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Original Article

The optimization study of core power control based on meta-heuristic algorithm for China initiative accelerator driven subcritical system

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A B S T R A C T

The core power control is an important issue for the study of dynamic characteristics in China initiative accelerator driven subcritical system (CiADS), which has direct impact on the control strategy and safety analysis process. The CiADS is an experimental facility that is only controlled by the proton beam intensity without considering the control rods in the current engineering design stage. In order to get the optimized operation scheme with the stable and reliable features, the variation of beam intensity using the continuous and periodic control approaches has been adopted, and the change of collimator and the adjusting of duty ratio have been proposed in the power control process. Considering the neutronics and the thermal-hydraulics characteristics in CiADS, the physical model for the core power control has been established by means of the point reactor kinetics method and the lumped parameter method. Moreover, the multi-inputs single-output (MISO) logical structure for the power control process has been constructed using proportional integral derivative (PID) controller, and the meta-heuristic algorithm has been employed to obtain the global optimized parameters for the stable running mode without producing large perturbations. Finally, the verification and validation of the control method have been tested based on the reference scenarios in considering the disturbances of spallation neutron source and inlet temperature respectively, where all the numerical results reveal that the optimization method has satisfactory performance in the CiADS core power control scenarios.

1. Introduction

The China initiative accelerator driven subcritical system (CiADS) is a promising nuclear facility constructed by the intense beam proton accelerator, the high power spallation target, and the lead-bismuth alloy cooled subcritical reactor, which has advantages in transmuting high radioactive nuclear wastes and relieving the burden of nuclear wastes storage underground [1]. The fundamental study of accelerator driven system has been launched by institute of modern physics Chinese academy of sciences (IMPCAS) since the year 2011, and the cooperation of CiADS project has been officially approved to be built by the national nuclear safety administration (NNSA) in the year 2018 [2]. Nowadays, the site of CiADS is in the land leveling and preparing stage in south-east China's Huizhou city, and the engineering, procurement and construction are expected to be started in the year 2021.

The CiADS reactor is running in subcritical mode driven by the external spallation neutron source that has the inherit safety feature without easily arousing the prompt critical effect [3]. Compared with the control strategies in traditional reactor system, the core power of CiADS reactor is only determined by the variation of proton beam intensity without considering any adjusting and control rods inserted in the reactor core, since the experimental facility is designed to verify the key technologies used for the coupling of three different nuclear systems with the potential of generating electricity energy in the future engineering stage [2]. The optimization of core power control in CiADS is a very important issue that has direct relation to the dynamic characteristic, the safety analysis, and the stable operation management, which

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should be kept within the range of variation values without the unexpected perturbation and the small reactor period in running process [4]. Additionally, the understanding of transient features in core power control has guiding significance for the subcritical reactor star-up, the shutdown procedures, the power regulation management, and the response strategies under normal and emergency conditions [5]. In this context, it is of great importance and necessity to study the optimization of core power control for the CiADS facility.

The advanced meta-heuristic algorithms have already been demonstrated with good performance in dealing with the complicated multi-object optimization problems, such as the adjusting of autonomous vehicles [6,7], operating the automatic voltage regulator [8], the controller design for robotic manipulator [9], and the optimal design of battery charge management [10]. Additionally, the research on dynamic control strategies for accelerator driven system is one of the hot issues in the field of nuclear engineering, and a lot of important work have been fulfilled by different institutes to study the simulation method, the kinetic behavior, the sensitivity analysis, and the uncertainty in comparison with experimental results [11,12]. For example, a hybrid transport point kinetic technique for the simulation of source transients in subcritical systems has been reported with the attractive features of flexibility and competitive computational effort, where two methods have been considered for the physical problem, including the source propagation effect and the ensemble response of the subcritical system [13]. Besides, the dynamic behavior of 80 MW lead-bismuth eutectic cooled experimental accelerator driven system (LBE-XADS) has been investigated using the lumped and zero dimensional description of the neutronic and thermo-hydraulic models, and the feed forward and feedback schemes have been adopted to analysis the corresponding control strategies [14]. Additionally, the beta-effective sensitivity and uncertainty analysis of multi-purpose hybrid research reactor for high-tech applications (MYRRHA) have been evaluated for the purpose of demonstrating the possible use in considering the nuclear data validation and improvement [15]. Furthermore, the experimental benchmarks on kinetic parameters in accelerator driven system with 100 MeV protons at Kyoto university critical assembly (KUCA) has been carried out to promote the required research work in simulation and operation process [16].

Considering the noteworthy achievements mentioned above and the stable control requirements in the engineering design stage without large perturbation, the optimization of core power control for CiADS based on meta-heuristic algorithm has been detailed and analyzed in this research work for the purpose of demonstrating the applicability and feasibility in the CiADS running process. The physical model for the dynamic simulation process has been introduced in Section 2, and the two different control approaches in changing the proton beam intensity have been explained, where the change of collimator and the adjusting of duty ratio have been discussed with the consideration of continuous and periodic features. Besides, the multi-inputs single-output (MISO) logical structure for the dynamic operation process has been established in Section 3 by means of the proportional integral derivative (PID) controller and the meta-heuristic algorithm. Moreover, two reference control scenarios have been employed in Section 4 to verify the applicability of core power control method in considering the influence of proton beam intensity and the inlet coolant temperature. Finally, the conclusions and perspectives have been drawn in Section 5.

2. The control approach and system modeling for CiADS

For the purpose of understanding the control strategy and operation process in CiADS, the system structure design and core power control approaches have been detailed in Section 2.1. Additionally, the system modeling for the subcritical reactor has been discussed in Section 2.2 by means of the point reactor kinetics method and lumped parameter method in considering the neutronics and thermal-hydraulics characteristics respectively.

2.1. The main structure and core power control approach

The CiADS experimental facility is a 10 MW pool type subcritical reactor cooled by liquid eutectic lead-bismuth (LBE) alloy that is driven by 250 MeV proton energy with the beam current around 1 mA. The main structure of CiADS layout is presented as shown in Fig. 1, where the external neutron source generated by the spallation reaction with wide spectrum is used to compensate the reactivity loss in the subcritical reactor and to keep the stable running of the coupling system. The core power control of CiADS is only affected by the variation of proton beam intensity without considering the effect of control rods in the current engineering design stage.

Two different approaches in modifying the proton beam intensity have been considered in the core power control process, namely the change of collimator and the adjusting of duty ratio. For the first kind of approach, the collimator has been installed at the location of low energy beam transport modular in the proton accelerator system, where the aperture of the collimator can be continuously adjusted in order to determine the pervious number of particles along the trajectory direction [17]. For the second kind of approach, the frequency of proton beam accelerator can be changed and manipulated in considering the different periodicities, and the pulsed proton beam intensity can be adjusted with different duty ratios subsequently [18]. The energy of proton beam is constant 250 MeV within the core power control process, and the flux of spallation neutron source has the linear relationship with the change of proton beam intensity [2]. Both of the two corresponding approaches can meet the control requirements in supervising and managing the variation of proton beam intensity in CiADS operation process.

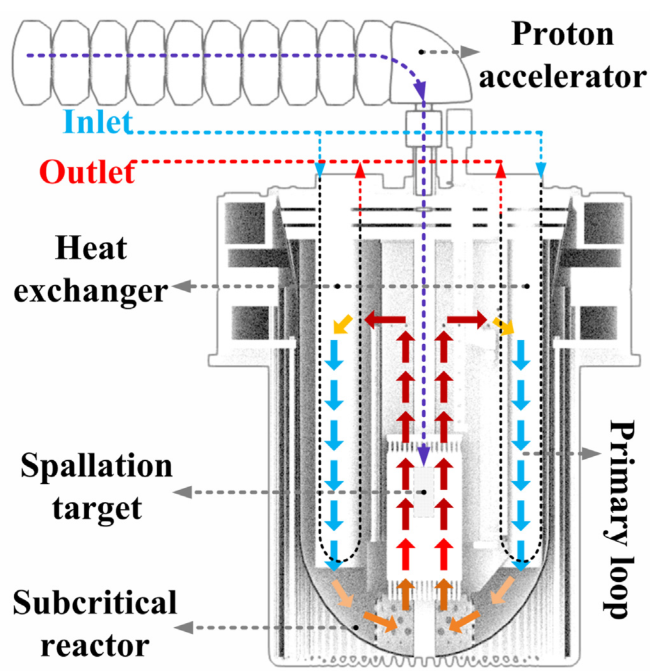

Fig. 1. The schematic of CiADS layout.

2.2. The system modeling for subcritical reactor

The point reactor kinetic method has already been proved having applicability and feasibility in analyzing the accelerator driven system [3]. For example, the dynamic characteristics and the transient safety analysis for accelerator driven systems have been reported using the point kinetic simulation method [19]. Besides, the modeling and control strategy of Italian LBE-XADS have been established based on the point kinetics equations for the purpose of understanding the variation of power and temperature in subcritical reactor [14]. In this research work, the point reactor kinetics method and lumped parameter method have been employed in order to fulfill the system modeling procedure. The set of govern equations as shown in Eq. (1) for the simulation process capture the neutronics and thermal hydraulics features in considering the delayed neutron precursors and the reactivity feedback with the change of core temperature simultaneously [20]. The basic assumption of the simulation method is that the whole coupling system is running in quasi-static state, where the neutron flux is assumed as the scalar magnitude without considering the spatial distribution in transient analysis.

$$\frac{d}{dt}\begin{bmatrix} p(t) \\ \zeta_i(t) \\ T_f(t) \\ T_c(t) \end{bmatrix} = \begin{bmatrix} \frac{\rho\left(t,T_f,T_c\right)-\beta}{\Lambda}p(t)+\sum_{i=1}^{6}\lambda_{d,i}\zeta_i(t)+s(t) \\ \frac{\beta_i}{\Lambda}p(t)-\lambda_{d,i}\zeta_i(t) \\ \frac{p(t)}{C_f m_f}-\frac{U}{C_f m_f}\left(T_f(t)-T_c(t)\right) \\ \frac{U}{C_c m_c}\left(T_f(t)-T_c(t)\right)-\frac{\Gamma_c}{m_c}\left(T_{out}(t)-T_{in}(t)\right) \end{bmatrix}$$

$$(\mathrm{i}\in\{1,2,3,4,5,6\}) \tag{1}$$

The govern equations as shown in Eq. (1) is the simplified system modeling for subcritical reactor, where the neutronics and thermal hydraulics are tightly coupled by the parameter of reactivity $\rho(t,\ T_f,\ T_c)$. The reactivity can be express as $\rho(t,T_f,T_c) = \rho(0,T_f(0),T_c(0))+\beta_f\Delta T_f+\beta_c\Delta T_c$ in considering the effect of reactivity feedback in dynamic control process, where the ΔT_f and ΔT_c are the variation of average temperature in fuel and LBE coolant, and the β_f and β_c are the corresponding reactivity coefficients for the fuel and coolant equaling to -0.713 pcm/K and -1.249 pcm/K respectively [2]. In the system modeling process, the neutronics equations describe the time-dependent change of core power $p(t)$ and delayed neutron precursor concentration $\zeta_i(t)$ that has been divided into six delayed neutron groups $\mathrm{i}\in\{1,2,3,4,5,6\}$ as shown in Eq. (1), where β is the total delayed neutron fraction, and $s(t)$ is the term of external spallation neutron source having linear relationship with the proton beam intensity. Additionally, the thermal hydraulics equations describe the heat and flow transfer mechanism between the fuel and coolant components in subcritical reactor, where U is the heat transfer coefficient between the elements of fuel and LBE coolant, and the temperature of LBE coolant $T_c(t)$ in Eq. (1) is treated as the average value of inlet and outlet temperature that can be described as $T_c(t) = (T_{in}(t)+T_{out}(t))/2$. The detailed descriptions and the values of main parameters in the CiADS power control have been presented in Table 1.

3. The logical structure and optimization method for the core power control

In order to obtain the better performance in core power control process, the PID controller has been designed based on the meta-heuristic algorithm for the study of dynamic characteristics in CiADS running process, where the logical structure of PID controller has been established in Section 3.1 to deal with the time-varying parameters, and the genetic algorithm has been detailed in Section 3.2 to search the optimized PID parameters for the stable and reliable operation strategy.

3.1. The logical structure of PID controller

The PID is the most acceptable controller used in the industrial operation process that has mature implementation in dealing with the programmable logic device, the single-loop controller, and the distribution control system in the field of nuclear engineering design [7,21]. The most important feature of PID controller is the effective feedback mechanism, which can eliminate the offsets in steady state through the integral operation, and anticipate the further action through the derivative operation. The obvious advantage of PID controller in CiADS core power control process is the simple and clear logical structure with small number of adjusting parameters, where the parameters have a great influence on the stability performance of the control system. However, the selection of unknown key parameters in PID controller has been considered as the difficult and trial-and-error process required professional operation experiences [22], which should be carefully studied in order to get the suitable set of parameters for the specific control scenario.

$$f(t)=k_p e(t)+k_i\int_0^t e(t)dt+k_d\frac{de(t)}{dt} \tag{2}$$

The PID controller for CiADS operation process can be split into three terms as shown in Eq. (2) [23], namely the proportional term $k_p e(t)$, the integral term $k_i\int_0^t e(t)dt$, and the derivative term $k_d\frac{de(t)}{dt}$, where the $f(t)$ denotes the controller output, and the $e(t)=r(t)-c(t)$ denotes the system deviation between the process value $c(t)$ and the reference value $r(t)$. The k_p in the first term denotes the proportional gain in considering the system compensation and response, where the larger value will arouse the process instability and oscillation. The k_i in the second term denotes the integral gain in considering the dynamic deviation between the feedback signal and the predefined value, where the corresponding value presents the convergence rate of deviation to the steady state. The k_d in the last term denotes the derivative gain in considering the predication of future deviation based on the current dynamic rate, which value has direct relation to the transient response and the overshoot effect [24]. The schematic of PID controller for core power control has been established with the feedback mechanism as shown in Fig. 2, which is the MISO structure in considering the variation of proton beam intensity and inlet temperature as the input parameters and the corresponding change of core power as the output result respectively. Additionally, the genetic algorithm has been adopted as the meta-heuristic optimization method to find the appropriate adjusting parameters k_p, k_i, k_d for the PID controller as shown in Fig. 2 that will be discussed in Section 3.2.

3.2. The genetic algorithm based optimization method

The genetic algorithm is one kind of meta-heuristic optimization method that has been widely used in searching the set of multiple parameters for the control system in nuclear engineering and industrial fields [4,25]. The schematic of genetic algorithm used in the CiADS core power control process is the iteration structure with convergence judgment as shown in Fig. 3, where the genetic algorithm can be split into three steps as presented in the dash line box, namely the selection process, the crossover process, and the mutation process. The selection process is also called reproduction operator that is used to get the next optimized generation of parameters based on the performance of current individuals with the appropriate elimination ratio. Additionally, the crossover process is used to compensate the insufficient population in considering the excellent genes of individuals and the genetic mechanism in the last generation of population. Moreover, the mutation process is used to preserve the diversity feature in the current population that can meet the global searching requirement without falling into the local optimal solution. Finally, the integral time absolute error Q has been employed as the threshold and convergence condition as shown in Fig. 3 in order to get the optimized parameters for the core power control process.

the proton beam intensity, the inlet temperature, and the core power, where the control of beam intensity in considering the change of core power has been studied in Section 4.1, and the core power control in considering the disturbance of inlet temperature has been discussed in Section 4.2.

4.1. The control of beam intensity

The verification of core power control approach for CiADS has been tested in the predefined control scenario by taking into account the decrease of core power from full capacity to the 96% percentage within 500 s operation time. In the control process, the inlet temperature is considered as the constant value, and the variation of proton beam intensity is the main impact factor for the change of core power, where the meta-heuristic algorithm based control method has been used to obtain the optimized parameters

$$\begin{cases} Encode\ operation: \ (X \in [\mathrm{p}_{min}, \mathrm{p}_{max}])_{decimal} \Rightarrow X_{DNA} = \left(\dfrac{X - \mathrm{p}_{min}}{\mathrm{p}_{max} - \mathrm{p}_{min}}\left(2^N - 1\right)\right)_{binary} \\ Decode\ operation: \ (X_{DNA})_{binary} \quad \Rightarrow X = \mathrm{p}_{min} + (\mathrm{p}_{max} - \mathrm{p}_{min})\dfrac{(X_{DNA})_{decimal}}{2^N - 1} \end{cases} \tag{3}$$

In the genetic algorithm, each individual adjusting parameter X with decimal format in the PID controller should be converted into the X_{DNA} with N-bit length of binary format using the encode operation as shown in Eq. (3), and the decode operation is the inverse process of the encode operation for the purpose of obtaining the optimized result in decimal format. In order to detailed explain the conversion process and the use of meta-heuristic method in the PID controller, the illustration of different steps in the genetic algorithm based optimization method has been presented as shown in Fig. 4. Fig. 4 (a) describes the example of encode process in considering the parameter $k_p \in [0, 3]$ in PID controller with the NDA encode length N equaling to 10, where the two cases $Case\#1$ and $Case\#2$ have been provided to demonstrate the conversion process from the decimal parameters k_p^1 and k_p^2 to the corresponding binary parameters $k_{p\ DNA}^1$ and $k_{p\ DNA}^2$ respectively. Additionally, the illustration of crossover instance between the parameters $k_{p\ DNA}^1$ and $k_{p\ DNA}^2$ has been presented in Fig. 4 (b), where the random cross position with the rate value 50% has been used to get the crossover result $k_{p\ DNA}^{crossover}$ in decimal format by means of the decode operation. Moreover, the illustration of mutation instance from the parameter $k_{p\ DNA}^{crossover}$ to $k_{p\ DNA}^{mutation}$ has been explained in Fig. 4 (c), where the mutation position with rate value 0.002% has been considered for the corresponding transfer process. In this context, the evolution of the main parameters in PID controller can gradually approach the optimal result, and the iteration procedure will be stopped until meeting the core power control requirements.

4. The verification of core power control method in CiADS

In order to demonstrate the effectiveness and advantage of meta-heuristic algorithm based optimization method in the CiADS core power control process, two different control scenarios have been used to test the corresponding control approaches for the purpose of analyzing the dynamic variation relationships among

for PID controller, and the design requirement for the control approach is to get the steady transition trend of core power by means of manipulating the proton beam intensity within acceptable range of perturbation.

In the optimized control method, the selection of appropriate adjusting parameters, such as k_p, k_i, and k_d in PID controller, take the important role for the purpose of achieving the smooth change of core power in the dynamic operation process without large perturbations. Because of all the adjusting parameters in different generations of genetic algorithm having different range of values, the equivalent parameters defined as $\tilde{k}_x = k_x / (k_p + k_i + k_d) \times 100\% \ (x \in \{p, i, d\})$ have been employed to analyze the evolution history in the optimization process, where the distribution of equivalent parameters in the different generations with index number 40, 80, and 147 have been presented in the ternary plots as shown in Fig. 5 (a), (b), and (c) respectively. The size and density of individuals in current generation denote the agglomeration degree of equivalent parameters, and it can be found from Fig. 5 that the evolution of population among different generations has the obvious convergence trend from No.40 to No.147. Moreover, the change of normalized core power within 500 s operation time for the different generations have been presented in Fig. 6, and the control approach in considering the variation of beam intensity for the different generations in the operation process have been displayed in Fig. 7. Compared with the optimization results in different generations, the variation of beam intensity has good accordance with the corresponding changing tendency of the core power, since the proton beam intensity has linear relationship with the external spallation neutrons, and the flux of spallation source has the approximate relation with the core power determined by the amplification factor in CiADS [2]. It can be found from Figs. 6 and 7 that the overshoot effect in the previous generation will slowly disappear during the iteration procedure, and the core power can gradually approach the preset value without large perturbation in the operation process, which demonstrate that the optimized PID controller can meet the design requirements in the control scenario, and the control

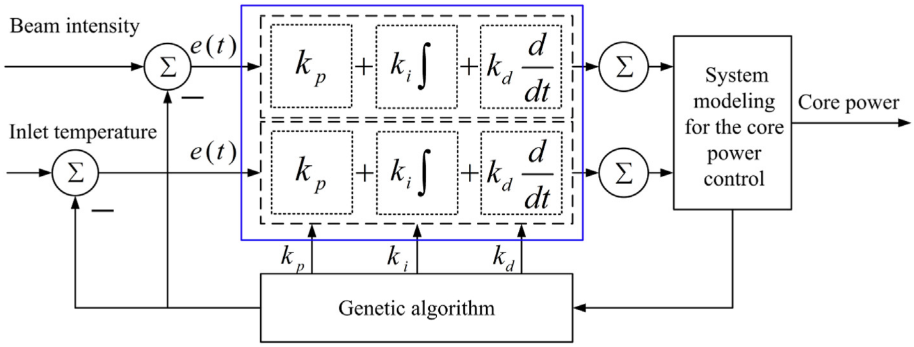

Fig. 2. The logical structure of genetic algorithm based PID controller for core power control.

method has the effectiveness and feasibility in dealing with the CiADS core power control tasks.

4.2. The core power control in considering the disturbance of inlet temperature

For the purpose of further verifying the performance of the PID controller and the optimization method used in the core power control process, a more realistic control scenario has been proposed to keep the operation of the coupling system in steady state with the consideration of the disturbance of inlet temperature and the control approach of proton beam intensity. In the control scenario, the dynamic small perturbation of the inlet temperature ΔT_{inlet} within 500 s operation time has been imported as the initial condition for the core power control process as shown in Fig. 8, and the variation of proton beam intensity is the important control approach to be studied in order to maintain the full power operation of the subcritical reactor without large perturbations in the optimization process.

The genetic algorithm has been employed to get the appropriate parameters for the PID controller, and the variation of proton beam intensity can be used to compensate the perturbation effect in the core power control process aroused by the inlet temperature disturbance. The optimized result for the control scenario has been presented in Fig. 9, including the relative variation rate of proton beam intensity and the corresponding change of core power within 500 s operation time. It can be found that the dynamic change of proton beam intensity in Fig. 9 has good consistency with the opposite trend of the inlet temperature in Fig. 8, where the largest disturbance value of inlet temperature is about 12 K, and the largest variation rate of proton beam intensity is less than 6% during the operation process. Moreover, the subcritical reactor can be considered as operating in the steady state over the control of proton beam intensity with the largest variation rate of core power less than 0.025% as shown in Fig. 9, which demonstrates that the meta-heuristic algorithm based optimization method has the potential in solving the core power control problems and can be used in the CiADS control scenarios.

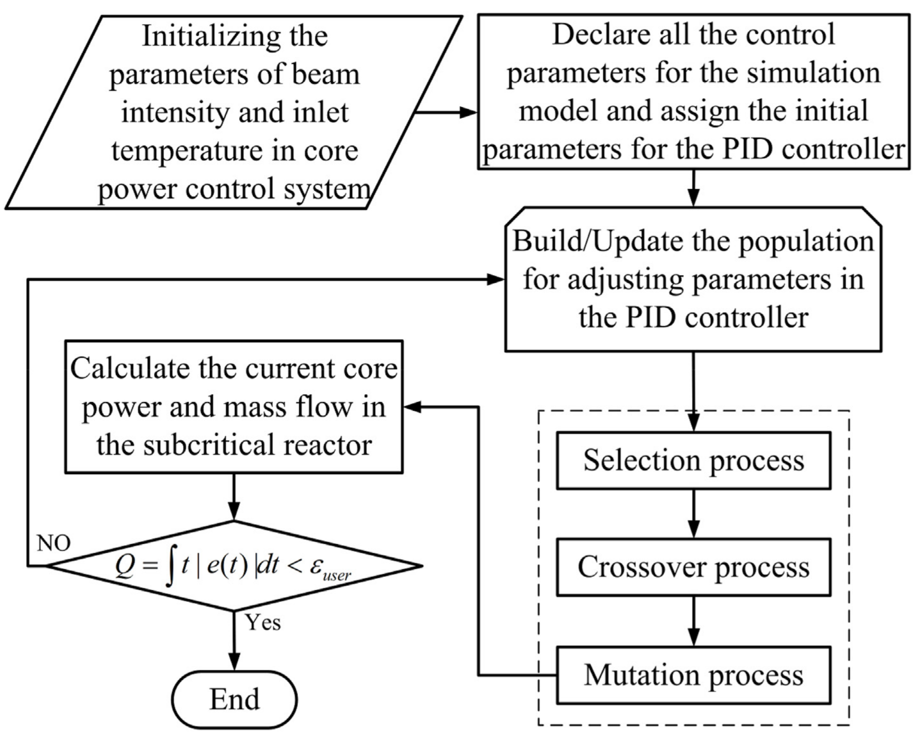

Fig. 3. The schematic of genetic algorithm based optimization method.

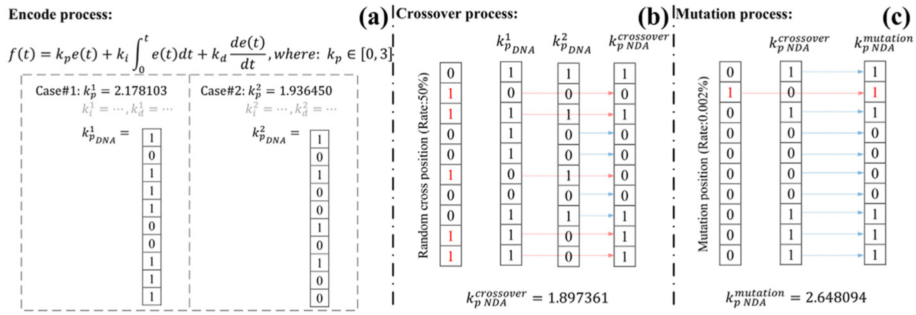

Fig. 4. The illustration of different steps in the genetic algorithm based optimization method ((a) the encode process for parameter k_p; (b) the illustration of crossover instance; (c) the illustration of mutation instance.).

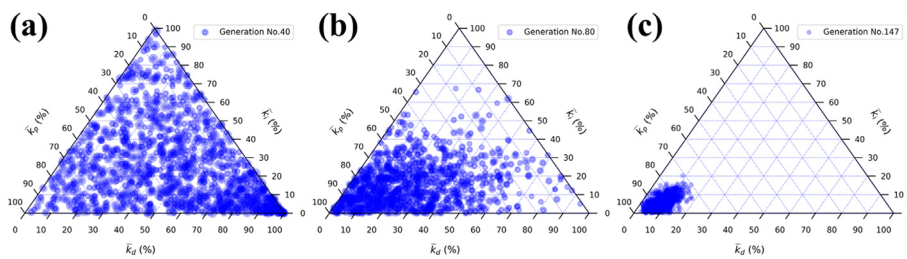

Fig. 5. The evolution of equivalent parameters in the core power control process ((a) the distribution of parameters in generation No.40; (b) the distribution of parameters in generation No.80; (c) the distribution of parameters in generation No.147.).

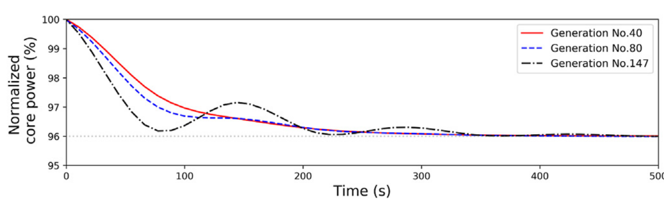

Fig. 6. The change of normalized core power within 500 s operation time for the different generations.

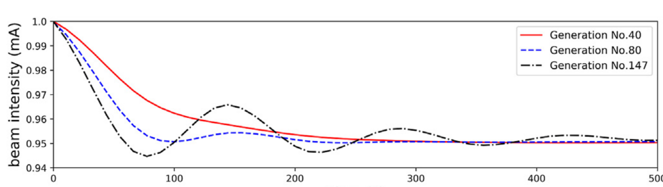

Fig. 7. The change of beam intensity within 500 s operation time for the different generations.

5. Conclusions and perspectives

The optimization of core power control for CiADS has been detailed in this research work, which has important instruction and practical value to the steady operation and the safety related characteristics in the coupling nuclear system. The manipulation of proton beam intensity has been adopted as the main control approach for the current engineering stage, where the change of collimator and the adjusting of duty ratio have been explained in order to fulfill the required control strategies. The physical model has been established by means of the point reactor kinetics method and the lumped parameter method in considering the neutronics and thermal-hydraulics features in the core power control process. Additionally, the PID controller with MISO logical structure has been constructed with the feedback mechanism for the purpose of obtaining the stable and reliable operation procedure, where the proton beam intensity and inlet temperature have been considered as the inputs, and the output is the corresponding power of subcritical reactor. Moreover, the genetic algorithm has been employed as the meta-heuristic method to get the optimized adjusting parameters for the PID controller. Finally, the performance of control method has been verified by the change of proton

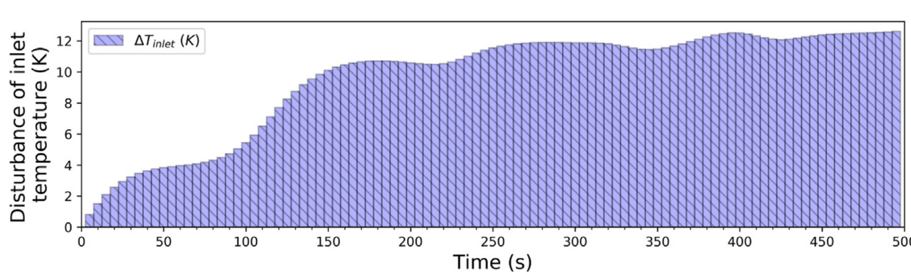

Fig. 8. The initial condition of inlet temperature disturbance within 500 s operation time.

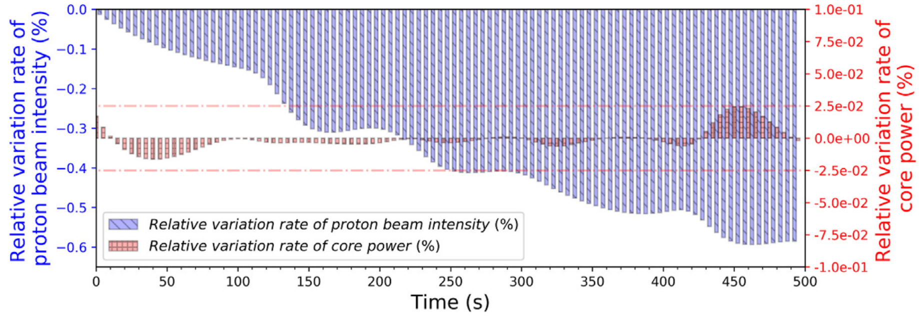

Fig. 9. The relative variation rate of proton beam intensity and the corresponding change of core power within 500 s operation time.

Table 1
The main parameters for core power control in CiADS.

Parameter	Description	Value
$p(t)$	Core power of subcritical reactor	$p(0) = 10$ MWth
$T_f(t)$	Average temperature of fuel	$T_f(0) = 683.4\ K$
$T_c(t)$	Average temperature of coolant	$T_c(0) = 604\ K$
$T_{in}(t)$	Inlet temperature	$T_{in}(0) = 554\ K$
$T_{out}(t)$	Outlet temperature	$T_{out}(0) = 654$ K
Γ_c	Mass flow rate	541 kg/s
m_f	Total mass of fuel	1.72 ton
m_c	Total mass of coolant	18.54 ton
C_f	Heat capacity for fuel	0.285 $kJ/(kg \bullet K)$
C_c	Heat capacity for coolant	0.148 $kJ/(kg \bullet K)$
$\rho(t, T_f, T_c)$	Total reactivity	$\rho(0, T_f(0), T_c(0)) = -0.025641$
Λ	Neutron generation time	$1.025641 \times 10^{-6}\ s$
β_i	Delayed neutron fraction for group i	$[0.215, 1.424, 1.274, 2.568, 0.748, 0.273] \times 10^{-3}$
$\lambda_{d,i}$	Decay constant of precursor group i	$[0.0124, 0.0305, 0.111, 0.301, 1.14, 3.01]\ s^{-1}$

beam intensity, and the applicability for core power control has been examined in considering the disturbance of inlet temperature, where all the simulation results demonstrate that the optimization method can meet the control requirements and can be used in the CiADS core power control process. The further development of the optimization control method is still in progress with the consideration of the high efficiency parallel algorithm and the interface to CiADS digital mock-up, which can provide the high speed response and intuitive characteristics for the practical engineering application.

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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