

Multi-objective optimization of adjustable orifice valve insulation lining based on thermal-solid coupling and improved whale algorithm

Shuxun Li

Lanzhou University of Technology

Jian Zhang

13803076123@163.com

Lanzhou University of Technology

Xinhao Liu

Yu Zhao

Lanzhou University of Technology

Jianlong Zhu

Lanzhou University of Technology

Article

Keywords: Thermal insulation lining, Thermal-solid coupling, Multi-objective optimization, Whale optimization algorithm, High temperature valve, Proxy model

Posted Date: August 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10508072/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Multi-objective optimization of adjustable orifice valve insulation lining based on thermal-solid coupling and improved whale algorithm

Shuxun Li^{1,2}, Jian Zhang^{1,2,*}, Xinhao Liu^{1,2}, Yu Zhao^{1,2} and Jianlong Zhu^{1,2}

¹ School of Petrochemical Technology, Lanzhou University of Technology, Lanzhou City, 730050, China;

² Correspondence Author: Jian Zhang. Email: 13803076123@163.com.

Abstract

Aiming at the problem that it is difficult to balance the thermal insulation performance and structural reliability of the adjustable orifice valve insulation lining in high temperature environment, the finite element analysis method is used to analyze the distribution characteristics of the two temperature fields and stress fields of the adjustable orifice valve lining structure with / without anchoring parts under high temperature conditions. The parametric modeling of the adjustable orifice valve insulation lining structure is carried out. Combined with the surrogate model and the improved L-TIWOA optimization BP neural network algorithm, the multi-objective optimization design of key parameters such as lining thickness and anchoring layout is carried out, and the optimal combination parameters are obtained. The results show that the optimal combination parameters obtained by optimization are anchorage spacing of 196.5 mm, diameter of 9.6 mm, lining thickness of 119.1 mm and coating thickness of 3.0 mm. The optimized insulation lining structure reduces the maximum equivalent stress of the lining by about 36.3 %. The above research provides a theoretical basis for the lightweight and long life design of high temperature valve insulation structure.

Keywords: Thermal insulation lining ; Thermal-solid coupling ; Multi-objective optimization ; Whale optimization algorithm ; High temperature valve ; Proxy model

1. Introduction

In the energy recovery system of modern refining and chemical industry, the adjustable orifice valve is the core regulating equipment, and its internal flow channel needs to withstand high temperature flue gas erosion above 770 °C [1,2]. In order to protect the metal valve body, the composite lining structure of refractory castable and metal anchorage is usually used [3]. However, this structural design faces severe challenges : the thermal expansion coefficient of refractory materials and metals is quite different, and the high thermal conductivity of metal anchors will destroy the continuous thermal insulation layer of the lining, forming local hot spots, resulting in

thermal stress cracks[4].

In recent years, domestic and foreign scholars have carried out a lot of work in the development of thermal insulation refractory materials for high temperature equipment, stress analysis and numerical simulation optimization of lining structure, but few special studies have been carried out on the structure and material of thermal insulation lining of regulating valves in catalytic cracking unit. In the research of thermal insulation lining structure and materials, the thermal conductivity and thermal shock resistance of new high-temperature thermal insulation materials such as lightweight mullite, alumina hollow spheres, silica aerogels have been continuously improved, which provides more choices for lining design. Pan Yuelei et al. [3] systematically summarized the application progress and technical challenges of silica aerogel thermal insulation materials in industrial pipelines and other fields. Song Qingjun et al. [5] established a simulation model of thermal insulation performance of plasma sprayed coatings and analyzed the influence of adhesive layer materials and porosity, which laid a foundation for the design of thermal insulation coatings. At the same time, the stress analysis of lining has gradually shifted from single thermal stress analysis to thermal-solid coupling analysis. The new refractory fiber module anchorage structure proposed by Tang Jiulin [4] has significantly prolonged the service life of the lining in the transformation of high-temperature heating furnace, which proves the key role of the anchorage system in the reliability of the lining. Qian Jixiang et al [6] analyzed the failure causes and proposed repair measures from the aspects of structure, material and construction for the lining damage of catalytic cracking unit. Su Weiguang et al [7] also pointed out that accurate analysis of the temperature and stress distribution of the refractory lining is the premise to avoid stress concentration and optimize the lining structure. Foreign scholars Sun et al. [8] and Samadi et al. [9] established the meso-mechanical model and high temperature failure constitutive model of refractory materials. JA Santos et al. [10] verified the energy saving effect of the optimized refractory lining configuration through the finite element model of ladle thermal cycle. In the aspect of simulation analysis and optimization method research, thermal-solid coupling finite element technology has become the mainstream method to reveal the distribution law of temperature field and stress field of high temperature equipment. Kang et al. [11] and Liu et al. [12] used different models to carry out thermal-mechanical coupling analysis of high temperature tunnel. Gasser et al. [13] verified the accuracy of thermal-mechanical coupling modeling of high temperature masonry through laboratory test bench. Lee et al. [14] 's thermal-structural coupling analysis of gas turbine compressor bleed valve also proved the applicability of this method in high temperature valve research. At the same time, the multi-objective optimization method based on the surrogate model has attracted more and more attention because it can significantly

reduce the computational cost. Zhang et al.[15] and Liu[16] used Kriging surrogate model combined with genetic algorithm to realize the strength optimization and lightweight design of gate valve body. Zong et al. [17] systematically studied the optimization method of valve design based on surrogate model. Liu [18], Chen [19] and Qingtong et al. [20] also combined multi-objective genetic algorithm with surrogate model and simulation tool respectively. It provides a reference for multi-objective optimization of complex engineering problems. However, there are still obvious deficiencies in the existing research : there is a lack of research on the lining structure of special regulating valves such as catalytic cracking adjustable orifice valves, and there is a lack of quantitative analysis based on the mechanism of anchorage-lining interaction. Most optimization studies aim at a single performance index, and the comprehensive consideration of thermal insulation performance, structural strength and economy is not sufficient. The application effect of surrogate model accuracy and optimization algorithm convergence performance in complex engineering problems still needs to be verified, and multi-objective collaborative optimization research for high temperature valve insulation lining is still relatively rare. In view of the above shortcomings, this paper takes the thermal insulation lining of the catalytic cracking adjustable orifice valve as the research object, and uses the thermal-solid coupling numerical simulation method to reveal the synergistic mechanism of the thermal insulation coating, the Ω -type anchorage and the lining. A high-precision surrogate model based on L-TIWOA improved whale algorithm to optimize BP neural network is proposed to carry out multi-objective collaborative optimization of thermal insulation performance, structural strength and economy, which provides a theoretical basis for the engineering design of high-performance thermal insulation lining of high-temperature valves.

2. Structural Design and Thermo-solid Coupling Analysis

2.1. Structural design

The research object is the typical thermal insulation lining structure inside the adjustable orifice valve. The structure consists of an outer metal valve body (SA-516), an intermediate thermal insulation lining (CO_2 material), an internal Ω -type metal anchor and a new thermal insulation coating on the innermost layer. In the design and application of large high temperature valves, the thermal insulation lining structure with anchors is the key engineering technology to achieve efficient thermal insulation and long-term structural integrity of the system. The structure forms a stable mechanical connection network by welding Ω -shaped anchors with array distribution on the inner wall of the valve body, so as to enhance the bonding strength and integrity between the heat-insulating refractory lining and the metal valve body matrix, and effectively resist the interface thermal stress caused by the difference of thermal expansion

coefficient in the long-term high-temperature service environment, the continuous erosion of high-speed medium fluid and the failure risk of lining cracking, peeling and even overall shedding caused by thermal cycle fatigue and other factors. The spatial arrangement, geometric parameters and density of the anchoring parts are reasonably designed, which can realize the rational distribution of temperature gradient inside the lining and at the interface, promote the minimum of thermal stress and the uniform and smooth transition of temperature field, so as to ensure that the thermal insulation lining can not only maintain its own micro and macro scale structural integrity under extreme high temperature, high pressure and complex thermal shock conditions, but also continue to play a stable and reliable thermal insulation performance. This designed lining system essentially constructs a continuous and strong thermal barrier inside the high-temperature valve, which significantly reduces the heat flux and wall temperature transmitted to the pressure-bearing metal shell of the valve, so that it can work safely within the allowable temperature range of the material, and fundamentally avoids a series of faults such as material creep, strength reduction and sealing failure caused by the high temperature of the shell. Therefore, the thermal insulation lining with optimized anchoring system is not only the core component of the thermal protection design of high temperature valves, but also the key technical measure to ensure the long period, high reliability and safe operation of the whole valve system under harsh process conditions. The overall structural layout of the thermal insulation lining is shown in Figure 1, which is shown in Figure 2 of the three-dimensional model of the Ω -type anchorage.

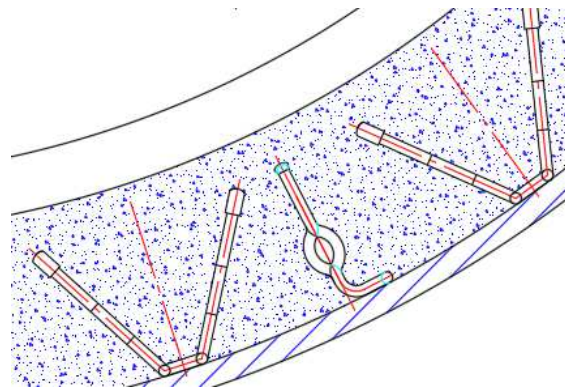


Figure 1. Overall structure layout diagram of thermal insulation lining

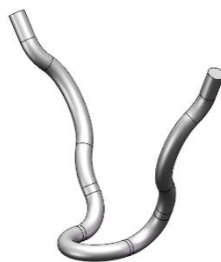


Figure 2. Ω type anchorage three-dimensional model diagram

2.2 Heat transfer mechanism of thermal insulation lining

In the metal-nonmetal composite structure composed of valve body and lining, the heat carried by high temperature flue gas is transferred to the external atmosphere through the heat insulation lining and the valve body wall in turn. Based on the heat balance relationship, the heat obtained by the thermal insulation lining from the high temperature flue gas is shown in equation 1.

$Q_1 = Q_2$	(1)
-------------	-----

In the formula, Q_1 represents the heat transferred from the high-heat flue gas to the lining, and Q_2 represents the heat released from the outer wall of the valve body to the outside. The form of the total heat transfer equation is shown in formula 2:

$q = \Delta t / R$	(2)
--------------------	-----

In the formula, q represents the heat transferred per unit area in unit time, W/m^2 ; Δt represents the temperature difference, $\Delta t = t_1 - t_0$; R denotes the thermal resistance per unit area, $R = R_1 + R_2 + R_3 + R_4$, $m^2 \cdot ^\circ C/W$; t_1 represents the initial high temperature flue gas temperature, $^\circ C$; t_0 denotes ambient temperature, $^\circ C$; R_1 represents the heat transfer resistance of high temperature flue gas to lining, $m^2 \cdot ^\circ C/W$; R_2 represents the thermal resistance of the lining, $m^2 \cdot ^\circ C/W$; R_3 represents the thermal resistance of the valve body, $m^2 \cdot ^\circ C/W$; R_4 represents the heat release resistance of the valve body to the atmosphere, $m^2 \cdot ^\circ C/W$.

The heat transfer inside the valve body mainly depends on the heat conduction mode. According to the theory of heat conduction, the differential equation of heat conduction in orthotropic solid materials is shown in equation 3.

$\nabla \cdot (k \cdot \nabla T) + q_v = \rho c_p \frac{\partial T}{\partial t}$	(3)
--	-----

In the formula, T represents the transient temperature of the valve, $^\circ C$; t represents the process time, s; k is a second-order tensor, which contains the thermal conductivity of k_x, k_y, k_z in three principal axis directions, $m^2 \cdot ^\circ C/W$; ρ represents the density of the material, kg/m^3 ; q_v represents the internal heat capacity strength of the material, W/m^3 ; c_p represents the specific heat capacity of the material, $J/kg \cdot ^\circ C$.

The density, thermal conductivity and specific heat at constant pressure of the material are all constant values, which are independent of temperature and time. If the material is isotropic, that is, $k_x = k_y = k_z = k$, then equation 4 can be simplified as:

$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v = \rho c_p \frac{\partial T}{\partial t}$	(4)
--	-----

By introducing the diffusion rate formula 5, equation 4 can also be written in the form of equation 6.

$a = k / \rho c_p$	(5)
$\Delta^2 T + q_v / k = (1 / a) \partial T / \partial t$	(6)

For the solid heat transfer problem in the thermal-solid coupling analysis, the solution of the temperature field depends on applying reasonable boundary conditions and initial conditions to the governing equations. In mathematics, this ensures the existence and uniqueness of the numerical solution. The boundary conditions commonly used in engineering mainly cover three basic forms, which together constitute the physical basis for simulating the heat exchange between the valve and the external environment [21,22].

(1) The first kind of boundary condition is given directly the boundary temperature, which is a known function of space coordinates and time.

$T_{r_1} = T_w$	(7)
-----------------	-----

Or

$T_{r_1} = f(x, y, z, t)$	(8)
---------------------------	-----

In the formula, r_1 denotes the boundary of the first boundary condition of the object ; T_w represents the known boundary temperature, °C; $f(x, y, z, t)$ represents the known boundary temperature function, °C.

(2) The second kind of boundary conditions directly give the boundary heat flux q , that is, the derivative of the temperature along the normal direction of the boundary is a known function :

$-(\partial T / \partial n) _{r_2} = q_2$	(9)
---	-----

Or

$-(\partial T / \partial n) _{r_2} = g(x, y, z, t)$	(10)
---	------

In the formula, γ_2 denotes the boundary of the second boundary condition of the object ; q_2 denotes the known boundary temperature, °C; $g(x,y,z,t)$ denotes the known heat flux function, °C.

(3) The third type of boundary conditions, that is, there is a linear relationship between the boundary heat flux and the boundary temperature and the external fluid temperature, which is the convective heat transfer relationship :

$-k\left(\partial T / \partial n\right)\Big _{r_3} = h\left(T - T_f\right)\Big _{r_3}$	(11)
--	------

In the formula, γ_3 denotes the boundary of the third boundary condition of the object ; T_f represents the known boundary temperature, °C; h is the heat transfer coefficient, W/m². T_f and h can be constants or functions varying with time and space. If T_f and h are not constants, their average values are often taken as constants in numerical calculations.

2.3 Thermal-solid coupling analysis of thermal insulation lining

2.3.1 Thermal-solid coupling geometric model

When carrying out full-scale numerical simulation calculation for the overall structure of high-temperature flue gas valves, due to the complex structure of the model and the large scale of calculation, the numerical solution time is significantly prolonged and the consumption of computing resources is sharply increased, which has become a prominent bottleneck in the process of engineering design and optimization. In order to ensure the reliability of physical field simulation in key areas while reasonably controlling the calculation cost, this study proposes a local refined modeling and efficient calculation method for key areas. On the premise of maintaining the physical authenticity of its geometric details and boundary conditions, this method can achieve efficient and accurate evaluation of the high temperature performance and long-term reliability of the valve insulation lining structure under limited computing resources. Based on thermodynamic analysis and actual working condition evaluation, it is determined that the calculation area is simplified to a typical characteristic area of 600.00mm × 350.00mm, which can fully reflect the core heat transfer characteristics of valve lining. The lining structure without the new thermal insulation coating is shown in Figure.3, and the lining thickness is 125.00 mm. The lining structure of the thermal insulation coating is shown in Figure.4, the thickness of the lining is 125.00 mm, and the thickness of the new thermal insulation coating is 8.00 mm. The three-dimensional structure of the Ω -type anchorage is shown in Figure.5; the distribution of Ω -type anchorages is shown in Figure.6.



Figure 3 Lining structure without new thermal insulation coating



Figure 4 Lining structure of new thermal insulation coating

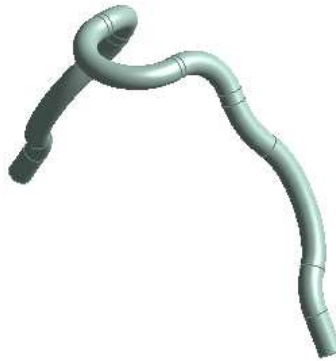


Figure 5 Ω-type anchorage model diagram

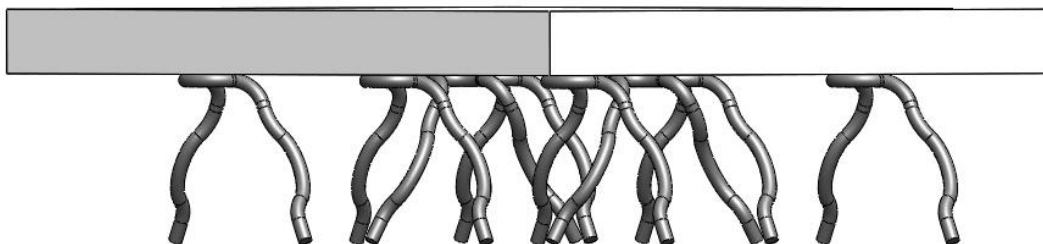


Figure 6 Ω-type anchorage distribution map

2.3.2 Grid division and independence verification

Mesh quality is one of the important factors affecting the accuracy and reliability of simulation software. In order to ensure the balance between the accuracy and computational efficiency of numerical simulation results, the geometric model of composite thermal insulation lining structure is meshed and mesh-independent. In order to ensure the balance between the accuracy and computational efficiency of numerical simulation results, the geometric model of thermal insulation lining is

systematically meshed and mesh-independent. The mesh generation uses the ANSYS Meshing module. In view of the complex geometric structure of the model, the multi-region scanning division method, local size control and boundary layer mesh encryption technology are comprehensively used. The critical areas for temperature field and thermal stress analysis, including the metal wall of the valve body, especially the contact interface between the thermal insulation lining and the anchor, are locally refined to ensure that the thermal gradient and stress concentration can be accurately captured. Among them, the hexahedral dominant grid is used in the thermal insulation lining and the adjacent metal area to improve the grid scheme. Under the same boundary conditions and material parameters, the steady-state temperature field and thermal stress field of the thermal insulation lining under rated high temperature conditions are solved. Based on the calculation results of scheme D, the value of the maximum value is compared. As shown in Table 1, when the grid is encrypted from scheme C to scheme D, the change rate of physical quantities at each monitoring point is less than 1 %. According to this, it is determined that the mesh density of scheme C has met the mesh independence requirements, and it is used as the final calculation model for all subsequent thermal-solid coupling analysis, so as to effectively control the calculation scale and solution time under the premise of ensuring the reliability of the results. The mesh model is shown in Figure 3.5.

Table 1 Mesh independence test of thermal insulation lining

Scheme	Number of elements	Maximum stress value (MPa)
A	237689	209.38
B	261051	220.69
C	283828	224.12
D	323576	226.89

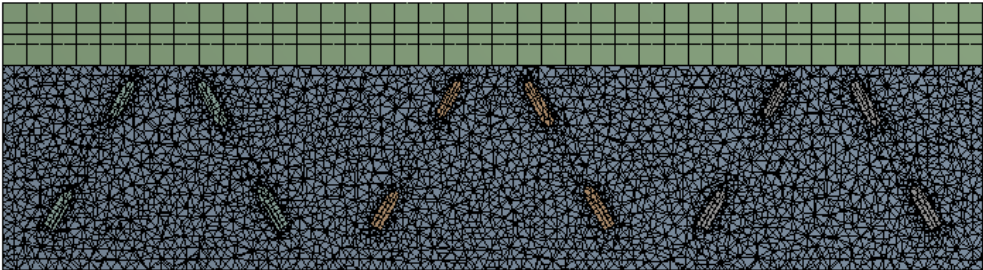
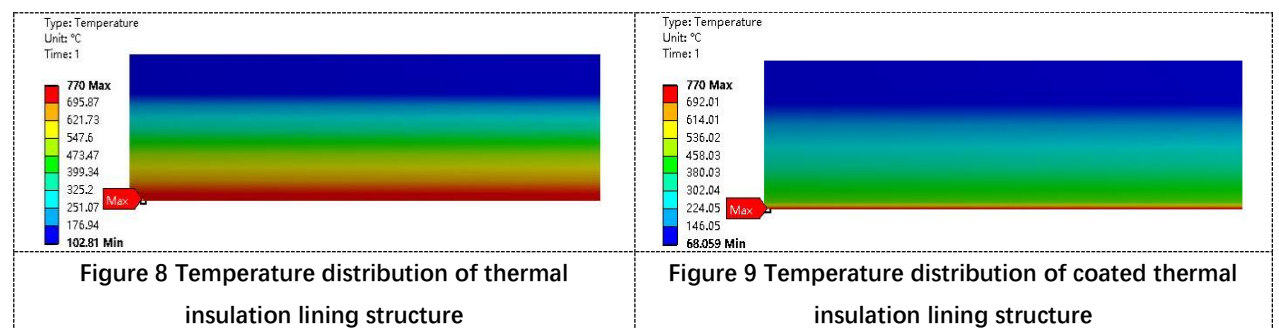
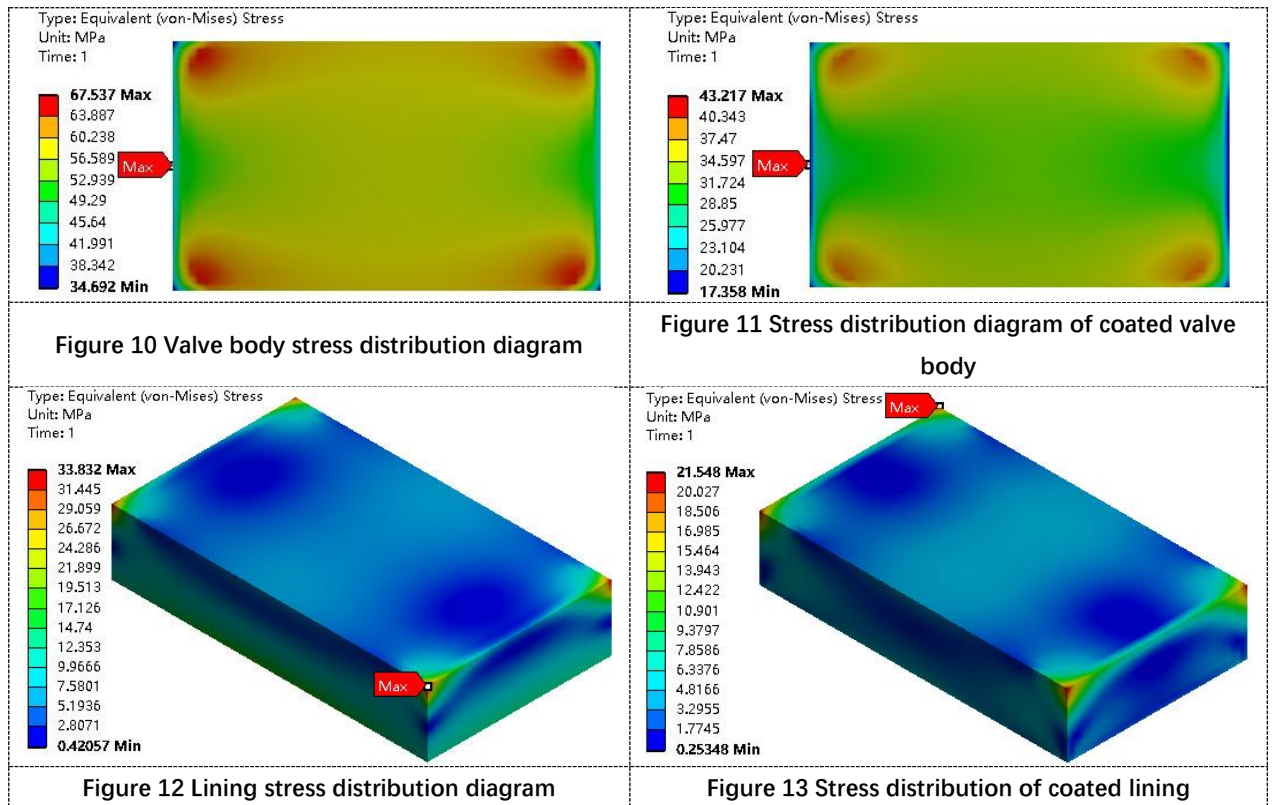


Figure 7 Grid model diagram

2.3.3 Analysis of numerical simulation results of thermal insulation lining structure without anchorage

The distribution results of temperature field and stress field of thermal insulation lining structure obtained by simulation analysis are shown in Figure.8 to Figure.13. When there is no thermal insulation coating, the minimum temperature of the lining structure is 102.81 °C, and the maximum stress values of the valve body and the lining are 67.54 MPa and 33.83 MPa, respectively. After the 8.00 mm thick insulation coating is laid, the minimum temperature of the lining is reduced to 68.06 °C, a decrease of about 33.80%. The maximum stress of the valve body is reduced to 43.22 MPa, a decrease of about 36.01%. The maximum stress of the lining is reduced to 21.55 MPa, a decrease of about 36.30%. This comparative analysis shows that the thermal insulation coating enhances the thermal resistance of the overall structure and makes the temperature gradient distribution more gentle. At the same time, due to the reduction of heat flux transfer, the thermal stress concentration caused by temperature difference is significantly alleviated. From the perspective of engineering optimization, the coating body has three aspects: at the thermal protection level, the efficiency is outstanding, which greatly reduces the temperature of the lining and valve body, and helps to prolong the service life of the refractory material; at the level of structural mechanics, the stress level of the valve body and the lining decreases synchronously, which improves the safety margin of the system under thermal-mechanical coupling load. At the level of stress distribution, the decrease of peak stress and the decrease of stress concentration area indicate that the coating alleviates the influence of interface due to different expansion coefficients to a certain extent. These characteristics jointly verify the applicability and superiority of the composite thermal insulation system in the adjustable orifice valve, and provide theoretical basis and data support for the reliability design and performance optimization of the thermal insulation structure under high temperature conditions.





2.3.4 Analysis of numerical simulation results of thermal insulation lining structure with anchorage

The anchor is the core stress component of the thermal insulation lining. Through the mechanical anchoring effect, the lining layer is closely combined with the equipment shell to ensure its structural stability. At the same time, it coordinates the thermal stress between the lining and the shell through its own specific design, and manages heat conduction to prevent weakening the overall thermal insulation effect. Although the use of anchoring parts enhances the adhesion of the lining material to the metal body, it will reduce the tensile, flexural and shear strength of the lining material itself to a certain extent, and will cause the thermal conductivity of the lining structure to be greater than the thermal conductivity of the lining material. Therefore, the temperature and strength of the lining are analyzed and studied by adding anchors to the lining material [23]. After finite element analysis, the temperature distribution of the thermal insulation lining structure is shown in Figure 14 and Figure 15, the stress distribution of the valve body is shown in Fig.16 and Figure 17, the lining stress is shown in Figure 18 and Figure 19, and the Ω stress diagram is shown in Figure 20 and Figure 21.

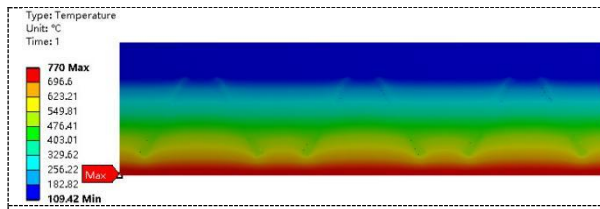


Figure 14 Temperature distribution of thermal insulation lining structure

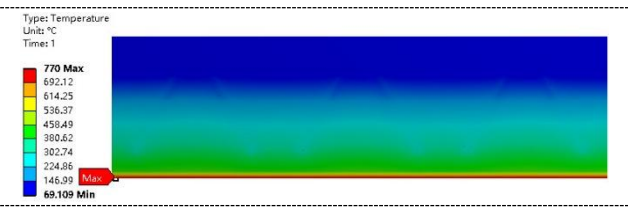


Figure 15 Temperature distribution of lining structure with thermal insulation coating

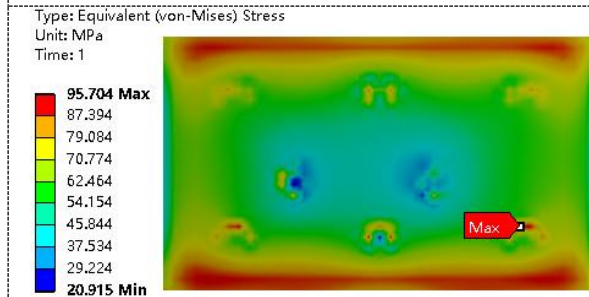


Figure 16 Valve body stress distribution diagram

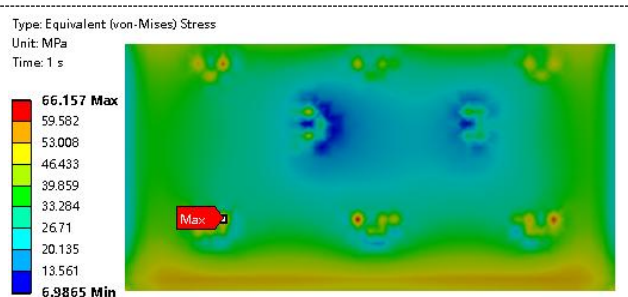


Figure 17 Stress distribution diagram of valve body with thermal insulation coating

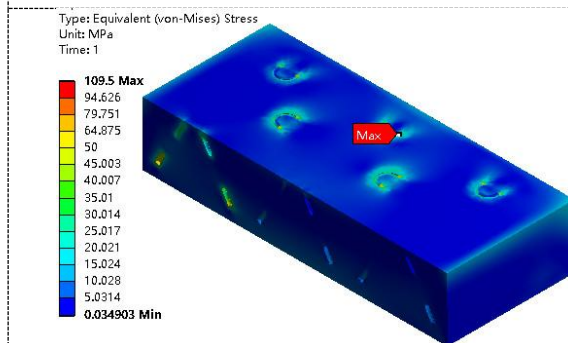


Figure 18 Lining stress distribution diagram

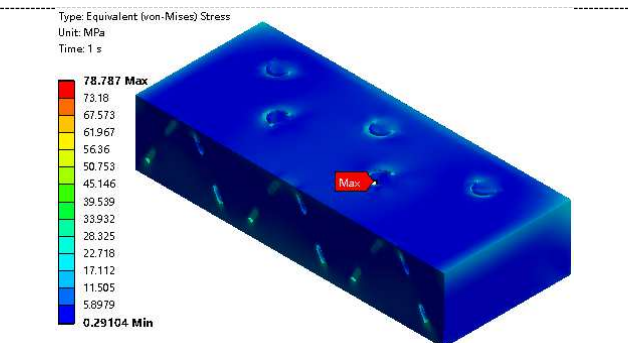


Figure 19 Stress distribution diagram of lining with thermal insulation coating

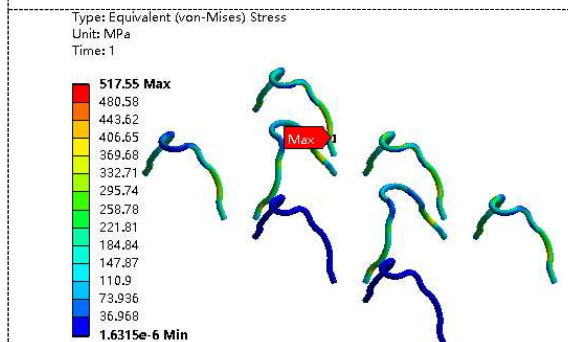


Figure 20 Anchor stress distribution diagram

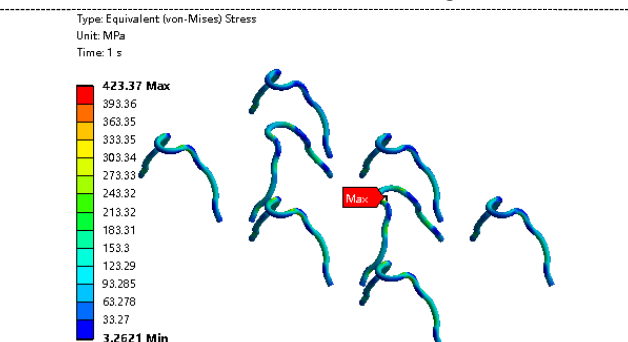


Figure 21 Stress distribution diagram of anchorage with thermal insulation coating

In order to analyze the synergy and trade-off relationship between the anchor and the thermal insulation lining, the thermodynamic response of the lining structure with anchors with or without thermal insulation coating is compared, and the simulation results of the structure without anchors are compared. As shown in Figure 14 and Figure 15, after adding a 8.00 mm coating, the temperature of the low-temperature side of the lining structure decreased significantly from 109.42°C to 69.11°C, a decrease of about 36.84% ; at the same time, the maximum stress of the valve body and the lining

decreased from 95.71MPa and 109.50MPa to 66.16MPa and 78.79MPa, respectively, with a decrease of 30.87% and 28.05%. The comparison results clearly show that the thermal insulation coating coated on the inner side of the lining can effectively reduce the heat transfer from the high temperature flue gas to the valve body by increasing the thermal resistance, reduce the overall temperature level and relieve the stress induced by the uneven thermal expansion. The thermal insulation effect of the thermal insulation coating is significant in the model with or without anchorage, indicating that the function of the thermal insulation coating has universal applicability.

However, compared with the lining structure without anchorage, the lining structure with anchorage causes complex local effects and mechanical reconstruction. At the thermal level, the thermal bridge formed by the metal anchorage leads to the local concentration of the surrounding heat flow, which makes the average temperature of the valve body with anchorage model slightly higher than that of the non-anchorage model, reflecting the influence of the anchorage on the ideal thermal insulation state. At a more critical mechanical level, the Ω -type anchorage changes the stress distribution pattern of the structure. As shown in Figure 16 and Figure 18, the maximum stress point is transferred to the geometric discontinuity: under the condition of no coating, the maximum stress of the valve body is concentrated on the welding root of the anchoring part, and the maximum stress of the lining appears at the contact interface between the anchoring part and the castable. The stress values of the two are much higher than those of the unanchored structure, which confirms that the anchoring part is a strong local stress concentration source. It is particularly noteworthy that the anchorage itself bears extremely high local stress under this working condition, with a peak value of 517.55MPa. (Note: This value is the theoretical extreme value under ideal binding contact, which is higher than the actual situation, and can be significantly reduced by setting a flexible buffer layer in the anchor).

Through comparative analysis, the dialectical relationship between a pair of cores in the design of high temperature valve insulation lining is clarified. The thermal insulation coating mainly undertakes the global thermal attenuation function, which can effectively reduce the thermal load and stress level of the system. The Ω -type anchorage is mainly responsible for the mechanical anchorage function. While ensuring the integrity of the lining structure, it will also cause a certain degree of stress concentration in the local area, making it a weak link under the thermal-mechanical coupling load. It can be seen that the design of high-performance lining must turn to the path of system collaborative optimization : on the basis of global thermal attenuation by coating, the fine design of anchorage system should be carried out, and the risk of stress concentration caused by it should be effectively controlled under the premise of

ensuring the reliability of connection by optimizing the layout and geometric configuration. This strategy of combining global thermal insulation with local force regulation is the key to improving the reliability of long-term operation of valves under extreme conditions, and also provides a clear theoretical basis for subsequent in-depth research and engineering practice.

3 Multi-objective optimization of key parameters based on surrogate model

3.1 Defining variables and experimental design

There are many parameters affecting the thermal insulation performance of the thermal insulation lining of the anchor system of the adjustable orifice plate valve, including the arrangement interval of the anchoring parts, the height of the anchoring parts, the diameter of the anchoring parts, the thickness of the lining layer and the thickness of the thermal insulation coating. There are many evaluation indexes for the influence of thermal insulation lining on thermal insulation performance, including valve body stress, lining stress, maximum stress of anchorage, average stress of anchorage, minimum temperature of valve body surface and so on. After consulting the literature and investigation, the common failure mode in the catalytic cracking unit is the cracking or even falling off of the lining layer. It may be that the layout and density of the anchoring system cannot effectively absorb the thermal stress, resulting in the concentrated cracking of the thermal stress and the poor stability of the traditional thick lining [24,25]. Considering comprehensively, the anchorage arrangement interval distance (X), lining layer thickness (L_1), anchorage diameter (D) and thermal insulation coating thickness (L_2) are selected as design variables. Lining stress (y_1), average stress of anchorage (y_2) and material price (y_3) are taken as optimization objectives.

The optimal Latin hypercube design can achieve uniform filling of sample points in the design space while ensuring the horizontal equilibrium distribution of each design variable, and effectively reduce the unsampled blank area, thereby significantly improving the global prediction accuracy of the fitting model. According to this method, combined with the level of each variable factor determined in Table 2, a sample set of design schemes for subsequent modeling and analysis is generated.

Table 2 Variable factor levels

Levels	Factor			
	X (mm)	L_1 (mm)	D (mm)	L_2 (mm)
-1	180.00	110.00	7.00	2.00
0	195.00	120.00	8.50	6.00
1	210.00	130.00	10.00	10.00

Through the thermal-solid coupling simulation method, the design schemes shown in Table 3 are calculated to obtain the corresponding evaluation index samples of each scheme, as shown in Table 4.

Table 3 Sample design schemes

serial number	X (mm)	L_1 (mm)	D (mm)	L_2 (mm)
1	186.25	113.33	8.88	9.33
2	192.50	115.00	9.25	2.33
3	187.5	128.33	8.00	8.33
--	--	--	--	--
48	208.75	117.50	7.38	7.00
49	206.25	127.50	7.88	5.33
50	200.00	130.00	9.50	6.67

Table 4 Sample simulation results of design scheme

serial number	y_1 (MPa)	y_2 (MPa)	y_3 (CNY)
1	44.76	76.19	633.17
2	71.66	128.31	252.80
3	58.94	84.02	594.95
--	--	--	--
48	78.51	103.46	510.81
49	56.95	102.29	430.25
50	52.45	86.32	506.14

In order to construct a high-precision finite element surrogate model instead of time-consuming, the standard BP neural network algorithm is improved, and the whale optimization algorithm is introduced to reduce the possibility of falling into the local optimal solution and improve the convergence speed and prediction accuracy of the network.

The whale optimization algorithm (WOA) was proposed in 2016, which was inspired by the special ' bubble net ' group predation strategy of humpback whales in nature. [27] In the WOA setting, the position of each whale represents a feasible solution. During the group predation process, each individual has three behaviors: randomly searching for prey, identifying the location of prey and encircling it, and using bubble nets to attack prey. Suppose that the position X of each whale in the n -dimensional solution space is:

$X = (x_1, x_2, \dots, x_n)$	(12)
------------------------------	------

When attacking prey ($p \geq 0.5$), in order to form a bubble net, the whale swims to the prey in a spiral motion. Its position update formula is:

$X_i^{t+1} = \left X_{best}^t - X_i^t \right e^{bl} \cos(2\pi l) + X_{best}^t$	(13)
--	------

In the formula, X_{best}^t is the position of the optimal individual in the population at time t ; X_i^t is the position of the whale individual at time t ; b is a constant used to define the shape of the spiral; l is a random number distributed in $[-1, 1]$.

When the prey is surrounded ($p < 0.5$), the whale decides to perform a contraction to surround the prey or randomly search the prey according to the size of A . When $|A| < 1$, the whale will swim to the individual with the best position to approach the prey. Its position update formula is:

$X_i^{t+1} = X_{best}^t - A \left CX_{best}^t - X_i^t \right $	(14)
---	------

When $|A| \geq 1$, the whale will also randomly look for prey, randomly select an individual in the group and approach it. Its position update formula is:

$X_i^{t+1} = X_{rand}^t - A \left CX_{rand}^t - X_i^t \right $	(15)
---	------

In the formula, X_i^{t+1} is the position of the whale individual at $t+1$; X_{rand}^t is the position of the random individual at time t . A and C are coefficients, and the calculation formula is as follows:

$A = 2 \times a \times r - a$	(16)
$C = 2 \times r$	(17)

In the formula, r is a random value in the interval $[0,1]$; a is a linear convergence factor. The advantage of WOA is that the operation is simple and easy to implement, and there are few parameters to be adjusted. It is a way to randomly generate the initial population, but this method has low search efficiency, weak global search ability, and is easy to fall into the local optimal solution. In order to solve the above problems, the Logistic-Tent (L-T) chaotic map is added to initialize the population, so that the population is more evenly distributed in the search space. Combined with the adaptive weight, a nonlinear decreasing adaptive sine factor w is introduced to update the individual position of the whale [28,29].

The expression of L-T chaotic map is as follows:

$x_{n+1} = \begin{cases} \left[rx_n(1-x_n) + \frac{4-r}{2}x_n \right] \bmod 1, & \text{if } x_n < 0.5 \\ \left[rx_n(1-x_n) + \frac{4-r(1-x_n)}{2}x_n \right] \bmod 1, & \text{if } x_n \geq 0.5 \end{cases}$	(18)
--	------

In the formula, x_n represents the value after the n th iteration, which is artificially controlled, usually between 3.57 and 4.

A nonlinearly decreasing adaptive sine factor w is introduced to satisfy the complex nonlinear changes in the WOA optimization process. Therefore, the position of the whale individual is updated as follows:

$w(z) = w_{\min} + (w_{\max} - w_{\min}) \sin(z\pi / \text{Max}_{\text{iteration}})$	(19)
$X_i^{t+1} = wX_{\text{best}}^t - A CwX_{\text{best}}^t - X_i^t $	(20)

BP neural network is one of the most widely used machine learning models at present. Its structure is shown in Figure 22. It includes three parts: input layer, hidden layer and output layer. Each layer neuron node is fully connected with the adjacent layer neuron nodes. BP neural network has a strong self-learning ability, which can grasp and store the mapping relationship between input and output data without knowing the mathematical equations that represent this mapping relationship in advance. However, in practical applications, BP neural network algorithm has the problems of slow convergence speed and easy to fall into local optimal solution. In order to solve these problems, L-TIWOA with global optimization ability is used to optimize the initial

weights and thresholds of BP neural network, so as to reduce the possibility of falling into local optimal solution, and improve the convergence speed and prediction accuracy of the network [26]. The flow chart of L-TIWOA-BP is shown in Figure 23.

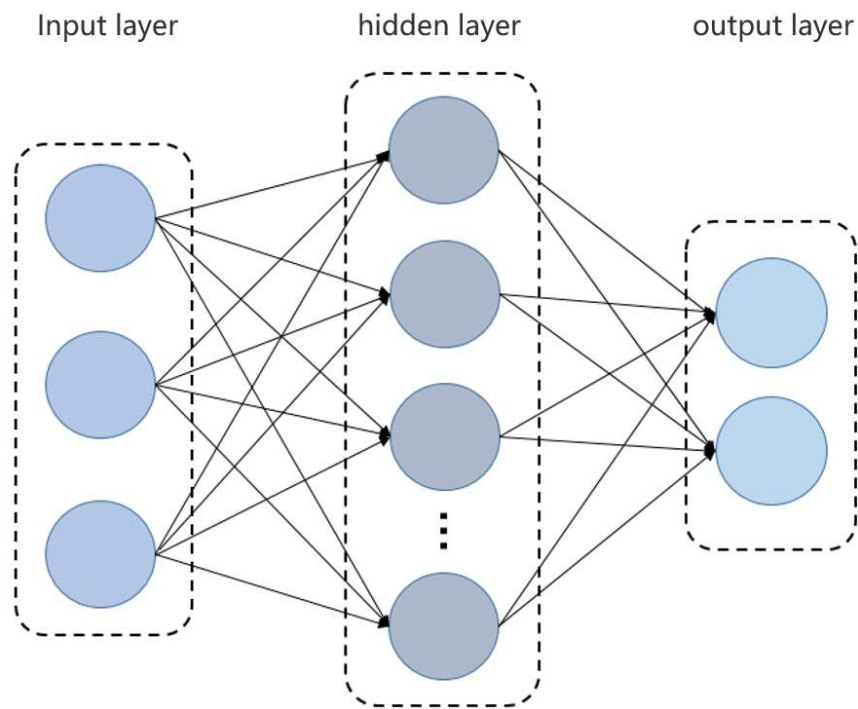


Figure 22 BP neural network structure diagram

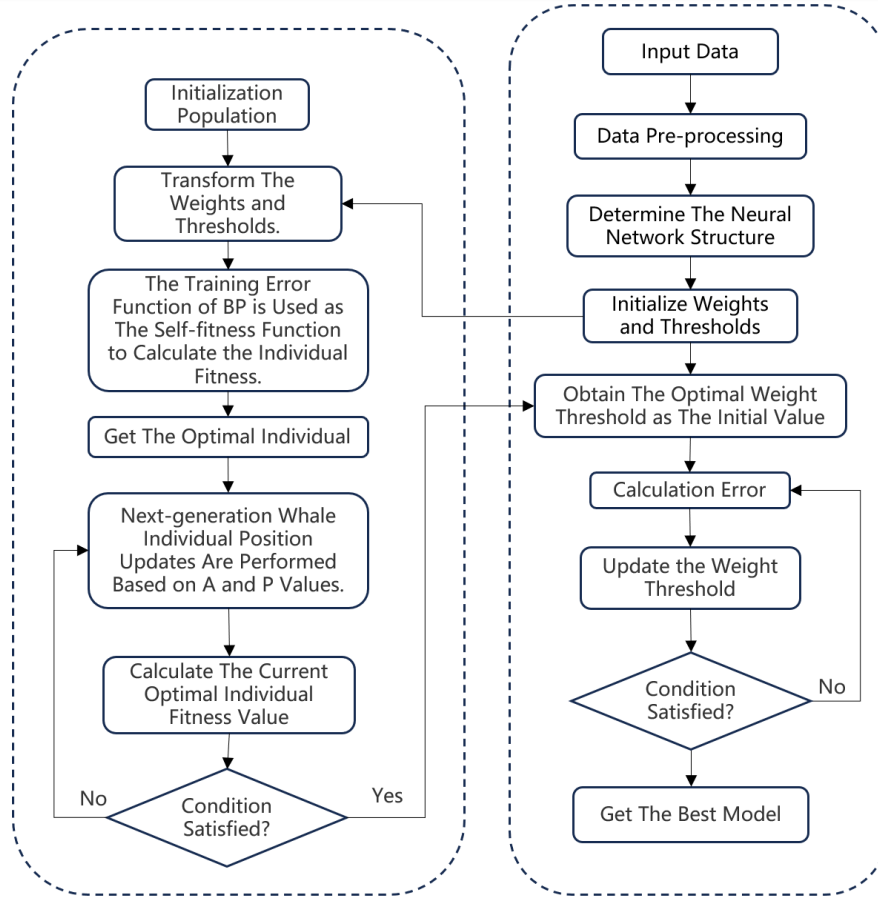


Figure 23 Flow chart of BP neural network optimized by L-TIWOA

The comparison diagram of the output effect between the predicted value of L-TIWOA-BP, the original BP predicted value and the true value is shown in Figure 24 (a) (c) (e). The predicted value of L-TIWOA-BP is much closer to the true value than the original BP predicted value; the error comparison diagram between the L-TIWOA-BP neural network and the original BP is shown in Figure 24 (b) (d) (f). The mean absolute error, mean square error and root mean square error of the BP neural network optimized by L-TIWOA are much smaller than the prediction error of the original BP. It can be seen from Figure.24 that the improved strategy improves the prediction accuracy of the surrogate model by magnitude, and the simulation progress fully meets the requirements of the engineering optimization for the surrogate model, which provides a reliable and efficient performance evaluation tool for the subsequent multi-objective optimization.

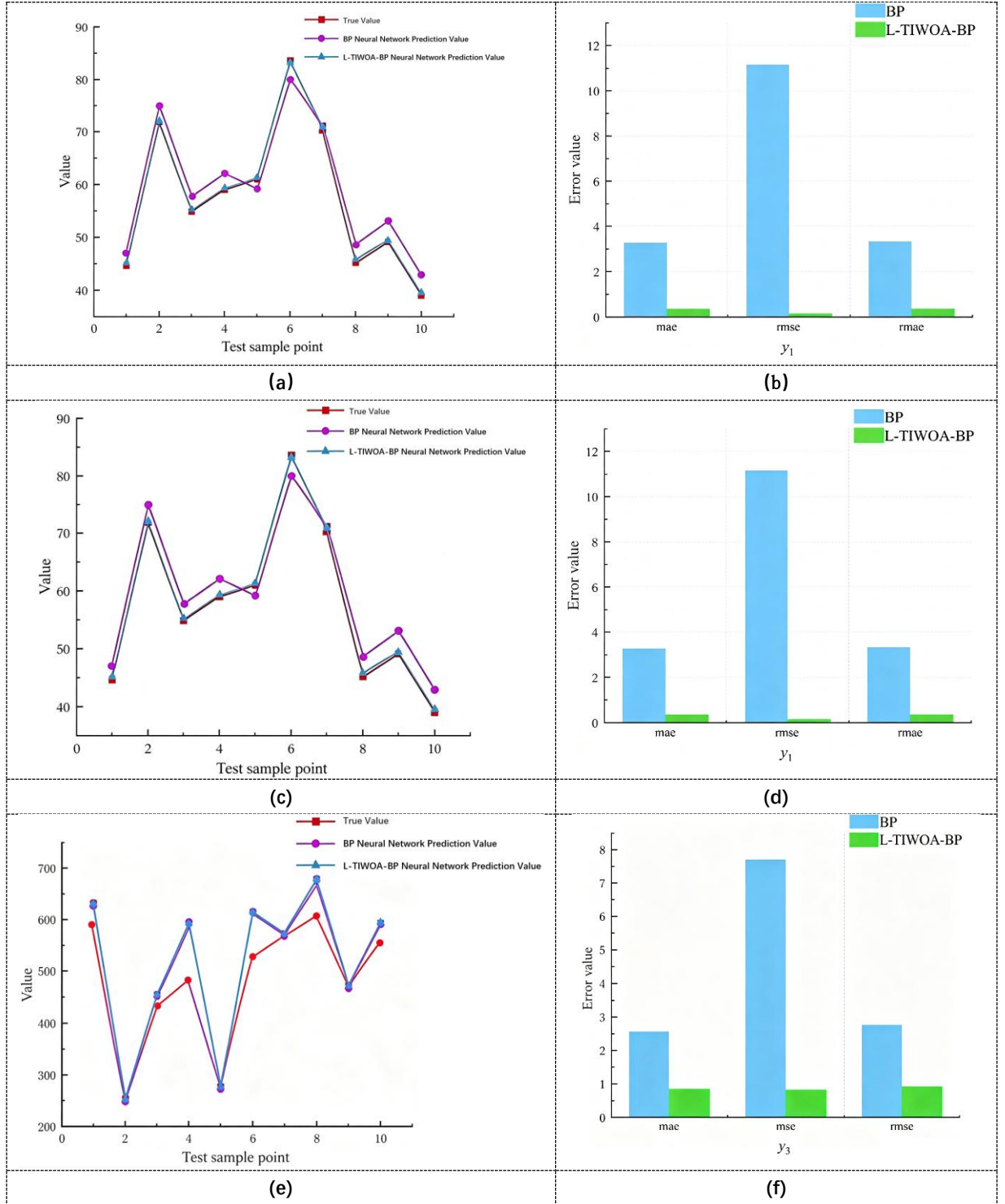


Figure 24 error graph

3.3 Optimization of key parameters of adjustable orifice valve insulation lining structure

The NSGA-II algorithm is a multi-objective evolutionary calculation method that combines a non-dominated sorting mechanism and an elite retention strategy, which is of landmark significance in the field of multi-objective optimization. The core principle and implementation steps of the algorithm can be summarized as follows: first, the initial construction of the population is completed, and then the hierarchy is divided

and sorted according to the dominance relationship between individuals, and the fitness value of each individual is evaluated accordingly. On this basis, the diversity of the population is maintained by genetic operations such as selection, crossover and mutation, and whether to enter the next iteration is judged based on the convergence degree of the current non-dominated frontier and the executed evolutionary algebra. When the preset termination condition is satisfied, the algorithm outputs the final optimized solution set [30 ~ 32].

In order to improve the speed of population optimization and avoid falling into local optimum, an adaptive mutation operator is proposed. It uses the effect of mutation to improve the convergence speed, improve the diversity and stability of the population, and improve the quality of the Pareto optimal solution, so as to achieve better convergence effect. The specific principle is as follows:

$\gamma(X) = 2 \frac{1}{n} \sum_1^n \gamma(X) - g(X)$	(21)
$g(X) = \frac{(\mu - 1) G_{avg}}{G_{max} - G_{avg}} G(X)$	(22)

In the formula, γ is the probability of individual mutation; $g(X)$ is the individual fitness, which is calculated by the fitness function after scale transformation. μ is the maximum value of the fitness after transformation should be equal to the specified multiple of the average value of the original fitness; $g(X)$ is the fitness function.

Based on the surrogate model, the NSGA-II algorithm is improved to optimize the structural parameters of the adjustable orifice valve insulation lining, and the process is shown in Figure 25.

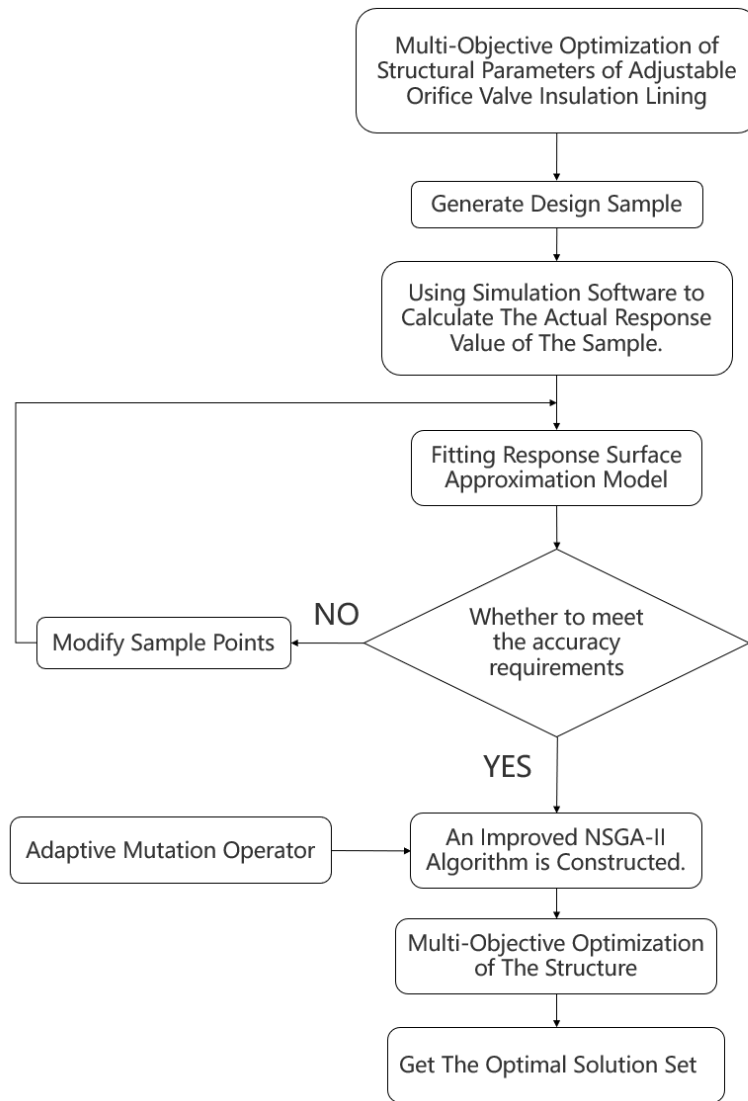


Figure 25 Improved NSGA-II algorithm flow chart

The thickness of the lining, the thickness of the thermal insulation coating, the diameter and distribution of the anchorage are selected as the key design variables, and the factor levels are set respectively. In order to construct a surrogate model that can accurately reflect the mapping relationship between design variables and system response, it is necessary to adopt an experimental design method with good spatial sampling characteristics. The improved NSGA-II algorithm based on the improved BP surrogate model is used to optimize the lining with anchorage system. The initial population size is set to 30, the maximum genetic algebra is 100 generations, and the crossover probability is 0.9. The Pareto front solution set of the multi-objective optimization problem is obtained as shown in Figure 26. Each point in the graph represents the response value of the objective function of a set of design schemes. It can be seen that there is a certain distribution difference in the pros and cons of the response values of the three objective functions. When the response values of the two

objective functions tend to the optimal solution according to a certain law, the response value of the third objective function does not tend to the optimal solution, and there is no design scheme with three indicators all optimal.

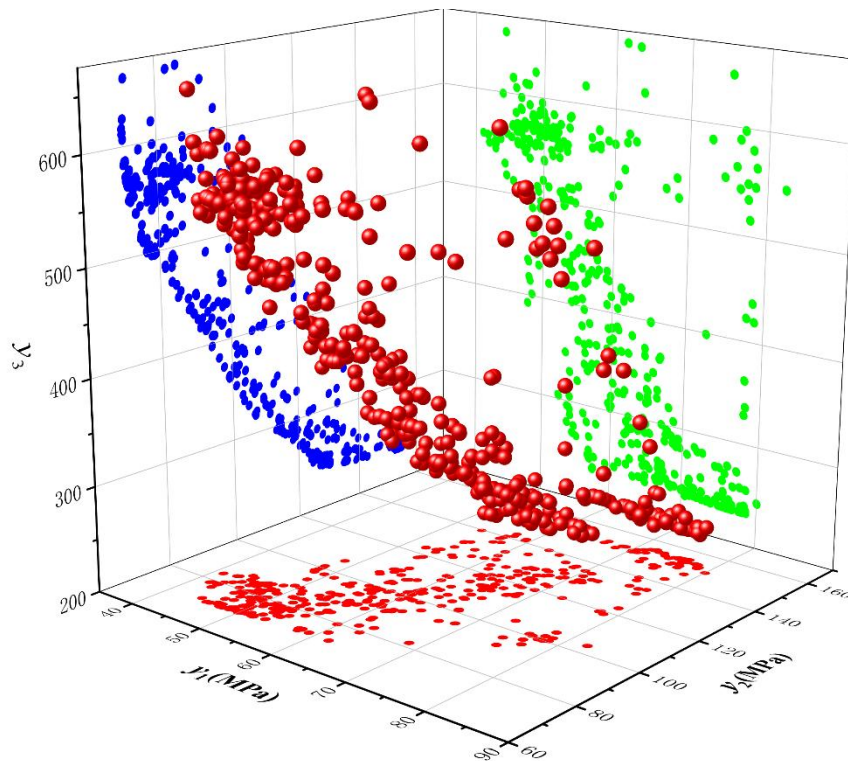


Figure 26 Multi-objective optimization algorithm optimization results

Table 5 Specific numerical comparison of each scheme

Compute	Structural Parameter				Required Value		
	$X(\text{mm})$	$L_1(\text{mm})$	$D(\text{mm})$	$L_2(\text{mm})$	$y_1(\text{MPa})$	$y_2(\text{MPa})$	$y_3(\text{CNY})$
A	182.79	112.33	8.50	7.85	41.11	84.00	556.71
B	192.34	117.64	9.24	8.59	47.47	70.71	611.28
C	197.45	117.85	7.51	2.00	78.13	153.85	232.13
Initial value 1	200.00	125.00	8.00	0	109.50	201.50	136.50
Initial value 2	200.00	125.00	8.00	8.00	78.79	87.06	573.30
Optimized	197.46	119.11	9.62	3.00	56.53	119.10	293.87

According to the Pareto front solution set shown in Figure 26, the scheme A with the smallest lining stress, the scheme B with the smallest average stress of the anchorage, and the cheapest C can be obtained. Considering the design scheme of the adjustable orifice valve and the structural characteristics of the thermal insulation lining

system, the optimal combination of structural parameters is obtained. The specific parameters and response values of each scheme are shown in table 5. The optimized results show that the design scheme improves the performance of the lining containing the anchoring system while ensuring the economy, indicating that the improved algorithm and optimization scheme are reasonable and play a good role.

3.4 Lining thermal insulation performance index comparison before and after optimization and literature verification

Based on the multi-objective optimization algorithm of the surrogate model, the optimal structural parameter combination of the lining with the anchoring system is obtained, which is the spacing distance of the anchoring parts 196.47mm, the diameter of the anchoring parts 9.62mm, the thickness of the lining layer 119.11mm and the thickness of the thermal insulation coating 3.00mm. Using these parameters, the same thermal-solid coupling method and related settings as the previous ones are used for numerical simulation calculation. The simulation results are shown in Figure 27-29. It can be seen that the numerical error between the maximum stress value of the lining and the optimized value is 2.70%, and the average stress value of the anchor and the optimized value is 1.19%, which shows the applicability and accuracy of the optimization method.

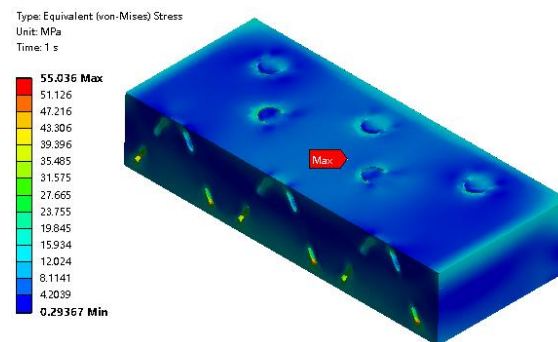


Figure 27 Lining stress distribution diagram

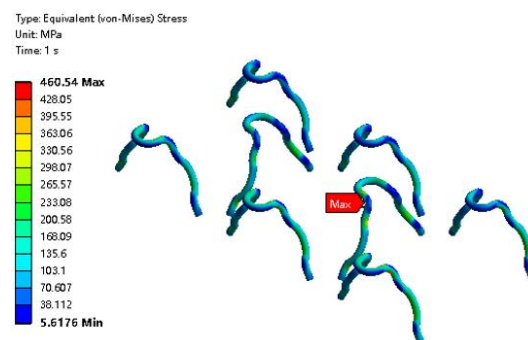


Figure 28 Anchor stress distribution diagram

Results	
☐ Minimum	5.6176 MPa
☐ Maximum	460.54 MPa
☐ Average	117.74 MPa

Figure 29 Anchor stress value

Comparing the verification results of this paper with those of Reference [33], the simulation error of the maximum stress value of the lining in this paper is 2.70%, and the simulation error of the average stress value of the anchorage is 1.36%, which are better than the average relative error level of 7.00 % in Reference [33]. This shows that the surrogate model constructed in this paper has higher prediction accuracy, and the multi-objective optimization method based on the surrogate model has good applicability and accuracy in dealing with the lining structure optimization problem with anchorage system.

4. Conclusion

Aiming at the thermal-solid coupling behavior and structural optimization of the adjustable orifice valve insulation lining of the catalytic cracking unit under high temperature conditions, the finite element models of two lining structures with and without anchors were established, and the temperature field and stress field distribution under high temperature conditions were analyzed. On this basis, a multi-objective optimization model is established with the minimum temperature of the outer wall of the valve body and the minimum equivalent stress of the lining as the objectives, and the key parameters such as the thickness of the lining and the spacing of the anchoring parts are collaboratively optimized by the surrogate model method. The following conclusions are obtained:

- (1) Through the thermal-solid coupling numerical simulation, the functions of two key parts of the thermal insulation lining are clarified. The thermal insulation coating mainly undertakes the global thermal attenuation function, which can effectively reduce the thermal load and stress level of the system, and is the core barrier to ensure the overall thermal insulation performance of the lining. The Ω -type anchorage is mainly responsible for the mechanical anchoring function. While ensuring the integrity and adhesion reliability of the lining structure, it will cause a certain degree of stress concentration in the local area, which may become a weak link under the thermal-mechanical coupling load.
- (2) The improved L-TIWOA algorithm is introduced to optimize the BP neural network to improve the convergence speed and prediction accuracy of the BP network. As a surrogate model, the multi-objective optimization algorithm is used to optimize the structure of the lining with the anchoring system. The optimal parameter

combination is obtained : the spacing distance of the anchoring parts is 196.47 mm, the diameter of the anchoring parts is 9.62 mm, the thickness of the lining layer is 119.11 mm, and the thickness of the thermal insulation coating is 3.00 mm. The same thermal-solid coupling method and related settings are used for numerical simulation calculation. The maximum stress value of the lining is 2.70 % compared with the optimized numerical error. The numerical error between the average stress value of the anchor and the optimized value is 1.19 %, which shows the applicability and accuracy of the optimization method, and improves the thermal insulation performance of the lining structure while ensuring the economy.

Funding: This research was funded by Gansu Provincial Department of Education:Industrial Support Plan Project: 2025CYZC-048.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Author Contributions: Conceptualization, J.Z. and S.L.; Methodology, S.L.; Validation, J.Z. and Y.Z.; Writing—original draft, J.Z. and X.L. Writing—review and editing, S.L. and J.Z. All authors have read and agreed to the published version of the manuscript.

References

- (1) Tasneem N, Ahmed S, Hossain M M. Enhancement of Olefins from Fluid Catalytic Cracking Processes: A Review on Effects of Catalysts and Kinetics [J]. Arabian Journal for Science and Engineering, 2024, 50(6): 1-22.
- (2) Lin Fengtao, Ai Zhongqiu. Thermodynamic calculation and optimal operation of catalytic cracking flue gas turbine unit [J]. Petrochemical equipment technology, 2025, 46 (04) : 13-16 + 23 + 75.
- (3) Pan Yuelei, Cheng Xudong, Yan Mingyuan, et al. Silica aerogel and its application in the field of thermal insulation [J]. Chemical progress, 2023, 42 (01) : 297-309.
- (4) Tang Jiulin, Yue Dong, Liu Bo, et al.. Application of new refractory fiber module anchorage structure in trolley heating furnace [J]. Industrial heating, 2023, 52 (09) : 23-27.
- (5) Song Qingjun, Li Wenping, Wang Mingming, et al. Analysis of the effect of thermal insulation coating on the temperature field and stress field of piston [J]. Automotive technology and materials, 2023 (06) : 51-57.
- (6) Qian Jixiang, Yin Fayuan. Repair of regenerator lining of heavy oil catalytic cracking unit [J]. Petrochemical equipment, 2024, 53 (05) : 70-75.
- (7) Su Weiguang, Shi Yuchen, Song Xudong, et al. Finite element analysis of temperature and stress fields in refractory lining of opposed multi-nozzle gasifier [J]. Coal Journal, 2021, 46 (01) : 274-283.
- (8) Sun Y, Lv S, Yang X, et al. Mechanical modeling of a stitched sandwich thermal protection structure with ceramic-fiber-reinforced SiO₂ aerogel as core layer[J]. Journal of Sandwich Structures & Materials, 2022, 24(2): 1028-1048.
- (9) Samadi S, Jin S, Gruber D, et al. Thermomechanical finite element modeling of steel ladle containing alumina spinel refractory lining[J]. Finite elements in analysis and design, 2022, 206: 103762.

- (10) SantosA J, SantosF M, MoreiraH M, et al. Evaluation of steel ladle refractories lining designs aiming energy savings using open-source finite element tools[J]. *International Journal of Applied Ceramic Technology*, 2024, 22(2): e14928-e14928.
- (11) Kang and Tang.Research on the evolution law of temperature field and stress field of high temperature tunnel under low temperature ventilation environment [J].*Journal of Water Conservancy and Construction Engineering*, 2021, 19 (03) : 166-170 + 187.
- (12) Liu Xingchen, Huang Feng, Zhou Yang, et al. Optimization of thermal insulation thickness of high temperature tunnel and thermal-mechanical coupling response analysis of lining [J].*Modern tunnel technology*, 2022,59 (05) : 108-117.
- (13) Gasser A, Poirier J. Thermomechanical testing of a laboratory pilot containing refractory masonries without mortar[J]. *Open Ceramics*, 2023, 13.
- (14) Lee S W, Kim Y H, Choi S W. Thermal and Structural Analysis for the Bleed Valves of Gas Turbine Compressors[J]. *Design & Manufacturing*, 2025, 19(1): 1-7.
- (15) Zhang Liqiang, Qi Changxin, Chen Gaopeng, et al. Structural optimization and sealing performance analysis of wedge gate valve based on Kriging model [J]. *Chemical Machinery*, 2021,48 (03) : 390-396.
- (16) Liu Xiong. Fluid-thermal-solid coupling analysis of ultra-supercritical electric gate valve and lightweight research of valve body structure [D]. *Wuhan University of Science and Technology*, 2022.
- (17) Zong C, Shi M, Li Q, et al. Design optimization of a nuclear main steam safety valve based on an E-AHF ensemble surrogate model[J]. *Nuclear Engineering and Technology*, 2022, 54(11): 4181-4194.
- (18) Liu Taiyu.Multi-objective optimization of sealing structure of LNG high-pressure axial flow check valve [D].*Lanzhou University of Technology*, 2020.
- (19) Chen Junxiang, Kong Xiangdong, Guo Yujie et al.. Comprehensive performance optimization of high-pressure threaded cartridge relief valve based on NSGA-II algorithm [J].*Journal of Mechanical Engineering*, 2025,61 (08) : 319-330.
- (20) Qingtong L, Fanglong Y, Songlin N, et al. Multi-objective optimization of high-speed on-off valve based on surrogate model for water hydraulic manipulators[J]. *Fusion Engineering and Design*, 2021, 173: 112949.
- (21) Zhang Limei, Yin Yueping, Zheng Hong et al. Numerical manifold method for nonlinear steady-state heat conduction problems [J].*Journal of Yangtze River Scientific Research Institute*, 2026,43 (02) : 181-191.
- (22) Deanesi S, Cammi A, Lorenzi S. Multiphysics modelling and preliminary analysis on the freeze valve behaviour in a Molten Salt Fast Reactor[J]. *Nuclear Engineering and Design*, 2025, 445114486-114486.
- (23) Yang Lei, Wen Cheng.Research on failure analysis and quality control of ' two devices ' lining of heavy catalytic device [J].*Journal of Gansu Normal University*, 2025,30 (04) : 58-64.
- (24) Wang D, Wang L, Wang W, et al. Design and optimization of interface morphology of thermal barrier coatings based on regulation of residual stress: a finite element simulation study[J]. *Coatings*, 2022, 12(7): 940.
- (25) Liu Chuchun, Fan Jilei, Li Desheng. Failure Analysis and Countermeasures of Cyclone Separator in Catalytic Cracking Regenerator [J]. *Refinery Technology and Engineering*, 2020,50 (04) : 46-49.
- (26) Yan Xu, Zhang Guocheng, Feng Duan, et al. Data correction of grid air quality monitor based on improved WOA-BP neural network [J].*Instrument technology and sensors*, 2024 (02) : 44-49 + 55.
- (27) Mirjalili S, Lewis A. The whale optimization algorithm[J]. *Advances in engineering software*, 2016, 95: 51-67.
- (28) Guo Xianfeng, Li Haohua, Wei Jinyu. Image encryption scheme based on Fibonacci transform and improved Logistic-Tent chaotic map [J].*Journal of Jilin University (Engineering Edition)*, 2023,53 (07) : 2115-2120.

- (29) Xu Fuqiang, Zou Dexuan, Li Can, et al. Improved particle swarm optimization algorithm with Circle mapping and sine cosine factor [J]. Computer Engineering and Application, 2023,59 (17) : 80-90.
- (30) Tang Zhaohui, Xu Zhihong. Optimization design method of AC contactor spring system based on response surface method [J]. Journal of Electrical Technology, 2022,37 (02) : 515-527.
- (31) Cao Liru, Wang Xiaoqiang, Wang Paigang, et al. Optimization of ultrasonic rolling extrusion process parameters based on NSGAI algorithm [J]. Plastic Engineering, 2022,29 (07) : 19-25.
- (32) Kumar R, Singh S, Bilga P S, et al. Revealing the benefits of entropy weights method for multi-objective optimization in machining operations: A critical review[J]. Journal of Materials Research and Technology, 2021, 10: 1471-1492.
- (33) A Rong, Qi Yin, Chen Xin, et al. Parameter optimization of two-way gas combined thermal test based on surrogate model [J]. Aerodynamics, 2023,38 (09) : 2097-2106. Sda