ADVANTAGES OF THERMAL INDUSTRY CLUSTER AND APPLICATION OF PARTICLE SWARM OPTIMIZATION MODEL

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This paper first analyzes that the waste heat before the flue gas of thermal power company enters the desulfurization tower can be heated by the low-pressure economizer, and then the heated condensate can be incorporated into the regenerative system, so as to recover the waste heat and improve the unit efficiency. In this paper, the possible layout scheme of the low pressure economizer in the thermal system is constructed firstly, and then the mathematical model of the equivalent enthalpy drop increment of the unit is established with the water partition coefficient as the independent variable. Particle swarm optimization and coordinate rotation are used to optimize the model, and the results show that particle swarm optimization is more effective in solving the problem. After the low-pressure economizer is added to the unit, the heat consumption of the whole plant of the unit is reduced by 61.131, the unit efficiency is increased by 0.783%, and the coal consumption of the whole plant is reduced by 2.293. Finally, from the perspective of industrial agglomeration, industrial diversification and economic resilience, this paper analyzes the advantages of diversified agglomeration of thermal power companies.

Key words*: flue gas waste heat; low pressure economizer; particle swarm optimization algorithm; industrial agglomeration; industrial diversification; economic resilience*

0 Introduction

In the wet flue gas desulfurization process of boiler of thermal power company, the flue gas of boiler needs to be reduced to about 50 ℃ before entering the desulfurization tower, otherwise the desulfurization efficiency will be reduced. After desulfurization, the flue gas needs to be heated above 80 ℃ to be discharged. In order to save energy, GGH is generally used in power plants to heat the net flue gas with the original flue gas heat, so that the net flue gas can reach the emission standard. If the flue gas temperature in front of the absorption tower is 125 ℃, the heat in the range of 80-125 ℃ in the power plant is not fully utilized. At present, the better way to use the residual heat of flue gas in power plant is to add low-pressure economizer in the thermal system. Literature [1] discusses the theory and research method of energy saving of low-pressure economizer. Firstly, this paper discusses the theory and research method of energy saving of low-pressure economizer in thermal power company. Secondly, from the perspective of industrial agglomeration, industrial diversification and urban economic resilience, this paper analyzes the advantages of diversified agglomeration of thermal companies, and divides industrial diversification into industrial related diversification and industrial unrelated diversification, and uses regression analysis to analyze the impact of these two classifications on urban economic resilience.

1. Application of particle swarm optimization model in coal saving of thermal engineering

1.1 Layout plan of low pressure economizer of thermal power company

The basic idea of adding low-pressure economizer in thermal power company is to draw part of condensate from the inlet of low-pressure heater and enter the low-pressure economizer. The condensate absorbs the exhaust heat in the low-pressure economizer and reduces the exhaust temperature. The condensate is heated and heated before returning to the regenerative system. If the output power of the unit is constant, the coal consumption and heat consumption of the unit will be reduced. According to the characteristics of energy utilization of the low-pressure economizer.

1.2 Establishment of calculation model of low pressure economizer in thermal power company

For the thermal system integrated with the low-pressure economizer and the unit, when the fuel saving operation mode is adopted, the total generating capacity is the same as the original coal-fired unit, and the condensate absorbs the heat provided by the low-pressure economizer. The heat transfer between flue gas and condensate is mainly convection.

1.2.1 Mathematical model of inlet parameters of low pressure economizer in thermal power plant

The condensation water and flue gas conduct convection heat exchange in the low-pressure economizer, the inlet temperature of flue gas is generally known, and the inlet temperature of the condensation water can be determined by the water separation coefficient and the enthalpy value of each pumping point. The mathematical model of the inlet enthalpy value of the low-pressure economizer is as follows:

$$\bar{t}_{w,in} = \frac{\bar{t}_8\beta_3 + \bar{t}_7\beta_2 + \bar{t}_6\beta_1}{\beta_1 + \beta_2 + \beta_3} \tag{1}$$

In the formula (1) I is the enthalpy value of the inlet water of heater .

1.2.2 The mathematical model of the parameters of low pressure economizer

When the structure of the low-pressure economizer is determined, the enthalpy value of the outlet flue gas and the enthalpy value of the outlet water meet the following energy balance formula [3,7,8]:

$$
\begin{aligned}
&B(I_{g,in}-I_{g,ex})= \\
&D_0(\beta_1+\beta_2+\beta_3)(\bar{t}_{w,ex}-\bar{t}_{w,in})
\end{aligned}
\qquad (2)
$$

$$B(I_{g,in}-I_{g,ex})=KA\Delta t_m \qquad (3)$$

Where k is the heat transfer coefficient, $W/(m^2\cdot K)$, A is the heat exchange area, m^2,B is coal consumption,t/h,Δt_m is the average temperature difference of heat exchange,D_0 is the flow of feed water,t/h The parameters of the outlet can be obtained by solving the above equilibrium equation.

1.2.3 Calculation model of flue gas enthalpy

From the above analysis, we can see that the enthalpy of water and flue gas is used in the solution process, the enthalpy of water can be obtained through the water vapor table, and the enthalpy of flue gas can be obtained through the following formula [3,7,8]:

$$I_g=I_g^0+(1-\alpha)I_a^0 \qquad (4)$$

In the formula(3), I_g is the flue gas enthalpy at the inlet and outlet of the low-pressure economizer, kJ/kg; a is the excess air coefficient, generally 1.2; I is the theoretical flue gas enthalpy, kJ / kg;I_a^0 is the theoretical air enthalpy; kJ / kg;

$$
\begin{aligned}
I_g^0 &= V_{CO_2}^0(c\vartheta)_{CO_2}+V_{SO_2}^0(c\vartheta)_{SO_2} \\
&+V_{N_2}^0(c\vartheta)_{N_2}+V_{H_2O}^0(c\vartheta)_{H_2O}
\end{aligned}
\qquad (5)
$$

$$I_a^0=V^0(c\vartheta)_{air} \qquad (6)$$

In formula (5)-(6), $V_{CO_2}^0$.$V_{SO_2}^0$.$V_{N_2}^0$. $V_{H_2O}^0$.V^0 is the theoretical amount of carbon dioxide, sulfur dioxide, nitrogen, water vapor and air in the flue gas,In the formula, m^3/kg.$(c\vartheta)_{CO_2}$.$(c\vartheta)_{SO_2}$.$(c\vartheta)_{N_2}$.$(c\vartheta)_{H_2O}$.$(c\vartheta)_{air}$ is the enthalpy of carbon dioxide, sulfur dioxide, nitrogen, water vapor and air in the flue gas,kJ/m^3 .

1.2.4 Calculation of heat transfer temperature difference

The heat exchange between flue gas and condensate is countercurrent heat exchange. In the case of no heat loss, when the outlet temperature of flue gas is determined, the heat release of flue gas is equal to the heat absorption of condensate. At this time, the outlet temperature of condensate can be calculated according to energy balance and formula (1). Calculate the outlet temperature of condensate. The heat transfer temperature difference of counter flow heat transfer is shown in formula (7), (8) and (9) [3,7,8]:

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln \frac{\Delta t_1}{\Delta t_2}} \quad (7)$$

$$\Delta t_1 = t_{g,in} - t_{w,ex} \quad (8)$$

$$\Delta t_2 = t_{g,ex} - t_{w,in} \quad (9)$$

1.3 Establishment of optimization model for layout of low pressure economizer in thermal power plant

1.3.1 Establishment of objective function

According to the equivalent enthalpy drop method, the extraction efficiency of each heater can be obtained. For the heaters involved in this paper, the air extraction efficiency can be calculated by the following formula [1]:

$$\eta_i = \frac{H_i}{q_i} \quad (10)$$

$$H_i = (h_i - h_c) - \sum_{j=i+1}^{z} \frac{A_j}{q_j} H_j \quad (11)$$

In the formula, η_i is the extraction efficiency of heaters at all levels; H_i is the equivalent enthalpy drop of heaters at all levels, kJ/kg; h_c is the enthalpy of extraction at all levels, kJ / kg; HC is the exhaust enthalpy, kJ/kg; q_j is the extraction enthalpy drop of heaters at all levels, kJ/kg; Z = 8 is the total extraction stages.

If class i is a collection heater, the feed water enthalpy rise is used in the A_j. If level i is drain type, then from level I and below to (including) the collection heater, the drain enthalpy drop γ_i is used instead, and the heat exchanger below the collection heater is used instead of τ_i; for the heat exchanger before reheating, the reheat heat absorption σ is added, as follows:

$$H_i = (h_i - h_c + \sigma) - \sum_{j=i+1}^{z} \frac{A_j}{q_j} H_j \quad (12)$$

In this paper, the equivalent enthalpy drop increment of the unit is taken as the objective function. the equivalent enthalpy drop increment of the unit can be obtained as follows:

$$
\begin{aligned}
\Delta H &= \beta_3\tau_8\eta_8 + \beta_6(\bar{t}_{w,ex} - \bar{t}_7)\eta_7 \\
&+(\beta_2 + \beta_3 - \beta_6)\tau_7\eta_7 + \\
&(\beta_1 + \beta_2 + \beta_3 - \beta_6 - \beta_5)\tau_6\eta_6 + \\
&\beta_5(\bar{t}_{w,ex} - \bar{t}_6)\eta_6 + \beta_4(\bar{t}_{w,ex} - \bar{t}_5)\eta_5
\end{aligned} \tag{13}
$$

$$
\beta_1 + \beta_2 + \beta_3 = \beta_4 + \beta_5 + \beta_6 \tag{14}
$$

In the formula, τ_i is the feed water enthalpy rise of heaters at all levels, kJ / kg. Since equation (14) is established, the increment of equivalent enthalpy drop is actually a function of five independent variables, that is to say, there are only five decision variables：

$$
\Delta H = f(\beta_1, \beta_2, \beta_3, \beta_4, \beta_5) \tag{15}
$$

1.3.2 Establishment of constraints

The flow restrictions are as follows:

$$
0 \le \beta_i \le D/D_0, 1 \le i \le 6 \tag{16}
$$

$$
0 \le \beta_1 + \beta_2 + \beta_3 \le D/D_0 \tag{17}
$$

D in the formula is the condensed water volume. Water temperature limit at the outlet of low pressure economizer [1,6]. Since the inlet flue gas temperature is 125 ℃, which is lower than the saturation temperature of water under local pressure, the outlet water must not be saturated, so this limit condition is automatically met. Considering the actual situation of the power plant, it is assumed that the temperature of flue gas outlet is not lower than 85 ℃:

$$
t_{g,ex} \ge 85 \tag{18}
$$

Hence, the whole optimization model is:

$$
\begin{aligned}
&\text{Max } \Delta H = f(\beta_1, \beta_2, \beta_3, \beta_4, \beta_5) \\
&\text{s.t } \begin{cases} 0 \le \beta_i \le D/D_0, 1 \le i \le 6 \\ 0 \le \beta_1 + \beta_2 + \beta_3 \le D/D_0 \\ t_{g,ex} \ge 85 \end{cases}
\end{aligned} \tag{19}
$$

1.3.3 Unit economy analysis

After the optimization of the low-pressure economizer, the thermal economy of the system can be analyzed by the principle of equivalent enthalpy drop, and the absorbed exhaust heat can be introduced into the system as the external pure heat. The equivalent enthalpy drop of the new steam is [3,9]:

$$H = h_0 - h_c + \sigma - \sum_{i=1}^{z} \tau_i \eta_i \qquad (20)$$

In the formula(20), h_0 is the enthalpy of new steam, kJ/kg ; h_c is the exhaust enthalpy, kJ/kg ; σ is the reheat heat absorption, kJ / kg. The relative improvement rate of unit efficiency is shown in formula(21) :

$$\Delta \eta_i = \frac{\Delta H}{H + \Delta H} \qquad (21)$$

ΔH is the equivalent enthalpy drop increment of the unit's new steam calculated above. The relative reduction of heat rate of the whole plant of the unit is shown in formula(22):

$$\Delta q_{cp} = \Delta \eta_i q_{cp} \qquad (22)$$

Δq_{cp} is the heat rate reduction of the whole plant of the unit; $kJ/(kW \cdot h)$ is the heat rate of the whole plant of the unit, $kJ/(kW \cdot h)$. The coal consumption reduction of the whole plant of the unit is as follows:

$$\Delta b_{cp} = \frac{\Delta q_{cp}}{29270} \qquad (23)$$

Δb_{cp} is the coal consumption reduction of the whole plant of the unit, $g/(kW \cdot h)$.

1.3.4 Analysis of boiler model

As the coal and ash are unconventional components, the value can not be obtained by the above methods. Since the energy of slag discharge and exhaust gas is almost impossible to be reused, in order to simplify the analysis, the Ո values of slag discharge and smoke exhaust are set to be 0, and the Ո value of coal is estimated by the following formula[24]：

$$\begin{aligned} Ex = {} & 363.439w(C) + 1075.633w(H) \\ & - 86.308w(O) + 4.147w(N) \\ & + 190.798w(S) - 21.1w(A) \end{aligned} \qquad (24)$$

According to the above settings, the simulation model of boiler combustion and heat transfer process is established by Aspen Plus, and the simulation results are shown in Table 1。

Table 1. The exergy of each flow in the system

number	Stream name	mass flow/Critical value/

		t·h^{-1}	GJ·h^{-1}
1	coal	213.63	4287.62
2	Decomposition products	213.63	6260.83
4	Inlet cold air	2132.67	7.85
5	Hot air	2132.67	173.33
6	Flue gas coal slag mixture	2346.31	3162.47
7	Deslagging	16.66	0.00
8	High temperature flue gas	2329.64	3162.47
9	Flue gas at air preheater inlet	2329.64	412.33
10	Smoke extraction	2329.64	0
11	Boiler feed water	1700.50	567.58
12	Main steam	1700.50	2184.73
13	Reheat steam cold section	1399.71	1288.78
14	Hot section of reheat steam	1399.71	1662.74

From the above simulation results, it can be seen that the simulation results of coal consumption and smoke exhaust rate of the boiler are 213.63t/h and 2329.64t/h respectively. In the actual operation, the coal consumption of the boiler is 220t / h, and the smoke exhaust volume is 2400t / h. The error between the simulation results and the actual value is less than 3%. Based on the above simulation results, the exergy loss, exergy loss rate and exergy efficiency of the main parts of the system are analyzed according to the "fuel product" model in thermoeconomics. The results are shown in Table 2.

Table 2 The exergy analysis result of each subsystem in the boiler system

Number	Subsystem	Fuel/ $kJ\cdot h^{-1}$	product/ $kJ\cdot h^{-1}$	Damage/ $kJ\cdot h^{-1}$	Efficiency	Loss rate
1.2.3	combustion system	4460.95	3162.47	1298.48	0.709	0.302
4	Main heat exchange surface of boiler	2750.14	1991.11	759.03	0.724	0.177
5	Air preheater	232.64	165.48	67.16	0.711	0.016
	Smoke exhaust process	179.69	0.00	179.69	0.000	0.042
	whole	4295.47	1991.11	2304.36	0.464	0.536

From the calculation results in the above table, it can be seen that the largest part of the boiler model is coal decomposition and combustion process, and the loss rate is 30.2%. The exergy loss in the combustion process can account for 20% - 30% of the total exergy value in the input system. The second is the heat transfer process between flue gas and main heat exchange surface, and the loss rate is 17.7%. In addition, through the analysis of the boiler as a whole, the overall efficiency of the boiler is 46.4%.

2. Advantage analysis of thermal industry cluster

Economic resilience mainly refers to the system resilience of a city after encountering external shocks. The study of economic resilience will lay a good theoretical foundation for the industrial transformation and upgrading of the thermal industry in the future. The impact of industrial diversification brought by industrial agglomeration on urban economic resilience is still controversial.

So what is the impact of industry-related diversification and industry independent diversification on urban economic resilience? How can we improve the development level of economic resilience of thermal industry? This is the topic of this paper.

2.1 Theoretical mechanism

2.1.1 Measurement method

2.1.1.1 Measurement method of economic toughness

At present, the academic community has not given a unified standard to measure the urban economic resilience. Most literatures use one or several core variables to measure urban economic resilience. These include employment or unemployment. In the process of measurement, we need to select a benchmark state to measure the local impact degree and recovery degree by measuring the gap value after impact. Xu Yuan (2019) uses the static van den's law to build the regression model between economic growth and employment, and uses gmm-sl-sar-re method to estimate. This method can overcome the lag between space and time, get the difference between the real economic conditions and the results without external impact, and measure the resilience level of urban economy. This method not only overcomes the mutual influence between spaces, but also overcomes the endogenous problem between index variables. At the same time, from the perspective of regional economics, the paper also analyzes the reasons for the heterogeneity of economic resilience in different regions, which paves the way for the following article to analyze urban economic resilience from the perspective of industrial diversification. Referring to the idea of van den's law, the regression equation of resilience economy is obtained as follows:

$$\ln y_t = a + \rho_1 W_N \ln y_{t-1} + \gamma \ln y_{t-1} + \beta \ln x_t + \xi_t \quad (25)$$

In formula (25), Y_T represents the level of urban economic resilience in period T, wnlnyt-1 represents the lag term in space, XT represents the urban economic resilience in year t, lnyt-1 represents the lag variable in time, ζ represents the residual term. Because the growth of output is conducive to the stable development of social economy, we expect that the impact of GDP growth rate on urban economic resilience is positive. With reference to Martin (2016), the resilience of urban economic resilience level in resistance period and recovery period is shown in formula (26) and formula (27), respectively:

$$\mathrm{Re}sis_i = \frac{\Delta y_i^c - \Delta \hat{y}_i^c}{\left|\Delta \hat{y}_i^C\right|} \quad (26)$$

$$Recov_i = \frac{\Delta y_i^r - \Delta \hat{y}_i^c}{\left|\Delta \hat{y}_i^c\right|} \quad (27)$$

In equation (26), Δy_i^c mainly refers to the change of GDP growth rate of city i during the resistance period. Δy_i mainly refers to the change of GDP growth rate in 2008. The resilience of urban economy reflects the resilience of the city in the face of external shocks. From the perspective of measuring industry related diversification and industry independent diversification in this paper, the difference between the real GDP growth rate of each year and the GDP growth rate of 2008 can be used as an indicator to measure the city's economic resilience, which, to a certain extent, can reflect the healthy degree of a city's economic development and the perfection of its social structure. The greater the difference, the higher the economic resilience level of the city.

2.1.1.2 Measurement of industrial diversification

Refer to Duranton (2000) to calculate the industrial diversification index (VaR), as shown in formula (30):

$$Var = \sum_{i=1}^{n} p_i \ln(1/p_i) (28)$$

In the formula, VaR is the entropy index, which also reflects the level of diversification. Its value range is between 0 and 1. The larger the value, the higher the industrial diversification index and the smaller the value, the lower the level of industrial diversification and the higher the level of industrial specialization. N represents the number of industries in the economic system, and PI represents the proportion of employees in a certain industry in a city.

2.1.1.3 Measurement of industrial related diversification

Industrial related diversification mainly refers to the distribution of industries with high degree of economic and technological correlation in a certain region or around. In order to further measure the urban industry related diversification index and industry independent diversification index, we assume that small industry I belongs to large industry SK, where k = 1,2,3,4..., K. The large sector of the city accounts for PK of the total proportion, and the small sector of the city accounts for Pi of the total industrial proportion. The results are as follows:

$$P_{\mathrm{k}} = \sum_{i \in S_K} p_i \ (29)$$

Then, the industry-related diversification index (RV) can represent the entropy index of small sectors under all major sectors, and HK can represent the entropy index of each small sector within major sectors.

$$\mathrm{RV} = \sum_{\mathrm{k}=1}^{k} P_K H_K \ (30)$$

$$\mathrm{H}_K = \sum_{\mathrm{i} \in SK} (P_i / P_{\mathrm{k}}) \ln(P_K / P\mathrm{i}) \ (31)$$

2.2 Data sources and empirical calculation

2.2.1 Data sources

The data of this paper comes from China's urban statistical yearbook 2003-2018. The indicators measured include the actual GDP of the city, the employed population, the fixed investment, the direct investment in trauma, the number of scientific and technological activities personnel, the number of scientific research institutions, the education funds, the number of patent authorizations, etc. the research scope is 264 prefecture level cities in China.

2.2.2 Regression model analysis of influencing factors

In order to explain the relationship between industrial agglomeration, industrial related diversification, industrial unrelated diversification and urban economic resilience, this paper adds scientific research and innovation level, the proportion of FDI in GDP, GDP level and the proportion of fixed asset investment in GDP as other control variables to analyze the influencing factors. The proportion of FDI in GDP represents the degree of opening to the outside world. The higher the proportion, the more vulnerable the city is to external shocks. Innovation represents the scientific research and innovation of the city. The better the level of scientific research and innovation, the stronger the level of improving the production capacity of the city. The proportion of fixed asset investment in GDP reflects the robustness of the economic development of a city.

$$RES_{it} = \beta_0 + \beta_1 PD_{it} + \beta_2 VAR_{it} + \beta_3 RV_{it} + \beta_4 UV_{it} + r\chi_{it} + \varepsilon_{it} \quad (32)$$

In formula (32), I represents a city i, t represents a year, β represents a symbol, χ represents other control variables, and ε represents a residual term.

2.2.3 Analysis of the impact of industry related diversification and unrelated diversification on urban economic resilience

As shown in the correlation coefficient analysis in Table 3, we conclude that Vif (expansion coefficient of variance) is less than 5, which indicates that all regression models do not have multicollinearity, so OLS method can be used to estimate their parameters. The fixed effect model and the random effect model are selected by Hausman test. When the p value is less than 0.05, we choose the fixed effect model, otherwise we choose the random effect model (as shown in Table 3).

Table 3 Regression analysis results of panel data of 264 prefecture level cities in China (2003-2018)

Variable	Model（1）	Model（2）	Model（3）	Model（4）	Model（5）
PD	0.00093*** （0.000）	0.000973*** （0.000）	0.000973*** （0.000）	0.0013*** （0.000）	0.0025*** （0.000）
PD_Sq	/	/	/	/	-5.16*** （0.0005）
VAR	/	5.75* （0.0706）	0.00051 （0.3984）	9.73 （0.9216）	-0.0086*** （0.0003）
VAR_sq	/	/	/	/	-1.20*** （0.0002）
RV	/	/	5.21*** （0.0002）	5.25*** （0.0002）	1.2*** （0.0001）
RV_sq	/	/	/	/	4.92** （0.0241）
UV	/	/	/	2.972 （0.5987）	-0.00018 （0.2401）
UV_sq	/	/	/	/	-6.50*** （0.0045）

INNOV	0.0159***	0.015905***	0.0162**	0.0016***	0.017***
	(0.0027)	(0.0028)	(0.0038)	(0.0039)	(0.0019)
OPEN	0.309***	0.3081***	0.317***	0.3167***	0.30807***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDP	4.73***	4.69***	4.58***	4.56***	4.27***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
FAI	-0.0051*	-0.0052*	-0.0059**	-0.0059**	-0.00559**
	(0.056)	(0.054)	(0.0393)	(0.0388)	(0.0502)
Constant	-2.886***	-2.89***	-3.08***	-2.96***	-1.5019**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.0229)
R^2	0.60	0.62	0.62	0.61	0.66
Observation	4224	4224	4224	4224	4224
Expansion factor	1	1.04	1.13	1.23	1.21

The results show that there is a positive U-shaped relationship between population density and urban economic resilience, which shows that when the population size of a city is in a certain range, the crowding effect and the high cost of living in a city are greater than the information spillover effect and technology spillover effect, and the population density of a city has a restraining effect on urban economic resilience. When the critical point is exceeded, the urban economic resilience will increase with the increase of urban population density. The relationship between industrial diversification and industrial unrelated diversification and urban economic resilience is not a simple linear relationship, but an inverted U-shaped relationship. That is to say, in the short term, the impact of industrial diversification and industrial unrelated diversification on urban economic resilience is positive, but in the long term, it is not conducive to the development of urban economic resilience. The industry-related diversification shows a positive U-shape, which shows that from a short-term perspective, the industry-related diversification index plays a restraining role in the city's economic resilience, but from a long-term perspective, the industry-related diversification promotes the exchange and learning between industries, helps the structural optimization and innovation between related industries, and promotes the city's economic resilience.

3. Conclusion

(1) Based on the equivalent enthalpy drop method, an optimization model of low-pressure economizer arrangement in power plant is constructed, and the particle swarm optimization algorithm is used for optimization. This optimization method is not only suitable for low pressure economizer, but also can be applied to other heat exchanger.

(2) The applicability of particle swarm optimization (PSO) and coordinate rotation method in this problem is compared. PSO can get the optimal solution accurately and has obvious advantages.

(3) The optimal arrangement of the low-pressure economizer of the unit is to divert water from the inlets of No.8 heater and No.7 heater to the low-pressure economizer for heating, and finally return water to the inlets of No.6 heater. After the low-pressure economizer is added to the unit, the heat consumption of the whole plant of the unit is reduced by 61.131, the unit efficiency is increased by 0.783%, and the coal consumption of the whole plant is reduced by 2.293.

(4) The agglomeration of thermal industry has a significant role in promoting the economic resilience of thermal industry. The level of urban economic resilience in China varies with time and space, so the agglomeration of thermal industry will promote industrial innovation effectively.

(5) There is a positive U-shaped relationship between related diversification of thermal industry and urban economic resilience, that is, it is not conducive to the development of urban economic resilience in the short term. However, from a long-term perspective, industry-related diversification is conducive to technology spillover and information exchange between industries, and to the improvement of economic resilience. Industry-independent diversification presents an inverted U-shaped relationship to urban economic resilience, that is, in the short term In the long run, it does not help to improve the urban economic resilience.

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