Journal of Thermal Analysis and Calorimetry (2020) 141:83–94
https://doi.org/10.1007/s10973-019-08871-9

Thermodynamic cycle analysis and optimization to improve efficiency in a 700 °C ultra-supercritical double reheat system

Mei Yang[1] · Yun-long Zhou[1] · Di Wang[1] · Jiayu Han[1] · Yujia Yan[1]

Received: 5 July 2019 / Accepted: 27 September 2019 / Published online: 1 November 2019

Abstract

When increasing steam parameters, the incomplete thermodynamic cycle and large irreversible system losses are bottlenecks in improving thermal efficiency in ultra-supercritical power plants. In this study, a comprehensive analysis of both parameter optimization and system cycle analysis is carried out for a 1000-MW double reheat ultra-supercritical thermal power plant. First, the genetic algorithm is used to optimize the primary and double thermal pressure, as well as the steam extraction parameters of the steam turbine. Then, a thermodynamic optimization model is proposed to analyze performance. Moreover, the exergy analysis method is applied to reveal the irreversibility mechanism in the thermodynamic cycle. In order to further solve the energy-grade mismatch problem, the performance of a regenerative steam turbine thermal system is improved based on the optimized system. The results indicate that the power generation efficiency of the optimized system is 0.31% higher than that of the prototype system, and the heat consumption rate is decreased by 43.67 kJ (kW h)$^{-1}$. The power generation efficiency in the regenerative steam turbine system is up to 52.42%, which is 1.44% higher than that of the optimized system. Therefore, an effective method to improve the thermal efficiency is obtained through the thermodynamic cycle analysis and optimization for 700 °C ultra-supercritical double reheats systems.

Keywords 700 °C ultra-supercritical power plant · Thermodynamic cycle optimization · Exergy analysis · The power generation efficiency · Thermodynamic performance

List of symbols

W	The amount of the work by a steam turbine, kJ kg^{-1}
η_T	The efficiency of the steam turbine system
e_0	The specific exergy of the supply system, kJ kg^{-1}
e_{w1}	The exergy of feed water, kJ kg^{-1}
D_0	The mass flow rate of main-steam, kg s^{-1}
D_{rh1}	The mass flow rate of steam single reheat steam, kg s^{-1}
D_{rh2}	The mass flow rate of double reheat steam, kg s^{-1}
p_0	The main-steam pressure
p_1	The first reheat pressure
p_2	The second reheat pressure
p_{0i}	No. i the extraction pressure
e_{rh1}	The exergy of intermedium-pressure turbines inlet steam, kJ kg^{-1}
e_{rh2}	The exergy of low-pressure turbines inlet steam, kJ kg^{-1}
e_2	The exergy of intermedium-pressure turbines exhaust steam, kJ kg^{-1}
e_3	The exergy of low-pressure turbines exhaust steam, kJ kg^{-1}
q_{cp}	The heat consumption rate
η^e	The exergy efficiency
Δe	The exergy losses, kJ kg^{-1}
$e_{m,in}$	The specific exergy of inlet, kJ kg^{-1}
$e_{m,out}$	The specific exergy of outlet, kJ kg^{-1}
e_q	The specific exergy of heat flux, kJ kg^{-1}
h_1	The specific enthalpy of the working medium at the given state, kJ kg^{-1}
h_{amb}	The specific enthalpy of the working medium at the environmental state, kJ kg^{-1}
T	The average temperature of heat absorption process of working medium, K
T_{amb}	The environment temperature, K
S_1	The specific enthalpy of the working medium at the given state, kJ (kg K)$^{-1}$

✉ Mei Yang
yangmei@neepu.edu.cn

[1] School of Energy and Power Engineering, Northeast Electric Power University, Jilin 132012, China

S_{amb}	The specific entropy of the working medium at the environmental state, kJ (kg K)$^{-1}$
Δs_g	The entropy production of irreversible processes, kJ (kg K)$^{-1}$
Q_{cp}	Heat consumption of power plants, kJ h^{-1}
P_e	The output power of generator, kW
B	The fuel consumption per unit time of boiler, kg h^{-1}
$Q_{net,p}$	The low heat value (LHV) of coal, kJ kg^{-1}
q_{cp}	The unit of heat consumption rate, kJ (kW h)$^{-1}$
w	The specific work of the power equipment, kJ kg^{-1}
q	Heat absorbed by the working medium kJ kg^{-1}
B	Boiler
HP	High-pressure cylinder
IP	Intermediate-pressure cylinder
LP	Low-pressure cylinder
G	Generator
C	Condenser
CP	Condensate pump
Hi	No. i regenerative heater

Introduction

According to BP's Energy Outlook, the global energy demand will grow nearly a third by 2035. Moreover, fossil fuels will still account for 75% of the energy mix [1], and currently are widely used as fuel for utility boilers to generate electricity through the steam Rankine cycle. Although the outlook for renewable energy has increased substantially in the past 3 years, coal is still a significant source of electricity in parts of Asia in 2040 [2]. Hence, coal-fired power plants, as the largest energy consumption, have become the focus of most attention [3, 4]. Therefore, efficient utilization of coal energy in power plants is of great significance for energy conservation and environmental protection. For the purpose of energy conservation and emission reduction, further improvement in thermodynamic cycle in large-scale coal-fired power generation is a major requirement [5, 6]. Thus, any improvement in the generation efficiency is worth studying and exploring.

At present, general methods of improving the energy conversion efficiency of coal-fired power generation are mainly divided into three types: The first is to optimize the thermal systems of coal-fired generating units [7], such as organic Rankine systems [8–10], the supercritical carbon dioxide cycles [11, 12], the ultra-supercritical power units [13, 14], and the regenerative cycle [15]. The second is to utilize waste heat efficiently. For the efficient utilization of waste heat, the grade analysis method is mainly used to study the energy-saving potential of a typical heat pump heating system in coal-fired thermal power plants [16]. Moreover, the absorption heat pump can absorb waste heat effectively to improve system efficiency [17, 18]. The third is to increase the initial working fluids' temperature and pressure [19]. Currently, the unit capacity of generators has reached 1000 MW in large power plants, and parameters for pressure and temperature of the main-steam are 25–30 MPa and 600 °C, respectively [20]. Zhou et al. [21] established the calculation model for the main-steam parameters to obtain the main-steam pressure and temperature of the unit under THA conditions. This is an effective measure to obtain higher steam parameters and appropriate feedwater temperature to improve the efficiency of thermal power plants [22, 23]. Much ultra-supercritical double reheat coal-fired thermal power generation can be widely applied, such as the 1000-MW ultra-supercritical unit of Guang Dong Jia Hu Wan power plant put into operation recently. In the foreseeable future, the steam parameters are expected to further increase to 30–35 MPa and 700 °C [24, 25] in many countries, such as the European Union [26, 27], the USA [28] and Japan [29].

In addition, methods to understand and improve energy systems using energy, exergy and economic analysis are an effective new approach. Yilmaz F [30] analyzed a novel hybrid ocean thermal energy conversion system for clean power production, while Ahmadi MH et al. [31] analyzed a system comprehensively including energy, exergy, economic (3-E) analyses, and their applications were related to various thermal power plants. Exergy analysis is a powerful method for determining the losses in a system [32, 33]. Naeimi et al. [34] investigated a waste heat recovery system and gas engine for power generation in a Tehran cement factory, while Gargari et al. [35] conducted energetic, exergetic, economic and environmental analyses of a biomass based multi-generation plant. Notably, the thermal efficiency is influenced by the initial working fluids' parameters and optimization of the thermodynamic cycle. Most of the studies related to steam parameters and process design of the steam cycle are focused on single 600 °C supercritical units. Wang [36] found that the optimal pressure ratios of reheating are 0.15–0.25 (for single reheat), 0.2–0.3 and 0.15–0.3 (for double reheat). Srinivas [37] presented the effect of steam injection mass ratio, deaerator pressure (or temperature ratio), steam reheat pressure ratio, HP steam turbine pressure, compressor pressure ratio and combustion temperature on the combined cycle's exergy efficiency. Espatolero [38] analyzed a strategy for the optimization of the feedwater heaters network and a flue gas heat recovery system design in supercritical coal-fired power plants. Few researchers have conducted comprehensive thermodynamic cycle analyses and optimization of 700 °C ultra-supercritical double reheat coal-fired thermal power generation systems.

In view of this, in this paper a study of parameter optimization and system structure is conducted based on a conventional 1000-MW double reheat ultra-supercritical thermal power plant: (1) to carry out parameter optimization in a 700 °C ultra-supercritical double reheat system. (2) To propose an improved thermodynamic cycle based on exergy analysis. (3) To compare thermodynamic performance under various conditions. Based on the above, an effective method to improve the thermal efficiency is presented.

System description and simulation assumptions

Prototype system

A 700 °C high-efficiency ultra-supercritical coal-fired power plant is taken as the research object. Figure 1 shows the flow diagram of the prototype system structure.

This unit adopts 10-stage steam extraction, including 4-stage high-pressure heaters, 5-stage low-pressure heaters, and one deaerator. The deaerator is considered as a regenerative heater. Other heaters are regarded as the surface heaters. The hydrophobic water flows step by step. The steam cycle includes high-pressure turbines (HPT), intermedium-pressure turbines (IPT) and low-pressure turbines (LPT). Then, the HPT's exhaust steam is returned to the boiler for the first reheat process and then sent to the IPT. The exhaust steam of the IPT is returned to the boiler for a second reheat process. The main-steam expands and works in the steam turbine to the condenser at pressure of 0.004 MPa. The capacity of the ultra-supercritical double

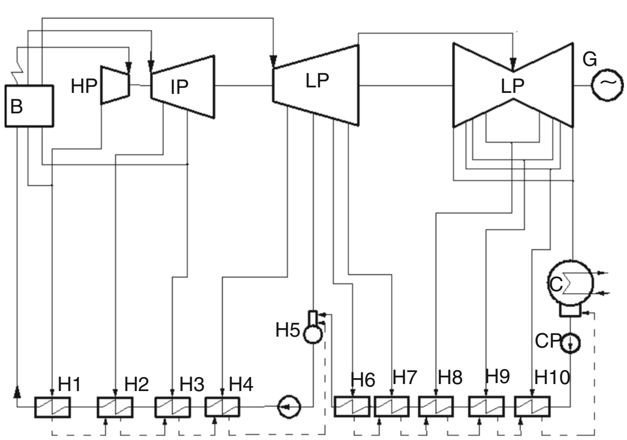

Fig. 1 Thermal system diagram of ultra-supercritical 10-stage regenerative double reheat unit

reheat system under the turbine heat acceptance (THA) load condition is 1000 MW. In the thermal calculation, the boiler efficiency is 94.5%, the pipeline efficiency is 99.2%, and the auxiliary power rate is 3.5% [39].

Model simulation overview and assumptions

In this study, the Ebsilon commercial software is used to simulate the parametric analysis and energy equilibrium of a 700 °C ultra-supercritical double reheat coal-fired thermal power generation. This software is widely used in the modeling and optimization of cycle processes in power plants [40–42]. Ebsilon Professional offers several calculation modes to characterize a model, and its applicability to simulate thermal systems in a power plant at different conditions has been previously validated [43–45].

The prototype cycle model is based on the heat balance diagram of the turbine and boiler, and a 100% THA load was selected as the design point of the model. In the prototype design model, the assumptions for the calculation of the related definitions were as follows:

1. The pressure drops of HP, LP and IP heaters are 3%, 5% and 5%, respectively;
2. The pressure drops of the first reheater, the second reheater and the pipeline are 6.4%, 6.4% and 10.2%, respectively;
3. The constant isentropic efficiencies of HP, LP and IP are 0.90, 0.915 and 0.89, respectively;
4. Each model's exergy output (electricity) is set at 1000 MW;
5. The pressure of each model condenser is set to 4.5 kPa.

Model validation

The comparison of the design's values to the simulation results of the N1000-25/600/610/610 ultra-supercritical double reheat plant is listed in Table 1. As indicated in the table, the simulation results were consistent with the design values and whose error value was lower than 1%, verifying the accuracy and reliability of this model.

In this study, p_0, p_1 and p_2 refer to the main-steam pressure, the first reheat pressure and the second reheat pressure, respectively. The p_1 is dependent on p_1/p_0. Similarly, the p_2 is dependent on the specified p_1 and p_2/p_1. In the analysis of the reheat pressure, the main-steam parameters of the steam-water cycle were set to 35 MPa and 700 °C, and the first and second reheat temperatures were both 720 °C, while the low-pressure cylinder exhaust pressure was set to 4.5 kPa. A ten-stage regenerative double reheat unit was selected as the prototype system and will be referred to as "case 1 (p_1/p_0 = 0.3 p_2/p_1 = 0.3)." It can be seen that the first and second reheat steam pressures

Table 1 Comparison design values with simulation results of ultra-supercritical double reheat unit

RHs	Steam pressure/MPa	Steam temperature/°C		Extraction mass flow	
		Design values	Simulation values	Design values	Simulation values
#1	7.81	413.9	413.7	41.78	41.89
#2	6.01	520.4	520.3	35.86	35.95
#3	4.73	350.61	350.52	23.78	23.68
#4	2.89	283.04	283.17	24.08	24.05
#5	1.17	489.96	489.93	18.76	18.71
#6	0.654	408.53	408.43	20.70	20.63
#7	0.356	330.85	330.91	21.62	21.51
#8	0.166	244.35	244.49	20.75	20.71
#9	0.066	154.43	154.56	20.14	20.19
#10	0.022	66.81	66.89	19.93	19.84

are 10.5 MPa and 3.15 MPa, respectively. The stream-water parameters of the regenerative heaters of each stage can be calculated according to the heat balance model, as shown in Table 2.

The thermodynamic performance evaluation criteria

In order to evaluate the thermodynamic performance of the 700 °C ultra-supercritical double reheat coal-fired thermal power generation system, the power generation efficiency and the heat consumption rate are selected as the evaluation indexes for the thermodynamic performance of the unit. The power generation efficiency represents the ratio of the effective energy (electrical energy) output to the total energy (chemical energy of fuel) input from the power plant, and is expressed as follows:

$$\eta_{cp} = \frac{3600P_e}{BQ_{net,p}} = \frac{3600P_e}{Q_{cp}} \tag{1}$$

The heat consumption rate represents the amount of heat consumed per unit of electric energy produced by a power plant, which is defined as follows.

$$q_{cp} = \frac{Q_{cp}}{P_e} = \frac{3600}{\eta_{cp}} \tag{2}$$

Exergetic evaluation

Based on the first and second laws of thermodynamics, the method of exergy focuses on the changes in functional forces in various dynamic processes. It evaluates the effect of the energy system from the aspect of energy quality, whose index is efficiency, i.e., the ratio of available energy for effective utilization. As far as the power plant is concerned, exergy efficiency can be calculated as follows:

$$\eta^e = \frac{w}{e_0} = 1 - \frac{\Delta e}{e_0} \tag{3}$$

The exergy losses of the thermal equipment can be determined using the exergy equilibrium equation:

Table 2 Extraction parameters of the prototype system of the super-supercritical double reheat unit

RHs	Steam pressure/MPa	Steam temperature/°C	Saturation temperature/°C	Extraction superheat/°C
#1	8.51	484.26	299.39	184.87
#2	5.95	616.38	275.08	341.3
#3	3.51	528.01	242.76	285.25
#4	1.54	593.25	199.57	393.68
#5	0.8	488.55	170.44	318.11
#6	0.47	411	149.55	261.45
#7	0.26	333.78	128.74	205.04
#8	0.13	253.87	107.14	146.73
#9	0.064	176.03	87.6	88.43
#10	0.024	87.57	64.06	23.51

$$\Delta e = \left(e_{\mathrm{m,in}} + e_{\mathrm{q}}\right) - \left(e_{\mathrm{m,out}} + w\right) \tag{4}$$

$$e_{\mathrm{m}} = (h_1 - h_{\mathrm{amb}}) - T_{\mathrm{amb}}(s_1 - s_{\mathrm{amb}}) \tag{5}$$

$$e_{\mathrm{q}} = q\left(1 - \frac{T_{\mathrm{amb}}}{T}\right) \tag{6}$$

The exergy losses of the unit working fluid caused by a certain irreversible thermal process or equipment in a temperature of T_{amb} environment can be expressed as:

$$\Delta e = T_{\mathrm{amb}} \Delta s_{\mathrm{g}} \tag{7}$$

Optimization of steam pressure of 700 °C ultra-supercritical double reheat system

Effect of main-steam pressure to exergy efficiency of the steam turbine

The second law is introduced to predict the thermodynamic performance of the unit, which is further analyzed with the efficiency of the unit as the evaluation standard. The efficiency of the steam turbine system is as follows:

$$\eta_{\mathrm{T}} = \frac{W}{D_0(e_0 - e_{\mathrm{w1}}) + D_{\mathrm{rh1}}(e_{\mathrm{rh1}} - e_2) + D_{\mathrm{rh2}}(e_{\mathrm{rh2}} - e_3)} \tag{8}$$

The effect of main-steam pressure and temperature on the exergy efficiency of the steam turbine is shown in Fig. 2. From the relationship between the efficiency of the turbine and the temperature under different main-steam pressures, given a main-steam pressure, the exergy efficiency of a steam turbine thermal system increases with increasing temperature. That is because as the steam temperature is growing, the enthalpy rises and the work energy increases. At a given temperature, there is a fixed pressure at which the enthalpy of water vapor is maximized. This

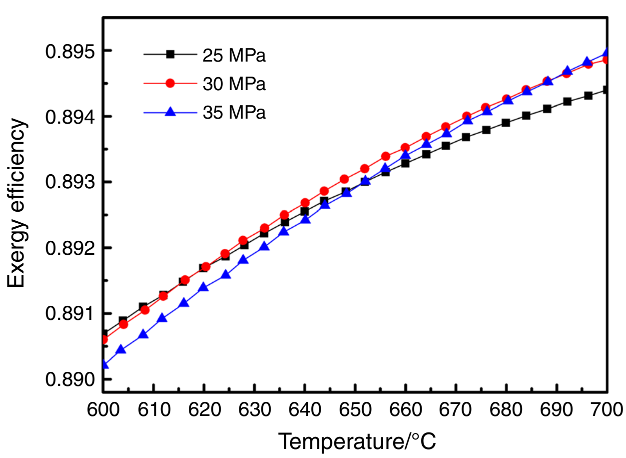

Fig. 2 Effect of steam parameters on steam turbine exergy efficiency

pressure can be considered as the optimum pressure for that main-steam.

When the main-steam temperature is 600 °C, the exergy efficiency at 25 MPa is basically the same as the exergy efficiency at 30 MPa, which is obviously higher than that for a steam pressure of 35 MPa, Therefore, the steam pressure should be 25 MPa. When the steam temperature rises to 650 °C, the steam pressure is 30 MPa, which is significantly more efficient than when the steam is at 25 MPa and 35 MPa. Hence, the main-steam pressure should be 30 MPa. When the steam temperature increases to 700 °C, the exergy efficiency is higher than that obtained at 25 MPa or at 30 MPa, Thus the main-steam pressure should be chosen to be 35 MPa. Consequently, a high-efficiency ultra-supercritical generator at 700 °C should have a main-steam pressure of 35 MPa.

Influence of parameter optimization on thermal thermodynamics of 700 °C ultra-supercritical double reheat system

In order to optimize the thermal economy of the 700 °C ultra-supercritical double reheat system, the reheat pressure and extraction parameters should be optimized and adjusted to maximize the thermal economy of the system. We firstly established the mathematical description of the parameter optimization problem. Then, we wrote the program interface of a MATLAB genetic algorithm and subsequently created an Ebsilon model. The GA method, a stochastic global search method first presented by Holland to simulate natural biological evolution [46–48], was adopted to optimize the parameter and obtain the maximum exergy efficiency.

When the genetic algorithm is optimized for the extraction parameters of the regenerative system, the absolute internal efficiency of the unit cycle is taken as the objective function, and the outlet temperature of each regenerator is optimized as a function variable. The heat consumption rate of the unit can be expressed as the objective function of heat consumption rate by Eq 9 under the boundary conditions of the determined main-steam pressure p_0, temperature t_0, reheat temperature t_{rh}, and back pressure p_{f}. According to the basic laws of thermodynamics, the extraction pressure at all levels should be reduced successively, and the ratio between the optimal reheat pressure and the main-steam pressure or the previous reheat pressure should be within a certain range. Based on this, the boundary conditions of the model were obtained, as shown in Eq 10.

$$h = f(p_1, p_2, p_{01}, p_{02}, \ldots p_{0n}) \tag{9}$$

$$p_0 > p_{01} > p_{02} > \cdots > p_{0n-1} > p_{0n}$$
$$p_1/p_0 = k; (k = 0.2 - 0.6) \quad (10)$$
$$p_2/p_1 = k; (k = 0.2 - 0.6)$$

In order to prevent the algorithm from local optimum convergence, the boundary conditions of the extraction parameter population of each stage need to be determined. The optimization parameters were set as shown in Table 3:

The stochastic global optimization genetic algorithm was used to optimize the reheat pressure and the extraction parameters of the double reheat plant at the tenth stage. When the first reheat pressure and the second reheat pressure were determined, the parameters of each stage of the reheat extraction steam can be obtained. The influence of p_1/p_0 and p_2/p_1 on power generation efficiency is shown in Fig. 3.

The power generation efficiency first increases sharply and then decreases gradually with the increase in the first reheat steam pressure. The impact of the second reheat pressure on the power generation efficiency is similar in tendency to first reheat steam pressure. The power generation efficiency is higher when p_1/p_0 is greater than 0.35 and the p_2/p_1 ratio is fixed at 0.25. When p_1/p_0 is less than 0.35 and p_2/p_1 is fixed at 0.35, the expected value of the power generation efficiency is higher than other conditions. The main reason is that the main-steam parameters in this paper are at 35 MPa and 700 °C, the enthalpy and the exergy of the main-steam increase sharply. The first reheat steam has done work in high-pressure turbines, which results in an increase in the steam extraction parameters of the regenerative system.

It is evident that the highest figure of the power generation efficiency is at p_2/p_1 and p_1/p_0 equal to 0.25 and 0.45, respectively, which represent the optimal values. This is consistent with the parametric analysis trend by Zhou et al. [49], whose peak point of power generation efficiency appears at p_1/p_0 = 0.4 and p_2/p_1 = 0.3 for the conventional conditions of 600 °C. The optimized reheat system (p_1/p_0 = 0.45 and p_1/p_2 = 0.25) will be referred to as "case 2."

Table 3 Parameters of GA

Boundary conditions	Parameter setting
Temperature rise per stage	≧ 10 °C
Number of population	250
Population initial value	Randomly generated
Population parent selection	Random uniform distribution
Hybrid probability	0.8
Migration probability	0.2
Convergence condition	$\Delta\eta_i \leq 10^{-6}$

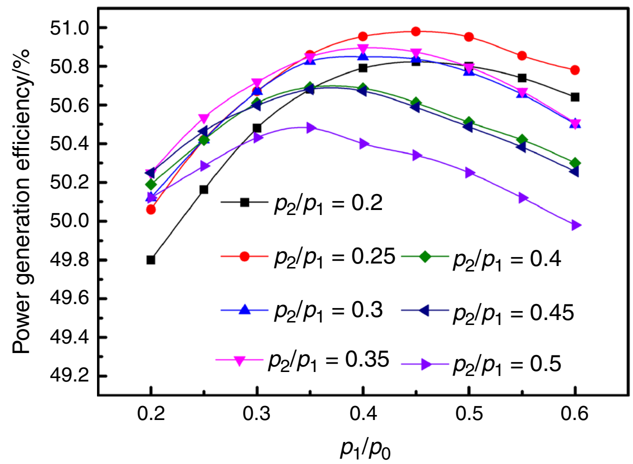

Fig. 3 Effect of reheat pressures on the power generation efficiency of the double reheat system

The same optimization method is adopted to obtain the optimal extraction parameters, which are shown in Table 4.

The following observations can be made according to Tables 2 and 4: (1) For the optimized regenerative system, the extraction steam pressure of the regenerative system is no less than the steam pressure of the extraction steam in case 1, due to the increase in the steam pressure for primary reheating. (2) The added enthalpy of feed water in the optimized double reheat plant is greater than that of case 1. Because the steam pressure of the reheat system increases in case 2, and the final feedwater temperature increases accordingly, resulting in a significant increase in the feed enthalpy.

Thermodynamic performance analysis of 700 °C ultra-supercritical double reheat system

The thermodynamic performance pairs of the 700 °C prototype system and the 700 °C optimized system are shown in Table 5. Since the regenerative extraction parameters are optimized for p_1/p_0 and p_2/p_1, the first reheat steam pressure increases from 10.5 to 15.72 MPa in the prototype system, and the double reheat steam pressure is separated from the prototype system. The second reheated steam pressure increases from 3.15 to 3.999 MPa. Compared with the feedwater temperature of the prototype system at 301.07 °C, the optimized system feedwater temperature is as high as 331.03 °C. This is because the extraction parameters of the regenerative system increase after the reheat pressure of the optimized system increases. The main-steam flow rate of the optimized system is 2234.5 t h^{-1}, which is higher than that of the main-steam flow of the prototype system. This is because the optimized feedwater temperature rises after the optimization, and

Table 4 Extraction parameters of the regenerative system of ultra-supercritical double reheat plant in case 2

RHs	Steam pressure /MPa	Steam temperature/°C	Saturation temperature/°C	Extraction superheat degree/°C
#1	12.75	549.59	329.38	220.21
#2	8.66	609.76	300.63	309.13
#3	4.45	499.05	256.79	242.26
#4	1.7	569.84	204.35	365.49
#5	0.8	452.54	170.44	282.1
#6	0.48	379.06	150.34	228.72
#7	0.26	302.8	128.74	174.06
#8	0.13	226.62	107.14	119.48
#9	0.064	152.8	87.6	65.2
#10	0.024	68.77	64.06	4.71

Table 5 Comparison of thermodynamic performance of prototype system and optimization system

Items	700 °C prototype system (case 1)	700 °C optimization system (case 2)
Exergy output (electricity)/MW	1000	1000
Main-steam pressure/MPa	35	35
Main-steam temperature/°C	700	700
Main-steam flow rate (t h^{-1})	2061.5	2234.5
First reheated steam pressure/MPa	10.5	15.72
First reheated steam temperature/°C	720	720
p_1/p_0	0.3	0.45
Second reheated steam pressure/MPa	3.15	3.999
Second reheated steam temperature/°C	720	720
p_2/p_1	0.3	0.25
Rated back pressure/MPa	0.004	0.004
Feedwater temperature/°C	301.07	331.03
Heat consumption rate/(kJ (kW h)$^{-1}$)	7105.42	7061.75
Decrement/(kJ/(kW h)$^{-1}$)	–	43.67
Power generation efficiency/%	50.67	50.98
Increment (%)	–	0.31

more extraction steam is needed to heat the feed water to achieve higher enthalpy.

In summary, the optimized power generation efficiency of the 700 °C ultra-supercritical ten-stage double reheat system is 0.31% higher than that of the prototype system and the corresponding heat consumption rate reduces from 7105.42 to 7061.75 kJ (kW h)$^{-1}$. The heat consumption rate decreases by 43.67 kJ (kW h)$^{-1}$.

Exergy analysis of ten-stage regenerative double reheat plant

The exergy analysis aims to reveal the main components of the parameters optimization that will improve the power generation efficiency. Table 6 illustrates the detailed exergy destruction of the prototype system and the optimized system.

It is clear that the exergy losses of the boiler in the optimized system are lower than those of the prototype system (case 1) by 0.57% point, which is mainly due to the higher temperature of the feed water in the optimized system (case 2). The exergy losses of the condenser in the optimized system are a little higher than those of the prototype system, namely by 0.05%. This is chiefly due to the increased main-steam mass flow rate of the optimized system, which leads to an increase in condenser depletion. In addition, the exergy destruction of the optimized system's regenerative heaters is higher than those of the prototype system by 0.22%, while the reheat steam pressure is increased. The energy utilization level of the optimized system will be weakened to a certain extent, which limits the capacity to further improve power generation

Table 6 Exergy analysis comparison of prototype system and optimization system

Items	700 °C prototype system case 1 (MW/%)		700 °C optimization system case 2 (MW/%)	
Exergy input (coal)	1973.55	100.00	1961.55	100.00
Exergy output (electricity)	1000.00	50.67	1000.00	50.98
Exergy destruction				
Boiler	814.89	41.29	798.67	40.72
Turbines	86.15	4.37	85.09	4.34
Regenerative heaters	25.36	1.28	28.61	1.46
Condenser	27.92	1.41	28.66	1.46
Generator	10.31	0.52	10.31	0.53
Other parts	8.02	0.41	8.91	0.45
Exergy result check				
Exergy output and destruction	1972.65	99.95	1960.25	99.93
Calculation deviation	0.90	0.05	1.30	0.07
Exergy efficiency	50.67		50.98	

efficiency. In general, the exergy efficiency of the ten-stage double reheat optimized system is increased by 0.31%, as shown by the exergy analysis comparison of the prototype system and the optimized system, which is consistent with the thermal efficiency improvements shown in Table 4. As noted above, the ratio of the exergy destruction of the regenerative heaters to the total exergy destruction in the optimized system is 0.26% higher than that of the prototype system, which will have a negative impact on any further improvement in the power generation efficiency.

The above analysis of Tables 4 and 6 reveals that the superheating degree of extraction steam in H2 and H4 heaters in the 700 °C optimized system reached 300 °C. This is because the double reheat makes the main-steam temperature rise markedly, and the temperature of the regenerative extraction steam after reheating also increases significantly. The superheating degree of H3 to H7 heaters is much higher than that of the other heaters, which results in an energy-grade mismatch problem. In other words, the energy is not fully utilized, and additional exergy losses are generated.

A 700 °C regenerative steam turbine thermal system

Reducing the superheating degree of the extraction steam can lead to better thermal performance of the whole cycle. In order to achieve this goal, a 700 °C super-supercritical double reheat regenerative steam turbine thermal system is proposed, as shown in Fig. 4.

A portion of the exhaust steam of the IP turbine is sent to a regenerative steam turbine instead of the reheater, and, as a result, the extraction steam in H2 to H7 originates from the extraction steam and exhaust steam of the regenerative steam turbine instead of being extracted from the IP and LP turbines. In this configuration, the superheating degree of the extraction steam in RH2 to RH7 is significantly reduced because this portion of extraction steam is not reheated. Consequently, the temperature difference between the heat transfer processes is also dramatically declined. Likewise, the quantity of steam entering the first and second reheaters of the boiler drops obviously, and, as a result, the heat absorption of the boiler decreases.

Due to the difference between the regenerative steam turbine thermal system and the conventional system, the optimized reheat pressure will be different. The maximum value of the generation efficiency is obtained by coupling the primary reheat pressure with the double reheat pressure. Using the method presented earlier, and optimizing the parameters of extraction steam, the highest point of the

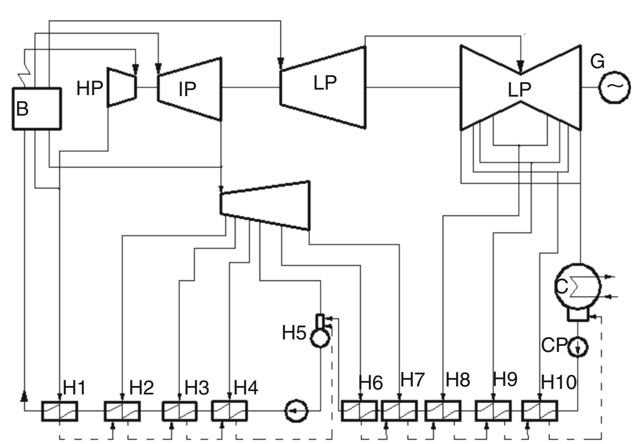

Fig. 4 Thermal system diagram of 700 °C regenerative steam turbine

power generation efficiency can be found. A modified optimized regenerative steam turbine system (where $p_1/p_0 = 0.24$ and $p_1/p_2 = 0.18$) is referred to as "case 3." The thermodynamic performance comparison of optimized system and regenerative steam turbine system is presented in Table 7.

Table 7 shows a comparison between the major thermal parameters of the 700 °C optimized system (case 2) and 700 °C regenerative steam turbine system (case 3). The main-steam flow rate is decreased in the 700 °C regenerative steam turbine system, which is attributed to the energy cascade utilization of the regenerative process as the related extraction steam temperature is reduced, resulting in a decrease in the feedwater temperature. Adopting a regenerative steam turbine system, the 146.75 t h^{-1} exhaust from the HP cylinder enters the regenerative turbine, instead of reheating. Thus, the ratio of the first reheat steam to main-steam is decreased from 0.915 to 0.685 in the regenerative steam turbine system.

In general, the heat consumption rate of the regenerative steam turbine system plant is decreased by 194.66 kJ (kW h)$^{-1}$, from 7061.75 kJ (kW h)$^{-1}$ in the optimized system (case 2) to 6867.09 kJ (kW h)$^{-1}$ in the regenerative steam turbine system (case 3). The power generation efficiency of the regenerative steam turbine system goes up to 52.42%, which is 1.44% higher than that of the optimized system. The regenerative steam turbine system can be used as an effective means to improve the thermal efficiency of the 700 °C ultra-supercritical double reheat cycle.

In order to analyze the efficiency improvement realized by adopting a regenerative steam turbine system, two types of system circulation process lines are drawn. The T–S diagram of the optimized system (case 2) and the

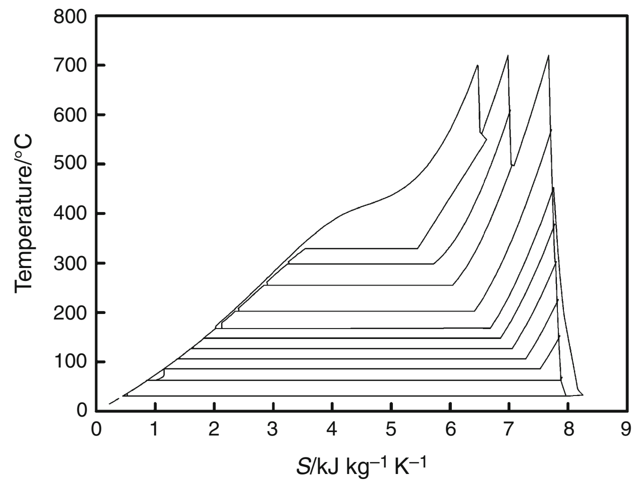

Fig. 5 T–S diagram of the double reheat unit in case 2

Table 7 Comparison of thermodynamic performance of the optimization system and regenerative steam turbine system

Items	700 °C optimization system (case 2)	700 °C regenerative steam turbine system (case 3)
Exergy output (electricity)/MW	1000	1000
Main-steam flow rate/(t h^{-1})	2234.5	2013.8
First reheat steam flow rate/(t h^{-1})	2045.3	1379.0
Second reheat steam flow rate/(t h^{-1})	1716.4	1379.0
Ratio of first reheat steam to main-steam	0.915	0.685
Ratio of second reheat steam to main-steam	0.768	0.685
Main-steam pressure/MPa	35	35
Main-steam temperature/°C	700	700
First reheated steam pressure/MPa	15.72	8.23
First reheated steam temperature/°C	720	720
p_1/p_0	0.45	0.24
Second reheated steam pressure/MPa	3.999	1.48
Second reheated steam temperature/°C	720	720
p_2/p_1	0.25	0.18
Rated back pressure/MPa	0.004	0.004
Feedwater temperature/°C	331.03	301.32
Heat consumption rate/(kJ (kW h)$^{-1}$)	7061.75	6867.09
Decrement/(kJ (kW h)$^{-1}$)	–	194.66
Power generation efficiency/%	50.98	52.42
Increment (%)	–	1.44

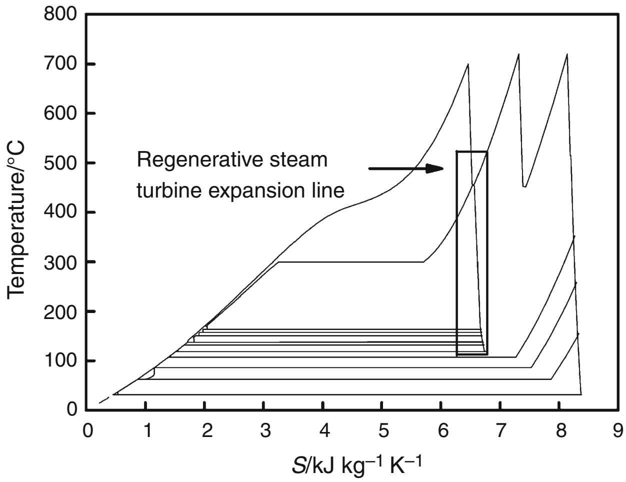

Fig. 6 T–S diagram of the double reheat plant in case 3

regenerative steam turbine system (case 3) are shown in Figs. 5 and 6, respectively.

It can be seen that an additional regenerative steam turbine expansion line is present in Fig. 6. This is because a part of the exhaust gas of the high-pressure cylinder of the regenerative steam turbine thermal system flows directly into the small steam turbine to do work, which results in a decrease in the portion of reheat under the original conditions. In case 2, the main-steam flow is 2013.8 t h^{-1}, while the steam flow into the regenerative steam turbine is about 634.8 t h^{-1}, which causes the steam flow to the reheater to be reduced. This is equivalent to reducing the additional cyclic dynamic coefficient of the conventional reheat cycle. The amount of heat that needs to be absorbed by reheating is reduced, leading to an improvement in power generation efficiency.

In another aspect, the additional power factor of the regenerative steam turbine thermal system decreases more quickly as the reheating pressure decreases, since the first reheat steam pressure of the regenerative steam turbine system is reduced from 15.72 to 8.23 MPa in the optimized system, and the second reheated steam pressure drops from 3.999 to 1.48 MPa.

Thermodynamic performance of 700 °C unit under variable working conditions

In order to meet the needs of modern power supply condition, large-scale ultra-supercritical coal-fired generating units need to undertake peak-shaving tasks. We therefore further analyze the thermodynamic characteristics of cases 3 under different loads. Four typical working conditions (THA (design conditions), 75% THA, 50% THA and 40% THA) were selected for the ultra-supercritical double reheat unit in this study. Table 8 shows the main parameters of the 700 °C double reheat system under these four typical conditions.

Table 8 Main parameters of 700 °C double reheat system under variable working conditions

Items	100%THA	75%THA	50%THA	40%THA
Main-steam flow rate/(t h^{-1})	2234.5	1615.5	1057.6	839.9
Main-steam pressure/MPa	35	26.82	23.83	13.75
Main-steam temperature/°C	700	700	700	700
First reheated steam pressure/MPa	15.72	11.76	7.92	6.31
First reheated steam temperature/°C	720	720	720	720
Second reheated steam pressure/MPa	3.999	3.02	2.06	1.65
Second reheated steam temperature/°C	720	720	720	720
Feedwater temperature/°C	331.03	311.65	285.37	271.04
Exergy output (electricity)/MW	1000	750	500	400

Table 9 Comparison of the heat generation rate between case 2 and case 3 under variable working conditions

Unit load	Double reheat unit (case 2)	The regenerative steam turbine system (case 3)	
		85% the relative internal efficiency	90% the relative internal efficiency
THA	7061.75	6965.9	6957.1
75%THA	7101.0	7057.0	7048.2
50%THA	7346.5	7294.9	7286.1
40%THA	7513.9	7418.8	7410.0

From Table 8, we see that the steam pressure decreases with the decrease in load, while the steam temperature generally levels off. This is caused by the use of sliding-pressure operation in large coal-fired generating units at variable loads. Furthermore, the use of sliding-pressure operation leads to a rapid increase in the superheat of the extraction steam, the problem of extraction steam overheating is more serious than at low load operation. Therefore, it is more meaning to examine the utilization of steam energy cascade in the regenerative system.

To that end, a comparative analysis of the heat recovery rate of the double reheat unit (case 2) and the regenerative steam turbine system (case 3) under different loads was carried out. Table 9 shows the heat generation rates of case 2 and case 3 under variable working conditions shown.

It can be seen that with the decrease in load, the heat generation rates of the 700 °C double reheat system and the 700 °C regenerative steam turbine system gradually increase, and the coal consumption of the regenerative steam turbine system is always lower than that of the double reheat system. When the relative internal efficiency of the regenerative steam turbine rises from 85 to 90%, the heat generation rate of the unit further reduces under different load conditions.

Conclusions

In this study, a comprehensive analysis of parameter optimization and system structure is conducted for a 700 °C ultra-supercritical double reheat cycle to obtain an effective method to improve thermal efficiency.

For the 700 °C ultra-supercritical ten-stage regenerative double reheat unit, when the p_2/p_1 and p_1/p_0 ratios are 0.25 and 0.45, respectively, the power generation efficiency reaches an optimal value which is 0.31% higher than that of the prototype system. To decrease the energy-grade mismatch, a regenerative steam turbine thermal system is presented based on the optimized system. The heat consumption rate of the regenerative steam turbine system unit is declined by 194.66 kJ (kW h)$^{-1}$, from 7061.75 to 6867.09 kJ (kW h)$^{-1}$. The power generation efficiency of the regenerative steam turbine system rises up to 52.42%. In order to study the large-scale ultra-supercritical coal-fired generating units' behavior under peak-shaving tasks, the thermodynamic characteristics were further analyzed under different loads. Under variable working conditions, the heat generation rates of the 700 °C double reheat system and the 700 °C regenerative steam turbine system gradually increase with the decrease in load. Meanwhile, the coal consumption of the regenerative steam turbine system is always lower than that of the double reheat system. When the relative internal efficiency of the regenerative steam turbine increases from 85 to 90%, the heat generation rates of the unit further reduce under different load conditions.

The optimized designs for 700 °C ultra-supercritical double reheat coal-fired power generation provide a new effective approach to improve energy utilization efficiency.

Acknowledgements This work has been supported by the National key research and development program (Project No. 2018YFB0604404), and Science and Technology Development Project of Jilin Province of China (Project No. 20190103008JH).

References

1. BP Energy Outlook 2017 Edition. BP. https://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2017/bp-energy-outlook-2017.pdf. Accessed 25 Jan 2017.
2. BP Energy Outlook 2018 Edition. BP. https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html. Accessed 20 Feb 2018.
3. Kumar R, Jilte R, Ahmadi MH, et al. A simulation model for thermal performance prediction of a coal-fired power plant. Int J Low Carbon Technol. 2019;14:122–34.
4. Kumar R, Jilte R, Nikam KC, et al. Status of carbon capture and storage in India's coal fired power plants: a critical review. Environ Technol Innov. 2018;13:94–103.
5. Li H, Ma L. Analysis on recent development of energy investment in China. Sino Global Energy. 2018;23:3–13.
6. Li Q, Wang C. Analysis on new energy development based on the 13th five-year electric power planning. Electric Power. 2017;50:30–6.
7. Cao Y, Hu B, Liang L, et al. Optimization of a combined reheating/regenerative/internal regenerative organic Rankine cycle based on exergy analysis. Renew Energy Resour. 2015;33:741–6.
8. Nouri M, Namar MM, Jahanian O. Analysis of a developed Brayton cycled CHP system using ORC and CAES based on first and second law of thermodynamics. J Therm Anal Calorim. 2019;135:1743–52.
9. Acar MS, Arslan O. Energy and exergy analysis of sola energy-integrated, geothermal energy-powered Orgranic Rankine Cycle. J Therm Anal Calorim. 2019;137:659–66.
10. Sadeghi S, Maghsoudi P, Shabani B, et al. Performance analysis and multi-objective optimization of an organic Rankine cycle with binary zeotropic working fluid employing modified artificial bee colony algorithm. J Therm Anal Calorim. 2019;136:1645–65.
11. Ziebik A, Gladysz P. Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant integrated with a CO_2 processing unit. Arch Thermodyn. 2013;34:105–22.
12. Crespi F, Gavagnin G, Sanchez D, et al. Supercritical carbon dioxide cycles for power generation, a review. Appl Energy. 2017;195:152–83.
13. Uysal C, Kurt H, Kwak HY. Exergetic and thermo economic analyses of a coal-fired power plant. Int J Therm Sci. 2017;117:106–20.
14. Fan C, Pei D, Wei H. A novel cascade energy utilization to improve efficiency of double reheat cycle. Energy Convers Manag. 2018;171:1388–96.
15. Łukowicz H, Dykas S, Rulik S, et al. Thermodynamic and economic analysis of a 900 MW ultra-supercritical power unit. Arch Thermodyn. 2011;32:231–44.
16. Liu Y, Sui J, Liu H. Research on heating system of serial-parallel coupling absorption heat pump for coal fired power plants. Proc CSEE. 2016;36:6148–55.

17. Zhang X, Chen H. Thermodynamic analysis of heat pump heating supply systems with circulating water heat recovery. Proc CSEE. 2013;33:2–8.
18. Demir H, Mobedi M, Ulku S. A review on adsorption heat pump: problems and solutions. Renew Sustain Energy Rev. 2008;12:2381–403.
19. Feng W. Developing green, highly efficient coal-fired power technologies. New York: Amer Soc Mechanical Engineers; 2015.
20. Feng W. Development of China's supercritical coal fired power generation unit. J Shanghai Univ Electric Power. 2011;27:417–22.
21. Zhou L, Hua M, Wang W, et al. A variable condition calculation method for main steam parameters and the heat rate correction curves. J Chin Soc Power Eng. 2011;31:387–90.
22. Srinivas T, Gupta A, Reddy BV. Sensitivity analysis of STIG based combined cycle with dual pressure HRSG. Int J Therm Sci. 2008;47:1226–34.
23. Espatolero S, Romeo LM, Cortés C. Efficiency improvement strategies for the feedwater heaters network designing in supercritical coal-fired power plants. Appl Therm Eng. 2014;73:449–60.
24. Cai X, Zhang Y, Li Y, et al. Design and exergy analysis on thermodynamic system of a 700°C ultra supercritical coal-fired power generating set. J Chin Soc Power Eng. 2012;32:971–8.
25. Xu C, Xu G, Zhu M, et al. Thermodynamic analysis and economic evaluation of a 1000 MW bituminous coal fired power plant incorporating low-temperature pre-drying (LTPD). Appl Therm Eng. 2016;96:613–22.
26. Bugge J, Kjaer S, Blum R. High-efficiency coal-fired power plants development and perspectives. Energy. 2016;31:1437–45.
27. European AD700 project. https://projectweb.elsam-eng.com/AD700/default.aspx. Accessed 27 Oct 2005.
28. Beer JM. High efficiency electric power generation: the environmental role. Prog Energy Combust Sci. 2007;33:107–34.
29. Weitzel P. Steam generator for advanced ultra-supercritical power plants 700 to 760 °C. In: ASME 2011 power conference. 2011.
30. Yilmaz F. Energy, exergy and economic analyses of a novel hybrid ocean thermal energy conversion system for clean power production. Energy Convers Manag. 2019;196:557–66.
31. Ahmadi MH, Nazari MA, Sadeghzadeh M, et al. Thermodynamic and economic analysis of performance evaluation of all the thermal power plants: a review. Energy Sci Eng. 2019;7:30–65.
32. Ahmadi MH, Sadaghiani MS, Pourfayaz F, et al. Energy and exergy analyses of a solid oxide fuel cell-gas turbine-organic rankine cycle power plant with liquefied natural gas as heat sink. Entropy. 2018;20:1–22.
33. Vakilabadi MA, Bidi M, et al. Exergy analysis of a hybrid solar-fossil fuel power plant. Energy Sci Eng. 2019;7(1):146–61.
34. Naeimi A, Bidi M, Ahmadi MH, et al. Design and exergy analysis of waste heat recovery system and gas engine for power generation in Tehran cement factory. Therm Sci Eng Prog. 2019;9:299–307.
35. Gargari SG, Rahimi M, Ghaebi H. Energy, exergy, economic and environmental analysis and optimization of a novel biogas-based multigeneration system based on gas turbine-modular helium reactor cycle. Energy Convers Manag. 2019;185:816–35.
36. Wang LG, Yang YP, Dong CQ, et al. Parametric optimization of supercritical coal-fired power plants by MINLP and differential evolution. Energy Convers Manag. 2014;85:828–38.
37. Srinivas T, Gupta AVSSKS, Reddy BV. Sensitivity analysis of STIG based combined cycle with dual pressure HRSG. Int J Therm Sci. 2008;47:1226–34.
38. Espatolero S, Romeo LM, Cortés C. Efficiency improvement strategies for the feedwater heaters network designing in supercritical coal-fired power plants. Appl Therm Eng. 2014;73:449–60.
39. Gu Y, Wang S. Thermal economic analysis of a double reheat ultra supercritical pressure unit. J Xi'an Univ Technol. 2013;29:357–61.
40. STEAG Energy Services GmbH, EBSILON Professional 2010.
41. Cifre PG, Brechtel K, Hoch S, et al. Integration of a chemical process model in a power plant modeling tool for the simulation of an amine based CO_2 scrubber. Fuel. 2009;88:2481–8.
42. Bruhn M. Hybrid geothermal-fossil electricity generation from low enthalpy geothermal resources: geothermal feed-water preheating in conventional power plants. Energy. 2002;27:329–46.
43. Xu G, Zhou L, Zhao S, et al. Optimum superheat utilization of extraction steam in double reheat ultra-supercritical power plants. Appl Energy. 2015;160:863–72.
44. Wang L, Yang Y, Dong C, et al. Multi-objective optimization of coal-fired power plants using differential evolution. Appl Energy. 2014;115:254–64.
45. Yan M, Zhang L, Shi Y, et al. A novel boiler cold-end optimization system based on bypass flue in coal-fired power plants: heat recovery from wet flue gas. Energy. 2018;152:84–94.
46. Holland JH. Adaptation in nature and artificial systems: an introductory analysis with applications to biology, control and artificial intelligence. Cambridge: MIT Press; 1992.
47. Wang J, Dai Y, Gao L. Exergy analysis and parametric optimizations for different cogeneration power plants in cement industry. Appl Energy. 2009;86:941–8.
48. Suresh MVJJ, Reddy KS. Thermodynamic optimization of advanced steam power plants retrofitted for oxy-coal combustion. J Eng Gas Turb Power. 2011;133:1–12.
49. Zhou L, Xu G, Zhao S, et al. Parametric analysis and process optimization of steam cycle in double reheat ultra-supercritical power plants. Appl Therm Eng. 2016;99:652–60.