International Conference on Applied Energy 2020
Dec. 1– Dec. 10, 2020, Bangkok/Virtual
Paper ID:0470

Main Steam Temperature Load Tracking Control Based on Improved Sailfish Optimization

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ABSTRACT

As the boiler characteristics are affected by load change, the traditional control method cannot realize load tracking to control the main steam temperature MST in real time. In this paper a system is designed to control the midpoint temperature to adjust the fuel-water ratio as the major control, and secondary superheating water spray cooling adjustment as minor control. Firstly, in order to meet the coordinated of the power grid and the power plant, the boiler steam turbine coordination control system is established to track load change control the boiler input and steam turbine output signals.And take the outlet water temperature of the water wall as the intermediate point temperature (MPT), obtain the oil-water ratio, load, MPT relationship from the actual equipment data, and establish the MPT nonlinear discrete controller, to reduce the spray water and quickly adjust the main steam temperature. Use the Sailfish algorithm (SFO) to optimizes PID parameters. At the same time, in order to further improve the SFO optimization ability, an initialization method based on chaotic mapping and reverse learning is proposed, to improve the population diversity and global search ability. Finally, to verify the model accuracy, the actual data input to the model, and compared with the actual data. The error between THE MPT and the actual value is 0℃~3℃, and the error between the MST and the target value is -1.7℃~0.3℃. Compared with the traditional PID, the ISFO-PID controller can reduce the steady-state error by 60%, adjust time by 68%, and spray volume by 40%. The self-adaptive tracking control of main steam temperature load is realized, which can significantly reduce the coal consumption rate and improve the power generation efficiency. It has great application value in energy conversion control.

Keywords: Main steam temperature,Load tracking,Fuel-water ratio,Water spray cooling,Improved sailfish optimization,ISFO-PID.

1. INTRODUCTION

Thermal power generation accounts for about two-thirds of China's total power generation, so it is of great significance to study the improvement of energy efficiency.At the same time, in order to adapt to the development demand of electric power enterprises, on the one hand, it is required that unit output can quickly track the change of power grid load, on the other hand, it is necessary to ensure the stable operation of unit when load changes, especially to keep the fluctuation of main parameters not exceeding the prescribed limit.The main steam temperature is the highest temperature in the while boiler steam-water system, and it is an important factor affecting the thermal cycling efficiency [1]. Too high or too low temperature will affect the safety and operation efficiency of the unit.According to the research data, when the temperature of the main steam decreases by 5℃, the thermal cycling efficiency decreases by about 1%, Moreover, the dynamic characteristics of the boiler are greatly affected by the load fluctuation, therefore, it is necessary to track the load for real-time control of the main steam temperature.

The main steam temperature is determined by the amount of fuel input by the boiler and the ratio of water input. In an ideal state, the main steam temperature at the outlet can be kept stable by maintaining a certain fuel -water ratio [2].However, in the process of random load, the change of load will affect the fuel-water ratio, so it is difficult to keep the fuel-water ratio stable only and the main steam temperature at the outlet needs to be adjusted by other methods.At present, flue gas and water spray temperature reduction are commonly used [3].The flue gas regulation changes the steam absorption heat by changing the heat exchange between the flue gas and the heating surface, which has higher requirements on the boiler internal structure and operation level of operators.Therefore, this paper adopts the two-stage water spraying to reduce the temperature, and then adjusts the main steam temperature at the outlet by cooling the first-stage superheater and heating the second-stage superheater.Under the traditional PID control, a good control effect can be achieved within a certain range, but the control parameters need to be manually adjusted according to experience[4], which is difficult to be adjusted in real time as the optimal parameter and cannot quickly adjust the main steam temperature to the set value.At the same time, the amount of water spraying has a great influence on coal consumption. For 500MW units, the water spraying amount is 10t/h, and the coal consumption increases by about 0.379g/kWh. Therefore, PID controller parameters need to be optimized.

Common PID parameter optimization methods include: fuzzy theory [5], neural network, particle swarm optimization, genetic algorithm, etc.Each of these methods has its advantages and disadvantages.Fuzzy theory needs to establish fuzzy rules;There are many training parameters of neural network.Particle swarm optimization algorithm is easy to fall into local optimal;Genetic algorithms are prone to prematurity.Sailfish algorithm is a new meta-heuristic optimization algorithm proposed by Shadravan et al in 2019[6].The formula is simple and easy to understand, with strong optimization ability.But not all optimization algorithms are suitable for the same problem.It is necessary to develop the best optimization algorithms to solve the difficult and complex problems in the real world and promote the development of intelligent computing.In order to further improve the optimization ability of SFO, the initialization method based on chaotic mapping and oppositional learning is adopted to improve the diversity of the population and the fitness value of the initial population and speed up the optimization speed.

Aiming at the control problem of main steam temperature in the process of variable load, a collaborative control method is proposed, which takes fuel-water ratio as the main control and water spray temperature reduction as the auxiliary control. Establish a fuel-water ratio control model, track load changes, adjust boiler input, stabilize fuel-water ratio; improve the original SFO algorithm, optimize the PID parameters of the water mist reducer, and adjust the PID parameters online according to load changes to obtain the most Optimal combination of parameters to achieve rapid adjustment of MPT. It was applied to a 500MW unit of a power plant and achieved good control effect.

2.MAIN STEAN TEMPERATURE COTROL STRATEGY

2.1 Boiler turbine coordinated control system

Thermal power plant is a process control that integrates fuel input, air, water supply and output power to the boiler. In order to meet the coordination of grid factories, the coordinated control method of boiler and steam turbine[7] is adopted, as shown in Fig 1.

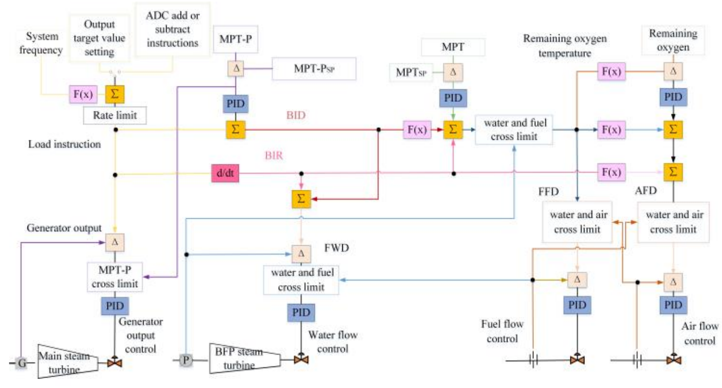


Fig 1 Coordinated control system

In Fig 1, BID is the sum of the boiler input command, that is, the load command and the intermediate point pressure deviation through PID calculation; BIR is the boiler input acceleration signal,the differential value of namely the load command [8].

A、Feedwater flow demand signal (FWD): It is composed of the addition of BID and BIR, and BID itself is used as a proportional action control signal.

B、Fuel flow demand signal (FFD): It is composed of the pre-control signal calculated by the function of BID, the correction signal of the intermediate point temperature deviation calculated by PID, the BIR, and the cross limit of feed water and fuel.

C、Air flow demand signal (AFD): It is composed of the signal obtained by function calculation of FFD and BIR and the oxygen correction signal.

D、Generator output control: adjust the opening of the turbine control valve to the corresponding position according to the load command, maintain the opening and other main steam pressure to return to a stable value, so that the generator output is consistent with the load command.

2.2 Establishment of fuel-water ratio model

Considering that the outlet main steam temperature has a certain delay to the change of the fuel-water ratio, the saturated steam temperature just after the steam-water separation is introduced as the midpoint temperature as the adjustment signal of the fuel-water ratio [9][10]. When the fuel-water ratio is balanced, the temperature at the midpoint of the steam-water stroke will remain stable, and the main steam temperature at the outlet will be stable. According to the actual equipment data of a 500MW power generation unit in a power plant as shown in Fig 2.a~d, the midpoint temperature control model is established.

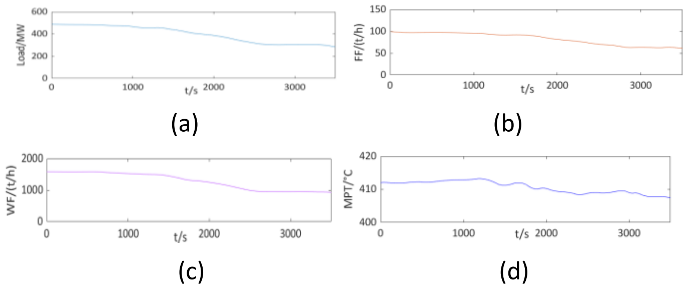


Fig 2 Actual data of thermal power plant： (a) Load curve; (b) Fuel flow rate change curve; (c) Change curve of feed water flow; (d)MPT change curve

According to bc and ad in Fig 2, the time curve of fuel-water ratio R can be obtained as shown in Fig 3, and the relationship curve between MPT and Laod is shown in Fig 4.

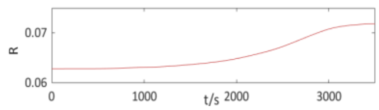


Fig 3 Change curve of R

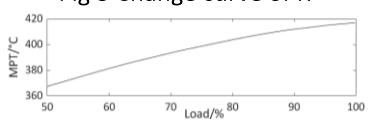


Fig 4 Curve of relationship between MPT and Load

According to Fig 3 and Fig 4, the stable load of 200MW、250MW、350MW、500MW is derived in the non-linear static state, and the intermediate value adopts the linear interpolation method,obtain the functional relationship between R, load and MPT, as shown in Fig 5.

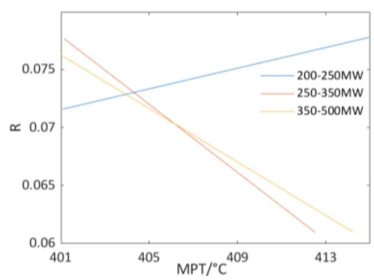


Fig 5 Relationship between fuel-to-water ratio, load and MPT

$$R = F(MPT, Laod) \tag{1}$$

The change of feed water flow has little effect on the temperature of the intermediate point, which is mainly adjusted by fuel. The MPT control model is shown in Fig 6.

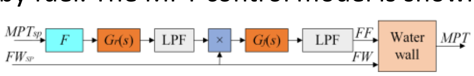


Fig 6 MPT nonlinear discrete control model

In Fig 6, $G_f(s)$ is the transfer function of the fuel to the boiler; $G_r(s)$ is the transfer function of the heat exchange between fuel and water in the water wall; LPF is the low-pass filter.

$$G_f(s) = \frac{1}{1+300s}, G_r(s) = \frac{1}{1+900s} \tag{2}$$

In order to verify the accuracy of the fuel-water ratio model, the actual data of water supply flow rate and fuel flow rate were input into the model, and the obtained MPT output was compared with the actual data. The results are shown in Figure 7.The error between the output of the model and the actual data is between 0℃ and 3℃, which is very small as MPT control, indicating that the established model is reliable.

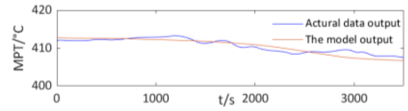


Fig 7 Model validation results

2.3 Water spray cooling control system

Usually a water spray desuperheater is added at the entrance of the secondary superheater. The water spray volume is part of the boiler feed water volume. It does not pass through the economizer, water wall, and primary superheater. When the main steam temperature is disturbed, it can respond quickly and make corrections in time. The system block diagram is shown in Fig 8.

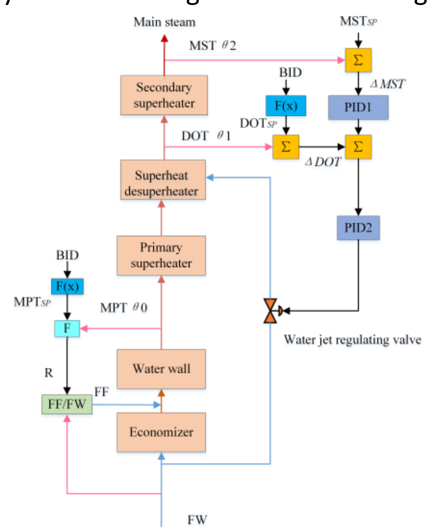


Fig 8 Water spray cooling control system

In Fig 8, ϑ_0 is the midpoint temperature(MPT); ϑ_1 is the outlet temperature of the desuperheater(DOT); ϑ_2 is the main steam temperature(MST); PID1 is the main controller; PID2 is the sub-controller. The change trend of ϑ_1 and ϑ_2 is consistent. When disturbance occurs, ϑ_1 responds earlier than ϑ_2, PID2 plays the role of "coarse adjustment", PID1 corrects PID2 and plays the role of "fine adjustment".

The objects in the lead zone and the inertia zone have the characteristics of high-order, inertia, pure delay, and self-balance. The transfer function model is：

$$G(s) = \frac{k}{(1+Ts)^n} \tag{3}$$

Where $G(s)$ is the transfer function of the controlled object, k is the amplification factor, T is the time constant, and n is the order.

Under different loads, the transfer function model is different. According to the step response curve of the controlled object, the two-point method and the tangent method can be used to obtain the parameters k, T, and n. In this paper, the two-point method is used to obtain the transfer functions of the leading zone and the inert zone under three typical loads, as shown in Table 1.

Table 1
The transfer function of each controlled object under different loads

Load(%)	Pre-leading area	Inert zone
50%	$\frac{3.81}{(1+25s)^2}$	$\frac{1.94}{(1+42s)^8}$
75%	$\frac{1.641}{(1+20s)^2}$	$\frac{1.37}{(1+27.6s)^7}$
100%	$\frac{0.817}{(1+18s)^2}$	$\frac{1.284}{(1+18.6s)^6}$

3. APPLICATION OF ISFO ALGORITHM IN PID

The PID controller is a linear combination of three controllers: proportional, integral, and derivative. The ISFO-PID controller structure is shown in Fig 9.

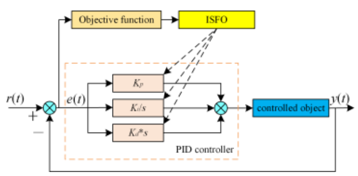


Fig 9 ISFO-PID controller structure

Control rule：

$$e(t)=r(t)-y(t) \tag{4}$$

$$u(t)=K_p e(t)+K_i\int_0^t e(t)dt+K_d\frac{de(t)}{dt}] \tag{5}$$

Where K_p、K_i、K_d are divided into proportional, integral, and differential constants.

The selection of PID control parameters can be described as an optimization problem. This paper selects ITAE as the error performance index, and uses the improved SFO algorithm to optimize the PID parameters to minimize ITAE. ITAE is the integral of time multiplied by the absolute value of the error, the expression is：

$$J_{ITAE}=\int_0^{t_s} t\left|e(t)\right|dt \tag{6}$$

Where t_s is the upper limit of the integral time.

3.1 Improved SFO Algorithm

The initial position distribution and initial value of the population affect the efficiency of the population optimization. In order to improve population diversity and global search capabilities, a population initialization strategy based on chaotic mapping [11] and opposition learning[12] (BCOL) is proposed. Use the good randomness, spatial ergodicity and non-repeatability of chaotic mapping to initialize the population, use the opposite learning method to generate its opposite individuals, and then select the best fitness as the initial individual. In this paper, Tent mapping is used to generate the initial population of chaotic sequences.

Sailfish and sardines use the same initialization strategy.The initialization steps are as follows:

Step1：Generate random numbers：

$$Z_{i,d}^k \in (0,1) \tag{7}$$

Where d is dimension ,d=1,2,...,D;k is iteration number;i is the position of the i-th sailfish.

Step2：Tent function Chaotic map：

$$Z_{i,d}^{k+1}=\begin{cases} Z_{i,d}^k/0.7, Z_{i,d}^k\in(0,0.7] \\ 10/3Z_{i,d}^k(1-Z_{i,d}^k), Z_{i,d}^k\in(0.7,1) \end{cases} \tag{8}$$

Step3：Generate N positions, namely the original population.

$$X_{SF}=\begin{bmatrix} x_{sf,1,1} & x_{sf,1,2} & \cdots & x_{sf,1,D} \\ x_{sf,2,1} & x_{sf,2,2} & \cdots & x_{sf,2,D} \\ \vdots & \vdots & \vdots & \vdots \\ x_{sf,N,1} & x_{sf,N,2} & \cdots & x_{sf,N,D} \end{bmatrix} \tag{9}$$

$$x_{sf,i,d}=x_{min,d}\times\left(1-Z_{i,d}^{k+1}\right)+x_{max,d}Z_{i,d}^{k+1} \tag{10}$$

Where $x_{max,d}$ and $x_{min,d}$ are the upper and lower limits of the sailfish's d-dimensional position.

Step4：Generate the position of the opposite individual based on the opposite learning, that is, produce the opposite population OX_{Sf}.

$$ox_{sf,i,d}=x_{min,d}Z_{i,d}^{k+1}+x_{max,d}\times\left(1-Z_{i,d}^{k+1}\right) \tag{11}$$

Step5：Combine the original population and the opposite population to calculate the individual fitness, and take the first N positions with high fitness as the initial population.

4. SYSTEM MODELING AND SIMULATION

4.1 Modular modeling system

The structure of thermal power plant is complex. Modular modeling (MMS) method is adopted to decompose the complex system into independent modules,and its mathematical model is established according to the design data (size, pressure, temperature, etc.) of the decomposed modules.It is compiled, packaged and stored in the module library, and connected according to certain rules to form a complete thermal power system. As shown in Fig 10.

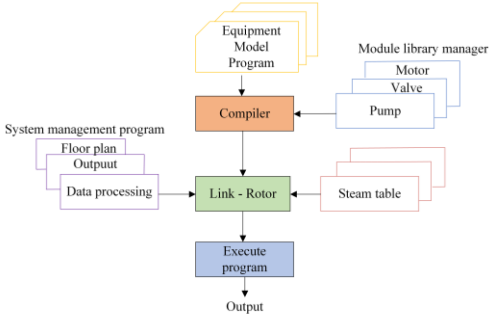
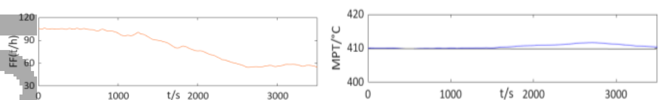


Fig 10 MMS structure

4.2 Simulation results and analysis

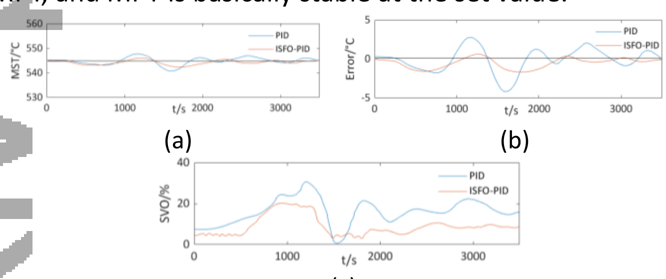
Based on MMS, a 500MW supercritical unit was established and the simulation experiment of 3600s was carried out.The adjustment of the fuel-water ratio is mainly realized by adjusting the fuel flow. Fig 11 and Fig 12 are the simulation results. Fig 11 shows the change curve of boiler input signal adjusted by using the temperature at the intermediate point as the correction value under load changes, and Fig 11 shows the change curve of the boiler output signal under the two spray water temperature reduction control methods.



(a) (b)

Fig 11 Change curve of boiler input signal: (a) Fuel flow curve; (b)MPT change curve

In Fig 12, a and b are the change curves of fuel flow and MPT respectively. In the case of load changes, fuel flow is adjusted according to the temperature deviation of MPT, and MPT is basically stable at the set value.



(a) (b)

(c)

Fig 12 Variation curve of boiler output signal: (a) MST change curve; (b) Error curve; (c) Water valve opening curve

It can be seen from Fig 12 that in the process of variable load, the main steam temperature and the opening degree of the spray valve under the sfo-pid control have small changes. Compared with the traditional PID control, the ISFO-PID control effect is better.

According to literature [13], the equivalent heat drop method is adopted to establish the relationship between coal consumption rate and the change of desuperheating water amount, as shown in Fig 13.

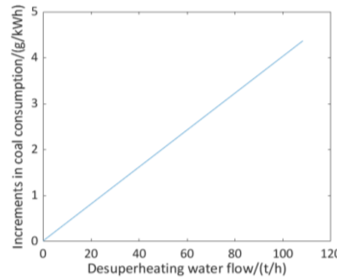


Fig 13 The relation curve between the temperature reduction water quantity and the increment of coal consumption

As can be seen from Fig 13, there is a positive linear correlation between the temperature reduction water and the increase of coal consumption for power generation. For every 10t/h increase of the temperature reduction water, the increase of coal consumption for power generation is 0.379g/kWh. Compared with traditional PID, ISFO-PID reduces coal consumption by 0.606g/ kWh. The performance index parameters of the control system are shown in Table 2.

Table 2
Performance index

control method	PID	ISFO-PID
Accommodation time /s	700	200
Temperature changing	[-4.9,2.5]	[-1.7,0.3]
Average temperature difference /℃	3.6	0.72
Steady-state error /℃	1.5	0.4
Average opening of spray valve %	19	11
working water jet capacity/t/h	38	22
Increased coal consumption /(g/kwh)	1.533	0.927

5. CONCLUSIONS

In this paper, a load tracking intelligent control system model of main steam temperature is established. Considering the influence of variable load process on the temperature of main steam, a method based on the fuel-water ratio as the main control and the temperature reduction by spraying water as the auxiliary control is proposed.At the same time to meet the network plant coordination set up the boiler steam turbine coordination control system, according to the load command to adjust the boiler input and output, so that the unit output can quickly track the load changes.In the fuel-water ratio control model, the temperature deviation of the intermediate point is taken as the correction signal of the fuel-water ratio, and the MPT nonlinear discrete controller is established to adjust the MPT through fuel flow to keep it stable.In the water-jet temperature reduction control model, the improved sailfish algorithm is used to optimize the PID parameters, and the PID parameters are corrected online according to the load change to obtain the best parameter combination. The water spraying quantity is adjusted in a fine way to maintain the stable output of the main steam temperature.To improve the SFO algorithm, an initial method based on chaotic mapping and oppositional learning is adopted in this paper. The Tent function is used to generate N individuals of chaotic sequence.Then, the oppositional learning idea is used to generate the oppositional individuals. Finally, the first N individuals are selected as the initial population after comprehensive evaluation of the fitness of all individuals. This method not only improves the diversity of the initial population, but also enables each individual to have a good initial position, which can accelerate the convergence speed and accuracy of the algorithm.

In the aspect of simulation and model accuracy test, this paper adopts modular modeling method to decompose the complex system and then connect it, which can truly represent the actual equipment.In this paper, the accuracy of the fuel-water ratio model is tested. The maximum error between the output MPT value of the model and the actual data is 3℃,within the allowable range, it indicates that the established model has high accuracy.Finally, this paper also conducts a comparison experiment between the two controllers of SFO-PID and traditional PID. From the simulation results, it can be seen that the control effect of SFO-PID is better, which can maintain the stable output of MPT, reduce the amount of water spraying and reduce the coal consumption.This study provides a new scheme for the control of main steam temperature and the measures of energy conservation and emission reduction in thermal power plants, which has strong theoretical significance and value for practical engineering applications.

REFERENCES

[1] Jiang Ni, MA Lixin. Intelligent Research on steam Temperature of Overshoot Prevention Boiler [J]. Information Technology,2015(07):142-146.

[2] Matsuura si lang, pingshan kaiichiro. Control technology in power generation equipment [M]. Beijing: machinery industry press,2012,3(9):2-31.

[3] Zhang qiusheng, liang hua, hu xiaohua,et al. Two typical coordinated control schemes for ultra-supercritical units [J]. China electric power,2011,44(10):74-79.

[4] Narinder Singh and Sandeep kumar, “ComparativeAnalysis of PID, Cascade and Fuzzy Logic Control for the Efficient Temperature control in CSTR” in International Journal of Advanced Research in Elactrical, Electronics and Instrumentation Engineering Vol.1, Issue 1, July 2012. ISSN: 2278-8875.

[5] Zhang liping, ma lixin, jin zhenzhen. Design of fuzzy adaptive PID furnace temperature control system [J]. Thermal processing technology,2012,41(14):234-236+229.

[6] Shadravan, S.,Naji, H. R.,Bardsiri, V. K.. The Sailfish Optimizer: A novel nature-inspired metaheuristic algorithm for solving constrained engineering optimization problems[J]. Engineering Applications of Artificial Intelligence,2019,80(APR.):20-34.

[7] Ma lixin, jiang ni, yuan shujuan. Intelligentization of coordinated control mode of load tracking power generation system [J]. Journal of Shanghai university (natural science edition),2013,19(02):144-149.

[8] Toshio Inoue, Haruhito Taniguchi, Yasuyuki Ikeguchi.AModel of Fossil Fueled Plant with Once-Through Boilerfor Power System Frequency Simulation Studies[J].IEEE Transactions on power systems, 2000, 15:1322-1328.

[9] Yuan shujuan, ma lixin, dai shuguang. Research on temperature control of intermediate point in real-time operation of supercritical dc boiler under variable working conditions [J]. Thermal energy and power engineering,2014,29(06):697-701+761-762.

[10] Menkina M.Possibility of robust temperature control of superheated steam of the through-flow boiler［C］//Proceedings of 13th International Carpathian Control Conference.Piscataway,NJ,USA: IEEE,2012: 474-479.

[11] Tavazoei MS, Haeri M.Comparison of different one-dimensional maps as chaotic search pattern in chaos optimization algorithms. Appl Math Comput ,2007,187(2):1076–1085

[12] Li Zhiming, Zhou Jia-quan, Huang Xiu-fang, et al. Moth-Flame Optimization Algorithm Using Elite Opposition-Based Learning[J]. Computer Science and Application,2020,10(05) :860-86.

[13] Gu Junjie, Yang Zhi, Ren Yanling,et al.Research on the influence of reheater water injection temperature reduction on coal consumption rate of the unit[J].Journal of North China Electric Power University (Natural Science Edition),2011,38(01):103-106.