Thermal-Hydraulic Sensitivity Analysis of Annular Fuel Elements Based on Grey Fuzzy Theory

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Date: 2025-08-22T00:00:00+00:00

Abstract

Annular fuel can significantly increase the power density of pressurized water reactor (PWR) cores, which is of great significance for reactor miniaturization design and improvement of economics. Research in this area has relatively focused on assembly arrangement patterns and combinations of a few geometric dimensions, while quantitative studies on the geometric structural dimensions of annular fuel elements are relatively scarce. Therefore, quantifying the influence of various geometric factors on the thermal-hydraulic performance of annular fuel elements is of great significance. This paper takes the annular fuel single-channel model as the research object and conducts thermal-hydraulic design based on parameters of PWR annular fuel elements designed by Westinghouse. Geometric factors such as the inner and outer diameters of the inner and outer cladding and the inner and outer diameters of the pellet were selected for study, and four evaluation criteria were established. Using grey relational analysis and fuzzy mathematics theory, the influence of each geometric factor on thermal-hydraulic performance was quantified. The results show that the sensitivity of each geometric factor is comparable in the MDNBR of the inner and outer channels, but differs significantly in the adiabatic surface location and the maximum fuel pellet temperature. This quantitative method provides a reference for the design and parameter adjustment of annular fuel in pressurized water reactors.

Full Text

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Abstract

[**Background**] Annular fuel has the potential to significantly enhance the power density of Pressurized Water Reactor (PWR) cores, which is of great significance for reactor miniaturization design and economic improvement. Previous research in this domain has primarily focused on component arrangement patterns and limited combinations of geometric dimensions, while quantitative studies on the detailed geometric structural dimensions of annular fuel elements remain relatively scarce. [**Purpose**] Therefore, quantifying the impact of various geometric factors on the thermal-hydraulic performance of annular fuel elements is of substantial importance. [**Methods**] This study adopts a single-channel model of annular fuel as the research subject and conducts thermal-hydraulic design calculations based on parameters from Westinghouse-designed PWR annular fuel elements. Geometric factors including inner and outer diameters of both inner and outer claddings and fuel pellets are selected for investigation, and four evaluation criteria are established. By applying grey relational analysis and fuzzy mathematics theory, the influence of each geometric factor on thermal-hydraulic performance is quantified. [**Results**] The results indicate that for the Minimum Departure from Nucleate Boiling Ratio (MDNBR) in both inner and outer channels, the sensitivities of various geometric factors are comparable. However, significant differences exist in the position of the adiabatic surface and the maximum temperature of the fuel pellets. [**Conclusions**] This quantitative approach provides a valuable reference for the design and parameter adjustment of annular fuel in PWRs.

Keywords: Annular fuel, Grey analysis, Fuzzy theory, Sensitivity analysis, Thermal-hydraulic

1. Introduction

In the early 21st century, the Massachusetts Institute of Technology (MIT) proposed a dual-cooled annular fuel element design for pressurized water reactors. Annular fuel elements are primarily used in PWRs, and studies have shown that this design can increase power density by 30% compared to conventional fuel elements while significantly enhancing safety margins [1]. Their excellent thermal-hydraulic performance substantially improves reactor safety and economics, attracting widespread international attention. Building on this foundation, Korea conducted a feasibility study in 2007 on using annular fuel to enhance reactor power in OPR-1000 [2]. Iranian research demonstrated that applying annular fuel in VVER-1000 reactors could increase power to 1.29 times the original level [3]. Additionally, scholars from Singapore, Egypt, and other countries have conducted studies on lead-cooled fast reactors and AP1000, respectively, showing that annular fuel can improve safety [4,5]. China officially launched research on annular fuel elements in 2010, aiming to improve reactor safety performance and fully exploit fuel potential to increase core power.

To date, through domestic multi-party collaboration, breakthroughs have been achieved in key technical areas such as annular fuel element design, manufacturing, and experimentation.

It should be noted that the influence of annular fuel geometric factors on thermal-hydraulic performance is a complex, nonlinear, multi-factor interaction process. Minor geometric variations can lead to changes in flow characteristics and heat transfer performance, thereby affecting thermal-hydraulic behavior, and different geometric factors may exhibit synergistic or competitive effects. Quantifying the impact of geometric factors on thermal-hydraulic performance enables direct observation of their mutual influence, providing references for reactor design. Therefore, this paper conducts a thermal-hydraulic sensitivity analysis of annular fuel elements based on grey fuzzy theory.

Domestic and international scholars have conducted extensive research on geometric factors as key influences on annular fuel thermal-hydraulic performance. Ji Songtao et al. [6] performed conceptual design and thermal-hydraulic studies on annular fuel, demonstrating the feasibility of its application in PWR nuclear power plants. Deng Yangbin et al. [7] developed a thermal-hydraulic calculation program for annular fuel elements, established three evaluation criteria to determine optimal dimensions, and validated the program' s accuracy through comparison with other studies. Zhang Geng et al. [8] investigated a zero-power annular fuel reactor, obtaining critical parameters and control rod worth to determine the optimal number of annular elements for core critical loading. Diao Junhui et al. [9] used the SAAF program to analyze the thermal-hydraulic performance of different arrangement patterns for the Qinshan Phase II PWR, confirming through multi-parameter coupling evaluation that the
13$×13*arrangementwasoptimal.ZhouYunlongetal.*[10]*usedComputationalFluidDynamics*(*CFD*)*tosimulate*
hydraulicdesignusingafull−coreVersatileInternalsandComponentProgramforReactors(*VIPRE*−
01)*modeltodetermineoptimaldimensionsandassemblyarraypatterns.Rowinskietal.*[4]*establishedadual*−
channelcoolingmodelforannularfuelandconductedthermal−*hydraulicanalysis*, *achievingafuelmaximumter*
cooledfastreactors, *withpressuredropreducedto*128*kPaforthesquarelattice*(18×$18)
scheme, supporting safe operation at 110% overpower.

Literature review reveals that related research has primarily concentrated on component arrangement patterns and limited geometric dimension combinations, with relatively few studies addressing variations in fuel element geometric structural dimensions. Moreover, no quantitative evaluation exists regarding the degree of influence of fuel element geometric dimensions on thermal-hydraulic performance. Therefore, this paper takes a single annular fuel rod element for PWR as the research object, selects geometric factors including inner and outer diameters of inner and outer claddings and fuel pellets, and quantitatively analyzes the sensitivity of various thermal-hydraulic performance indicators to these geometric factors, providing references for further optimization design and parameter adjustment of annular fuel.

This paper addresses the selection of annular fuel geometric dimensions through the following approach: First, an appropriate core physical model is selected to confirm the basic parameters for thermal-hydraulic calculations. Second, mathematical methods including grey relational analysis and fuzzy evaluation are employed to quantify the influence degree of each geometric factor on key thermal-hydraulic indicators. Finally, through computational analysis, the sensitivity relationship between annular fuel element thermal-hydraulic performance and geometric factors is established.

2. Methodology

2.1 Geometric Structure

Annular fuel elements employ an annular fuel pellet design, with independent claddings covering both inner and outer surfaces, and gas gaps existing between pellets and claddings. Coolant can flow through both inner and outer channels simultaneously to cool the fuel element, where the outer channel is an open channel and the inner channel is a closed channel. The cross-section of an annular fuel element is shown in Figure 1 [Figure 1: see original paper], and PWR design parameters are listed in Table 1 .

Figure 1 Schematic cross-sectional diagram of a single annular fuel channel

Table 1 Pressurized water reactor (PWR) reference design parameters

Reactor Parameters	Value
Initial geometric parameters	
Inner channel cladding inner radius	Value/mm
Linear power density /kW · m^{-1}	
Coolant inlet mass flow rate	
Inner channel cladding inner radius Rc,ii	
Inner channel cladding outer radius Rc,io	
Coolant inlet temperature/K	
Coolant inlet pressure/MPa	
Fuel pellet inner radius	
Fuel pellet outer radius	
Outer channel cladding inner radius	
Axial power factor	
Fuel material	
Cladding material	
Cladding gas gap	
Outer channel cladding inner radius Rc,oi	
Outer channel cladding outer radius Rc,oo	
Zircaloy-4	
Rc,oo	
Active core height	
Pitch	

2.2 Two-Phase Calculation Model

In PWRs, coolant fluid undergoes phase change (boiling) when flowing through heated pipes due to variations in heat transfer coefficients at the pipe wall, meaning the fluid is no longer single-phase liquid but contains vapor. Consequently, the coolant can be divided into four distinct regions along the channel based on the degree of phase change: single-phase region, high subcooled boiling region, low subcooled boiling region, and saturated boiling region. Phase change significantly affects heat transfer and flow characteristics, complicating conditions within the pipe. Therefore, this study employs a two-phase model for thermal-hydraulic calculations. For the single-phase region (coolant in liquid state with no bubble departure from the wall), convective heat transfer is calculated using the Dittus-Boelter correlation, while different models are applied for two-phase flow sections: the Thom correlation for boiling heat transfer, the Zuber-Findlay drift-flux model for void fraction calculation, and the homogeneous flow model for two-phase pressure drop.

2.3 Heat Distribution Model

The dual-cooling channel structure of annular fuel elements requires heat generated in the pellet to be distributed between inner and outer channels. By setting a virtual adiabatic surface at the temperature extremum point in the pellet, the pellet is divided into inner and outer heat sources that heat the two channels respectively. Assuming uniform fission power distribution and an adiabatic surface radius of , the ratio of volumetric heat generation rates inside and outside the adiabatic surface is [12]:

Solving the heat conduction differential equation yields the analytical expression for the radial temperature distribution within the fuel pellet: ; coefficients and are as follows:

where and are the inner and outer surface temperatures of the fuel pellet, respectively, ; is radius, ; and is pellet thermal conductivity,

2.4 Flow Distribution Model

The inner and outer dual-coolant channel design of annular fuel must satisfy the flow distribution criterion of essentially identical pressure drops. Based on the geometric configuration and flow characteristics of the channels, a comprehensive pressure drop calculation model incorporating acceleration pressure drop , gravitational pressure drop , frictional pressure drop , and form pressure drop is established. Accordingly, the total pressure drop along the coolant channel can be expressed as:

where is the form loss coefficient, is coolant density, is the friction factor, is coolant flow velocity, and is the two-phase friction multiplier.

When the fluid flow in the channel is single-phase liquid throughout, the two-phase frictional pressure drop can be expressed as the product of single-phase frictional pressure drop and the two-phase friction multiplier. The relationship for is as follows:

where is flow quality; and are the differences in specific volume between saturated liquid and saturated vapor, , and viscosity coefficient, respectively; and are the specific volume of saturated liquid, , and viscosity coefficient of saturated vapor, , respectively.

Based on the heat balance equation:

where is total mass flow rate, ; is coolant specific heat at constant pressure; and represent inner channel inlet and outlet temperatures, respectively; and represent outer channel inlet and outlet temperatures, respectively. From the system of four equations (7), determining the inner and outer coolant outlet temperatures allows determination of the coolant flow distribution ratio. Additionally, due to the unique design principle of annular fuel, the flow rates allocated to inner and outer channels are not identical, and the flow and boiling states may also differ, resulting in different outlet temperatures between inner and outer channels with a certain temperature difference.

2.5 Material Properties Model

The material properties model includes coolant water, cladding, fuel, and gap properties. This study develops cladding material property expressions based on the book *Thermophysical Properties of Materials for Nuclear Engineering* (2nd revised and enlarged edition) by Russian scholar Kirillov [13], combined with REFPROP data and thermophysical property expressions as references for property calculations. MATLAB is used to indirectly call REFPROP software to obtain relevant properties of light water and fit property correlations. The contact conductance model is employed for gap heat transfer, with an equivalent heat transfer coefficient set to .

2.6 Thermal-Hydraulic Performance Evaluation and Program Development

2.6.1 Evaluation Indicators To quantify the influence of annular fuel geometric factors, thermal-hydraulic performance evaluation indicators must be established. Based on Diao Junhui et al.' s [11] research on thermal-hydraulic analysis of PWR annular fuel elements, this study selects four key thermal-hydraulic performance evaluation indicators:

1. **Minimum Departure from Nucleate Boiling Ratio (MDNBR) for inner and outer channels**: MDNBR is a critical parameter involving coolant boiling state and heat transfer conditions. A larger MDNBR indicates better heat transfer conditions and higher safety margins for fuel elements.
2. **Maximum fuel pellet temperature**: According to reactor thermal design criteria, the maximum fuel pellet temperature should remain below

the melting point. Therefore, lower maximum fuel pellet temperatures are preferable for safe reactor operation at the same power level.

3. **Adiabatic surface position**: In annular fuel pellets, the annular boundary with zero heat flux is defined as the adiabatic surface, which divides generated heat into two portions transferred to inner and outer cooling channels and is located at the radial temperature maximum. An adiabatic surface position closer to the pellet’ s radial geometric center indicates better temperature field distribution symmetry and more adequate cooling.

2.6.2 Program Development This study performs calculations using THCAFS, a C-language-based program developed by Chen Zhao et al. [14] for two-phase flow thermal-hydraulic analysis of annular fuel elements. THCAFS calculates key parameters including boiling inception point, quality distribution, heat transfer coefficient, and pressure drop to achieve flow distribution and temperature field analysis for inner and outer channels, ultimately outputting safety parameters such as DNBR and fuel temperature to provide technical support for the design and safety assessment of annular fuel elements in nuclear reactors. The specific calculation flow is shown in Figure 2 [Figure 2: see original paper].

Figure 2 THCAFS program thermal-hydraulic calculation flow chart

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3. Experimental Design and Analysis Methods

3.1 Orthogonal Experimental Design

Orthogonal experimental design is an efficient method that systematically analyzes multi-factor influences through scientifically arranged minimal experiments, widely applied in medicine, agriculture, industry, and scientific research. By arranging only a few experiments, it significantly saves experimental costs and time. The process involves: selecting primary influencing factors and determining their value levels based on research objectives; choosing an appropriate orthogonal array from standard tables according to the number of factors and levels; combining factor levels according to the orthogonal table to form experimental schemes; conducting experiments according to the designed scheme and recording data; and finally using range analysis to identify the influence of each factor and their interactions on results to determine optimal combinations.

Deng Yangbin et al. [7] noted that a factor that must be considered in thermal-hydraulics is the balance of cooling capacity between inner and outer channels. Accordingly, six geometric factors are selected: inner and outer diameters of inner cladding, inner and outer diameters of fuel pellets, and inner and outer diameters of outer cladding. Deng Yangbin et al. [7] also obtained the optimal fuel dimension design range for these six geometric factors (inner cladding inner diameter: 0.85-0.875 cm, inner cladding outer diameter: 0.9643-0.9893 cm, pellet inner diameter: 0.9767-1.0017 cm, pellet outer diameter: 1.4007-1.4182 cm, outer cladding inner diameter: 1.4131-1.4306 cm, outer cladding outer diameter: 1.5274-1.5449 cm). Conducting research on fuel dimensions within this design range enables more precise investigation of the influence of fuel geometric dimensions on thermal-hydraulic performance and is more meaningful. Therefore, we select the design range provided by Deng Yangbin et al. to determine upper and lower limits. The experimental factor value ranges [7] are shown in Table 2 , factor levels are shown in Table 3 , and 72 orthogonal experimental groups are designed based on factor levels combined with orthogonal arrays.

Table 2 Ranges of experimental factors

Parameters	Upper bound	Lower bound
Inner cladding inner diameter /mm		
Inner cladding outer diameter /mm		
Fuel pellet inner diameter /mm		
Fuel pellet outer diameter /mm		
Outer cladding inner diameter /mm		
Outer cladding outer diameter /mm		

Table 3 Factor level table

Factor level	Inner cladding inner diameter /mm	Inner cladding outer diameter /mm	Fuel pellet inner diameter /mm	Fuel pellet outer diameter /mm	Outer cladding inner diameter /mm	Outer cladding outer diameter /mm

3.2 Grey Relational Analysis

When simultaneously considering the influence of multiple factors on annular fuel assembly thermal-hydraulic performance, the analysis becomes extremely complex and difficult. The underlying mechanism can be understood as a grey model. Grey relational analysis [15] evaluates the correlation between influencing factors through the geometric similarity of sequence curves. Using THCAFS to calculate parameter combinations from orthogonal experimental designs yields result data, which is then processed using grey relational analysis to obtain the correlation degree between various thermal-hydraulic performance indicators and geometric factors of annular fuel elements. The grey relational analysis process is shown in Figure 3 [Figure 3: see original paper], with specific steps as follows:

Figure 3 Flowchart of Grey System Analysis

3.2.1 Determination of Reference and Comparison Sequences The thermal-hydraulic performance evaluation indicators of annular fuel elements are selected as reference sequences , and geometric influencing factors are selected as comparison sequences . Taking several values for each yields corresponding values for , resulting in matrix forms for and as:

where is the parameter value of the geometric factor, and is the calculated thermal-hydraulic performance indicator value corresponding to the geometric parameter.

3.2.2 Data Dimensionless Processing Since the dimensions of various factors are not completely consistent and their numerical values differ significantly, mean normalization is applied to and in the analysis to eliminate dimensional effects, expressed as:

where is the mean of the thermal-hydraulic performance indicator corresponding to the geometric parameter, and is the mean of the geometric factor.

3.2.3 Calculation of Correlation Coefficients The values in the correlation coefficient matrix are calculated through Equation (12), where is the distinguishing coefficient taken as 0.5:

3.2.4 Calculation of Relational Degree The magnitude of correlation coefficients qualitatively reveals the relative importance of different geometric parameters on thermal-hydraulic performance. The primary value of quantitative analysis lies in precisely identifying key design parameters to guide research and optimization resources toward dominant factors. Furthermore, the quantitative results provide an objective, data-driven basis for weight allocation of decision variables in multi-objective optimization, supporting the construction of more scientifically reliable optimization models to explore optimal system performance balance solutions. The grey relational degree calculation formula is as follows:

is the grey relational degree of the geometric factor in the thermal-hydraulic performance indicator. The relational degree is proportional to the influence degree of that factor’ s variation on the indicator (thermal-hydraulic performance), enabling assessment of different geometric parameters’impact on thermal-hydraulic performance and identification of which performance indicators exhibit greater sensitivity to parameters. However, grey relational analysis results are limited to measuring the correlation between geometric factors and single thermal-hydraulic performance indicators, unable to provide comprehensive information about geometric parameters’ overall impact on thermal-hydraulic performance. This method can only present relative relationships between geometric parameters and specific performance indicators, not comprehensive quantitative analysis. Therefore, in addition to preliminary sensitivity analysis through grey relational analysis, this paper further combines other methods for global sensitivity analysis of geometric factors on annular fuel thermal-hydraulic performance.

3.3 Fuzzy Comprehensive Evaluation of Geometric Factor Sensitivity

Fuzzy comprehensive evaluation considers interactions among multiple factors and assigns appropriate weights to accurately assess the comprehensive impact of multi-factor influences on performance. For global sensitivity evaluation of geometric factors' overall impact on annular fuel, a comprehensive evaluation model must be established for each thermal-hydraulic performance indicator according to its characteristics. The modeling steps for the comprehensive evaluation model are as follows.

3.3.1 Establishment of Factor Set and Evaluation Set The fuzzy comprehensive evaluation model combines factor sets and evaluation sets to transform fuzzy relationships into numerical evaluation results, thereby achieving comprehensive problem evaluation. The set composed of all geometric factors from Table 3 constitutes the factor set. This study considers thermal-hydraulic calculation results as the evaluation set:

3.3.2 Factor Evaluation This study considers thermal-hydraulic calculation results as the evaluation set. The evaluation set indicators are of different types. The selected indicators are categorized into maximum-type indicators, minimum-type indicators, and intermediate-type indicators. Maximum-type indicators refer to those where larger observed values represent better performance in that attribute dimension. Minimum-type indicators are the opposite. Intermediate-type indicators refer to those where performance is best when the indicator is at a certain position within an interval, with better performance as the evaluation object approaches the optimal position. Let the original data matrix obtained from initial calculations be , and matrix be the transformed matrix. Different values represent different thermal-hydraulic indicators, and both and are 6th-order square matrices. The transformation relationships for maximum-type, minimum-type, and intermediate-type indicators are as follows:

Through Equation (19), the membership degree matrix is obtained by summing and normalizing matrix . Different rows of the matrix represent the membership degree of different geometric factor values to that thermal-hydraulic indicator.

3.3.3 Entropy Weight Method The entropy weight method is a weight determination approach based on information entropy concepts, used to measure the degree of indicator dispersion. The entropy weight method determines weights based on data itself, reducing subjective influence on decision results and providing strong objectivity. The calculation formulas are as follows:

Probability matrix :
Information utility value :
Entropy weight and weight vector :

3.3.4 Fuzzy Operation and Comprehensive Evaluation Constructing a comprehensive evaluation model is crucial for assessing the magnitude of geometric factor influence, directly affecting final result accuracy. Combining fuzzy mathematics, the comprehensive evaluation model for the global impact of geometric factors on different thermal-hydraulic performance indicators of annular fuel is given below, with the calculation flow shown in Figure 4 [Figure 4: see original paper]:

Figure 4 Computational flowchart

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4. Results and Discussion

4.1 Thermal-Hydraulic Calculation Results

Based on the THCAFS annular fuel thermal-hydraulic analysis program, simulations are conducted using the single-variable method (changing one geometric parameter at a time while keeping others at baseline values). The adiabatic surface calculation results are shown in Figures 5 [Figure 5: see original paper] through 7 [Figure 7: see original paper]. Although the slope and trend of the result curves can qualitatively reflect geometric factor influences, direct slope comparison cannot effectively assess sensitivity differences due to inconsistent dimensions and magnitudes among parameters. To achieve objective quantitative comparison of each geometric parameter’ s sensitivity, this paper applies a combined method of grey relational analysis and fuzzy comprehensive evaluation.

(a) Inner cladding inner diameter (b) Inner cladding outer diameter
Figure 5 Influence of inner cladding inner and outer diameters on radial position of adiabatic surface

(a) Pellet inner diameter (b) Pellet outer diameter
Figure 6 Influence of pellet inner and outer diameters on radial position of adiabatic surface

(a) Outer cladding inner diameter (b) Outer cladding outer diameter
Figure 7 Influence of outer cladding inner and outer diameters on radial position of adiabatic surface

4.2 Grey Relational Degree Calculation

The adiabatic surface position, inner channel MDNBR, outer channel MDNBR, and maximum fuel pellet temperature of annular fuel elements are selected as reference sequences, denoted as ; geometric factors including inner and outer diameters of inner cladding, pellet, and outer cladding are selected as comparison sequences, denoted as . Using geometric parameter settings from orthogonal experimental designs for thermal-hydraulic calculations, comparison and reference sequence matrices (8) and (9) are established for each geometric parameter value and thermal-hydraulic performance indicator result for grey relational analysis. Lü Feng et al. [16] noted that changes in the value can adjust the value domain of correlation coefficients. As decreases, the minimum correlation coefficient decreases while the maximum remains 1, thus enlarging the value domain. From a certain perspective, a larger value domain better reflects their correlation. In the original grey system theory proposed by Deng Julong et al. [17], takes values in (0, 1], with = 0.5 commonly used as an empirical default value to achieve a compromise effect. Therefore, for simplified calculation, this paper takes = 0.5. When the distinguishing coefficient is 0.5, the correlation coefficients between various thermal-hydraulic performance indicators and geometric factors calculated based on the grey relational algorithm are shown in Table 4 :

Table 4 Association coefficients between thermal-hydraulic performance metrics and geometric parameters

The solution results show that when multiple geometric factors change simultaneously: Taking the adiabatic surface position ( ) of annular fuel elements as an example, the geometric factor relational degrees are: . When considering multiple factors, increases in both inner cladding outer diameter and fuel pellet inner diameter are positively correlated with adiabatic surface position. This occurs because increased inner cladding outer diameter narrows the inner gap, enhancing internal heat conduction capacity and causing the adiabatic surface to move outward, while increased fuel pellet inner diameter widens the inner gap but reduces pellet thickness. After comprehensive consideration, internal heat conduction capacity increases, causing the adiabatic surface to move outward.

Taking inner channel MDNBR ( ) of annular fuel elements as an example, the geometric factor relational degrees are: , indicating that inner channel MDNBR is most significantly affected by outer cladding inner diameter. This is because changes in outer cladding inner diameter significantly affect flow distribution, thereby altering inner channel MDNBR.

Taking outer channel MDNBR ( ) of annular fuel elements as an example, the sensitivity degrees of geometric factors are: , showing that inner cladding outer diameter and fuel pellet outer diameter significantly affect outer channel MDNBR. This is because these two parameters can change inner gap width, altering heat conduction capacity and thus affecting outer channel MDNBR.

Taking maximum fuel pellet temperature ( ) of annular fuel elements as an example, the geometric factor relational degrees are: , indicating that maximum pellet temperature is most significantly affected by outer cladding. This is because changes in outer cladding inner diameter significantly alter gap width, changing heat conduction capacity and affecting maximum pellet temperature.

Through grey relational degree calculation for annular fuel geometric factors, the sensitivity degree of each factor regarding different thermal-hydraulic performance indicators can be obtained. However, model limitations require proposing other models to evaluate the overall influence of geometric factors on each indicator to obtain global geometric factor sensitivity.

4.3 Global Sensitivity Fuzzy Evaluation of Geometric Factors

According to the definition of MDNBR, a larger MDNBR indicates that the fuel element surface maximum heat flux is further below critical heat flux, effectively preventing core overheating and melting. Therefore, MDNBR is selected as a maximum-type indicator in this study. Maximum fuel pellet temperature is directly related to core melt risk, and lower core maximum temperatures are desired in reactor design, making it a minimum-type indicator. When the adiabatic surface is at the geometric center, heat transfer to inner and outer channels is more uniform, making adiabatic surface position an intermediate-type indicator. Based on the benchmark problem, the optimal position is selected as 6 mm in this study. Combining Equations (14)-(25), the matrix is calculated. Multiplying corresponding elements of the matrix with the grey analysis matrix (Table 7) yields the global sensitivity coefficient matrix, with its heat map shown in Figure 8 [Figure 8: see original paper].

Figure 8 Global sensitivity heat map

Figure 8 shows that for MDNBR in both inner and outer channels, the sensitivity coefficients of all geometric parameters are distributed between 0.10-0.12, indicating relatively similar influence degrees. This suggests that in annular fuel element design, all geometric dimensions must be considered synergistically to achieve precise matching and optimization of inner and outer channel flows for MDNBR improvement. However, for adiabatic surface position and maximum fuel center temperature, parameter sensitivities show significant differences. Specifically, fuel pellet dimensions themselves (ID_{PELLET} and OD_{PELLET}) exhibit the highest sensitivity to adiabatic surface position because they directly define the fuel body' s geometric configuration and radial thickness, which are the dominant factors determining the entire element' s radial temperature field and heat flux distribution to inner and outer walls. Their minor changes significantly alter heat conduction, dramatically affecting heat flux distribution and causing obvious adiabatic surface position shifts. Outer cladding inner and outer diameters (ID_{OC} and OD_{OC}) show the highest sensitivity to maximum fuel pellet temperature because outer cladding outer diameter changes simultaneously affect cladding thickness and outer channel flow area, influencing heat transfer capacity. Overall, their combined effect has the greatest impact on heat transfer capability. Outer cladding inner diameter changes primarily affect gap thickness; as is well known, the gap' s small thermal conductivity significantly affects heat conduction and heat storage capacity, so outer cladding inner diameter directly influences fuel heat conduction and heat storage capacity through gap thickness, indirectly affecting maximum fuel pellet temperature.

Combined with research by Xiang Zhaocai et al. [18], when other parameters remain constant, increasing pellet thickness (i.e., increasing pellet inner and outer diameters) reduces volumetric heat generation rate, decreasing heat transfer from pellet to exterior and increasing maximum pellet temperature. Similarly, with other parameters unchanged, increasing inner cladding thickness (i.e., increasing inner cladding inner and outer diameters) enlarges the temperature difference between inner cladding inner and outer surfaces, lowering inner cladding inner surface temperature and reducing coolant cooling effectiveness, thereby increasing pellet inner surface temperature, moving the adiabatic surface toward the pellet inner surface, and increasing maximum pellet temperature. The influence of outer cladding inner and outer diameters on fuel element thermal performance is similar to that of inner cladding inner and outer diameters.

In summary, the thermal-hydraulic analysis results of annular fuel elements based on grey fuzzy theory in this study are consistent with findings from other scholars, validating the feasibility of this new method.

5. Conclusions

Regarding geometric factors affecting the thermal-hydraulic performance of PWR annular fuel elements, this paper proposes a methodology based on grey analysis models and fuzzy mathematical theory. Combined with thermal-hydraulic calculation results, the global sensitivity magnitude of each geometric factor is quantified within the studied geometric parameter range, yielding the following conclusions:

1. Grey relational analysis reveals the influence degree of inner and outer cladding diameters and fuel pellet diameter parameters on different indicators, providing a research foundation for quantitative analysis of global sensitivity under multiple geometric factor influences.
2. The development and application of fuzzy mathematical models can quantify phenomena in fuzzy systems with limited information and multiple factors, helping to draw new conclusions in annular fuel thermal-hydraulic analysis.
3. The development and application of grey relational analysis and fuzzy mathematical models provide a feasible quantitative method for sensitivity analysis of annular fuel thermal-hydraulic performance.
4. The six geometric factors have comparable effects on MDNBR in both inner and outer channels, requiring comprehensive consideration of all geometric dimensions in reactor design involving MDNBR.
5. Fuel pellet dimensions exhibit the highest sensitivity to adiabatic surface position, and reasonable design of fuel pellet dimensions can significantly achieve optimal adiabatic surface position.
6. Outer cladding outer diameter shows the highest sensitivity to maximum fuel pellet temperature by affecting cladding thickness and outer channel flow area, while outer cladding inner diameter affects it by influencing gap thickness.

5.1 Limitations and Future Work

The limitation of this study lies in its continued use of the single-channel model to analyze the influence of annular fuel element geometric dimensions on thermal-hydraulic performance based on previous research. While this model can effectively quantify the influence degree of geometric parameters within a single channel, it fails to consider interactions during multi-channel parallel operation in real cores, particularly inter-channel flow redistribution and fluid mixing effects. When coupling effects are weak, these results provide guidance for reactor design. However, when coupling effects must be considered, the research results can provide valuable trend references and mechanistic guidance for actual system design, but caution is still required when quantitatively extrapolating to multi-channel systems, necessitating further validation with multi-channel model analysis. Additionally, numerous fuzzy comprehensive evaluation and correlation analysis methods exist, and alternative methods could be considered for more precise results.

Based on the findings and limitations of this study, future work will focus on the following directions:

1. Establish multi-channel models to analyze the influence of annular fuel element geometric dimensions on thermal-hydraulic performance while considering coupling effects. Quantify errors between single-channel and multi-channel models under different coupling effects, provide indicators for quantifying coupling effects, and define the capability ranges of single-channel and multi-channel models based on these indicators to simplify calculations and save computational resources.
2. Employ other fuzzy comprehensive evaluation operators and correlation analysis methods.

Author Contributions

Deng Junjie: Drafted the manuscript, analyzed/interpreted data
Fu Zhenyu: Conducted research, collected data
Zhao Pengcheng: Acquired funding, reviewed and revised manuscript, provided theoretical guidance

References

1. Kazimi M S, Hejzlar P, Carpenter D M, et al. High performance fuel design for next generation PWRs[R]. Massachusetts Institute of Technology. Center for Advanced Nuclear Energy Systems. Nuclear Fuel Cycle Program, 2006.
2. Shin C H, Chun T H, Oh D S, et al. Thermal hydraulic performance assessment of dual-cooled annular nuclear fuel for OPR-1000[J]. Nuclear

Engineering and Design, 2012, 243: 291-300.

3. Mozafari M A, Faghihi F. Design of annular fuels for a typical VVER-1000 core: Neutronic investigation, pitch optimization and MDNBR calculation[J]. Annals of Nuclear Energy, 2013, 60: 226-234.
4. Rowinski M K, White T J, Zhao J Y. Innovative model of annular fuel design for lead-cooled fast reactors[J]. Progress in Nuclear Energy, 2015, 83: 270-282. DOI: 10.1016/j.pnucene.2015.04.002.
5. Hassan I A, Badawi A A, El Saghir A, et al. Viability of uranium nitride (UN) as annular fuel for AP-1000[J]. Progress in Nuclear Energy, 2019, 110: 170-177.
6. Ji Songtao, He Xiaojun, Zhang Aiming, et al. Study on feasibility of annular fuel applied in PWR nuclear power plants[J]. Atomic Energy Science and Technology, 2012, 46(10): 1232-1236.
7. Deng Yangbin, Wu Yingwei, Zhang Weixu, et al. Geometric size optimization of dual-cooled annular fuel element[J]. Atomic Energy Science and Technology, 2015, 49(7): 1208-1214. DOI: 10.7538/yzk.2015.49.07.1208.
8. Zhang Geng, Xia Zhaodong, Zhu Qingfu, et al. Critical experiment of double-sided moderated annular fuel reactor[J]. Atomic Energy Science & Technology, 2021, 55(9): 1670-1676.
9. Diao Junhui, Ji Songtao, Han Zhijie. Methodology study of thermal-hydraulic analysis for PWR annular fuel assembly array[J]. Atomic Energy Science and Technology, 2015, 49(8): 1374-1379. DOI: 10.7538/yzk.2015.49.08.1374.
10. Zhou Yunlong, Wu Mingting, Huang Nan, et al. Numerical study on coolant flow and heat transfer characteristics in annular fuel[J]. Atomic Energy Science & Technology, 2023, 57(6).
11. Feng D D, Hejzlar P, Kazimi M S. Thermal-hydraulic design of high-power-density annular fuel in PWRs[J]. Nuclear Technology, 2007, 160(1): 16-44. DOI: 10.13182/nt07-a3882.
12. Yang Y S, Shin C H, Chun T H, et al. Evaluation of a dual-cooled annular fuel heat split and temperature distribution[J]. Journal of Nuclear Science and Technology, 2009, 46(8): 836-845. DOI: 10.1080/18811248.2007.9711593.
13. Kirillov. Thermophysical properties of materials for nuclear engineering[M]. Beijing: China Atomic Energy Press, 2011.
14. Chen Zhao, Xiao Yingjie, Zhao Pengcheng, et al. Research on effective temperature calculation method of annular fuel cell[J]. Nuclear Techniques, 2022, 45(12): 120603. DOI: 10.11889/j.0253-3219.2022.hjs.45.120603.

15. Liu Sifeng, Yang Yingjie, Wu Lifeng. Grey system theory and its application[M]. 7th ed. Beijing: Science Press, 2014.
16. Lü Feng. Research on the identification coefficient of relational grade for grey system[J]. Systems Engineering —Theory & Practice, 1997, (06): 50-55.
17. Deng Julong. Grey system theory[M]. Wuhan: Huazhong University of Science and Technology Press, 2002.
18. Xiang Zhaocai, Zeng Fulin, Zhao Pengcheng. Study on the influence of geometric size of annular fuel element on thermal performance[J]. Nuclear Techniques, 2023, 46(1): 010602. DOI: 10.11889/j.0253-3219.2023.hjs.46.010602.
19. Wang Yuxuan, Ma Longhui, Zhao Pengcheng, et al. Key factors affecting the thermal performance of annular fuel elements in LFR[J]. Nuclear Techniques, 2021, 44(10): 100607. DOI: 10.11889/j.0253-3219.2021.hjs.44.100607.
20. Ma Huiqiang, Yu Tao, Chen Zhenping, et al. Study on calculation method of one-dimensional steady temperature field of annular fuel pellets[J]. Nuclear Techniques, 2020, 43(6): 060603. DOI: 10.11889/j.0253-3219.2020.hjs.43.060603.
21. Zeng Fulin, Tang Mao, Zhao Pengcheng, et al. Influence of the pitch-to-diameter ratio on the circumferential non-uniformity of annular fuel outer temperature distribution[J]. Nuclear Techniques, 2023, 46(9): 090601. DOI: 10.11889/j.0253-3219.2023.hjs.46.090601.
22. Wang Ting, Zhao Pengcheng, Liu Zijing, et al. Thermal-hydraulic analysis method for the annular fuel structure of lead-bismuth reactor[J]. Nuclear Techniques, 2021, 44(10): 100604. DOI: 10.11889/j.0253-3219.2021.hjs.44.100604.
23. Wang Chang, Xiao Hao, Liu Zijing, et al. Geometric configuration of fuel assembly for small lightweight lead-bismuth reactor[J]. Nuclear Techniques, 2023, 46(9): 090606. DOI: 10.11889/j.0253-3219.2023.hjs.46.090606.
24. Ji Songtao, Han Zhijie, He Xiaojun, et al. Development progress of annular fuel assembly for PWR[J]. Atomic Energy Science and Technology, 2020, 54(S1): 240–245. DOI: 10.7538/yzk.2020.zhuankan.0440.
25. Sobol' I M. Sensitivity analysis for non-linear mathematical models[J]. Mathematical Modeling & Computational Experiment, 1993, 1.
26. Faghihi F, Saidi nezhad M. Two safety coefficients for a typical 13 × 13 annular fuel assembly[J]. Progress in Nuclear Energy, 2011, 53(3): 250–254. DOI: 10.1016/j.pnucene.2010.11.003.

27. Morra P. Design of annular fuel for high power density BWRs[D]. Massachusetts Institute of Technology, 2006.

Note: Figure translations are in progress. See original paper for figures.