td>80 μm</td>
<td>65–75 μm (65 μm in this paper)</td>
</tr>
<tr>
<td>Internal cladding</td>
<td>Material: Zr-4</td>
<td>Material: CVD-CMC (inside out)</td>
</tr>
<tr>
<td></td>
<td>Thickness: 0.57 mm</td>
<td>CVD thickness: 0.155 mm</td>
</tr>
<tr>
<td>External cladding</td>
<td>Material: Zr-4</td>
<td>Material: CMC-CVD (inside out)</td>
</tr>
<tr>
<td></td>
<td>Thickness: 0.74 mm</td>
<td>CMC thickness: 0.510 mm</td>
</tr>
<tr>
<td>Fuel Density</td>
<td>95% TD</td>
<td>95% TD</td>
</tr>
<tr>
<td>Enrichment</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>Heilium fill pressure</td>
<td>4.0 MPa</td>
<td>6.0 MPa</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>556.15 K</td>
<td>556.15 K</td>
</tr>
<tr>
<td>Coolant Pressure</td>
<td>15.5 MPa</td>
<td>15.5 MPa</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0.68 kg s⁻¹</td>
<td>0.68 kg s⁻¹</td>
</tr>
</tbody>
</table>

Fig. 8. Power history of solid fuel and annular fuel.

Fig. 9. Fuel temperatures of different fuel elements.

(a) Peak fuel temperature

(b) Average fuel temperature

Fig. 10. FGR and plenum pressure of dual-cooled annular fuel.

Fig. 11. Coolant and heat split of dual-cooled annular fuel.
From Fig. 14, the minimum mechanical gap in UO₂-two-layer-SiC system was larger than 20 µm, indicating that the brittle SiC was far away from PCMI. Due to the presence of outward swelling in SiC, both the fuel and claddings deformed outward during the long operation, resulting in no gap closure. Therefore, the relocation in the UO₂-two-layer-SiC system could develop freely in both internal and external directions (make both inner and outer gap sizes decrease) without any recovery, leading to more similar sizes of inner gap and outer gap, as shown in Fig. 14 and more balance heat split as shown in Fig. 11. Fig. 15 presents the stress variation of cladding. For Zircaloy cladding, the stress was at a low level until the external mechanical gap closed. After that, the stress of external cladding increase dramatically due to strong PCMI. Finally, the stress curve entered a relevantly steady period because of the balance of outward creep of cladding and outward swelling/expansion of pellet. During the operation, the radial gradients of thermal expansion strain and swelling strain changed with power and irradiation dose, which dominates the stress closure.

**Fig. 12.** DNBR of dual-cooled annular fuel.

**Fig. 13.** Fuel and cladding deformations of dual-cooled annular fuel.

**Fig. 14.** Gap size variation of dual-cooled annular fuel.
5. Conclusions

In this study, an innovative fuel combined dual-cooled annular geometry and SiC cladding materials was proposed. The fuel design, optimization and preliminary performance evaluation were conducted with the upgraded FROBA-ANNULAR code. The following conclusions could be drawn:

1. Although the thermal conductivity SiC reduced significantly after irradiation, the advantages of annular fuel over traditional solid fuel on thermal performance were retained, including low fuel temperature, low FGR and large MDNBR.
2. PCMI and stress-induced failure were successfully avoided in the simulation with realistic operation conditions, and the mechanical safety of the optimal fuel design was confirmed.
3. Overall, combining the excellent thermal-hydraulic performance of annular fuel and prominent accident tolerant ability of SiC cladding, the dual-cooled annular fuel with SiC cladding could be a promising nuclear fuel rod system for LWRs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.06.025.

References