Optimization of Air Supply Conditions for Large Space Radiant Air Conditioning Based on Response Surface Analysis

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Abstract. In large spaces, the comfort control of radiant air conditioning systems still has deficiencies. Mainly reliant on traditional parameter control methods, the interaction effects of diverse operating conditions are not taken into account, and the control results are still in need of optimization. To improve indoor air conditioning comfort control and address gaps in existing research, the response surface analysis method combined with numerical simulation is applied to determine the optimal air supply conditions for large-space radiant air conditioning. With the real model as a reference, simulations are carried out in Airpak, selecting four factors: supply air temperature, supply air humidity, air supply volume, and air supply angle for the response surface design. Discussions on interaction effects are carried out based on the simulated results of various scheme designs, determining eight groups of air supply schemes with the highest comfort. The research concludes that the response surface analysis method, considering the interactive effects of impacting factors, can lead to the strategy of high comfort and reasonable air supply conditions. Additionally, a set of recommendations are proposed for future practical application and promotion.

Keywords: Radiant air conditioning; Response Surface Methodology; Computational Fluid Dynamics (CFD) Model.

1. Introduction

Air conditioning in large spaces has always been of great concern [1]. Although the traditional centralized air conditioning system can meet the requirements to a certain extent, it still has shortcomings such as difficulty in comfort adjustment, high noise and high energy consumption, making it difficult to meet the needs of environmental quality and energy saving in large spaces [2].With the widespread application of radiant air conditioning and displacement ventilation technology in small space environments, some scholars have begun to explore the application of radiant air conditioning systems in large spaces [3]. In view of the characteristics of large spaces such as high vertical temperature differences, difficulty in temperature adjustment, and high demand for fresh air volume, how to solve these problems while ensuring the comfort of radiant air conditioning has become an important research topic and direction [4, 5].

At present, the comfort control of radiant air conditioning in large spaces mainly relies on a single air parameter control [6]. Shan and Lu have proposed the PMV (Predicted Mean Vote) control method to consider the impact of multiple environmental parameters [7]. Common PMV control methods include nonlinear model control prediction, computer control based on genetic neural networks and adaptive fuzzy PID (Process Identifier) control [8, 9]. However, existing research methods ignore the influence and interaction of various factors on PMV, so there is still a lot of room for optimization in radiant air conditioning control. RSM (Response Surface Methodology) is to find quantitative patterns between experimental indicators and factors by operating on variables and fitting mathematical equations with a high degree of combinatorial effects [10]. Compared with existing control methods, RSM can not only save a lot of experimental data, time and resources in obtaining experimental results, but can also handle multi-factor analysis and optimization [11]. RSM adopts an optimization method based on statistics and recommends accurate mathematical modeling based on algorithmic calculations. It can also recommend scientific and appropriate control results based on the influence of multiple factors, which has the advantages of prediction and optimization. Traditional response surface analysis typically models and optimizes a single response variable [12]. However, in practical problems, there may be multiple interrelated response variables, such as multi-objective optimization problems. The response surface analysis method under multi-objective optimization can consider multiple response variables at the same time to find a balance point or generate a set of optimal solutions. Liu et al. conduct a response surface experiment on the cooling performance of a thermal storage air conditioning system based on heat pipe heat exchange, and use regression equations to evaluate the impact of different influencing factors on cooling capacity [13]. Zhang finds that using the response surface method to design working conditions can obtain a regression model between evaluation indicators and influencing factors when performing multi-objective optimization of airflow organization [14]. And the TOPSIS (Technique for order Preference by Similarity to ideal solution) evaluation method can also make decision-making optimization plan. The issues of inadequate airflow and discomfort in the office ventilation environment of industrial buildings can also be analysed through RSM to obtain the impact results of various air supply conditions [15]. Mao et al. study the impact of supply air temperature and air flow rate on air conditioning energy saving and indoor comfort in a small workstation air conditioning system [16]. It is found that the RSM method has better performance under multi-factor control. Based on these, the study uses RSM to optimize the air supply conditions of large space radiant air conditioners to clarify the application advantages of radiant air conditioners in large spaces.

2. Research methods

2.1 Numerical model

Take the research object of a large commercial atrium in Suzhou City in summer. To ensure calculation accuracy while simplifying calculations, the 3D model is built by Airpak. In Figure 1, due to the symmetrical physical characteristics of the model, a quarter model is used for simulation in Airpak.

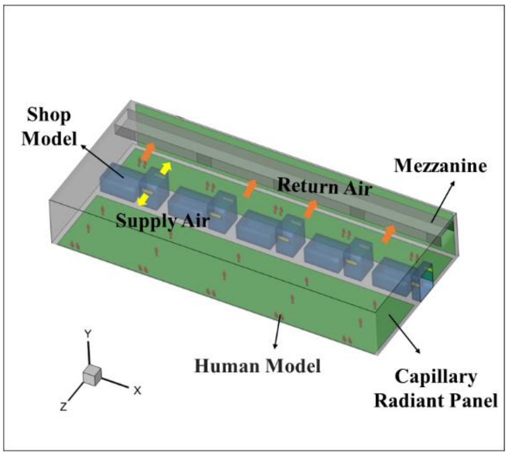


Fig. 1 Physical Model in Airpak

Environmental parameters refer to the annual average meteorological conditions of Suzhou City in summer: under atmospheric pressure conditions, the outdoor calculated dry bulb temperature is 34.6 °C, the wet bulb temperature is 28.2 °C, and the air moisture content is 61.95 % [17].

The basic parameters used in the model are calculated based on actual CAD drawings. The building materials: the heat transfer coefficient of the exterior wall is 0.52 W/(m^2·K), the floor area is 1466.25 m^2, the floor radiation net laying area is 1036 m^2, and the wall radiation net laying area is 481.6 m^2. The power of the radiant panel is 50 W/m^2, the number of personnel is 30, the heat dissipation is 60 W/person, the personnel clothing degree is 0.38, the shop model size is 6 m×2.8 m×4 m, and the air unit model size is 3 m×4.8 m×4 m. Since the shop has independent air-conditioning control, its walls are by default insulated and there is no heat exchange with the indoor atrium environment. The total area of the air supply vents is 7.1 m^2, and a mezzanine is built above the wall. The total area of the return air vents on the mezzanine is 22 m^2. After the Airpak grid check function, the distortion amount is less than 0.15 %, and the grid quality is close to 1, ensuring the accuracy and reliability of the building physical model.

In figure 2, comparing the simulated values with the actual measurement data, the maximum error between the simulated values and the actual values is 0.084767, which is less than 0.1.

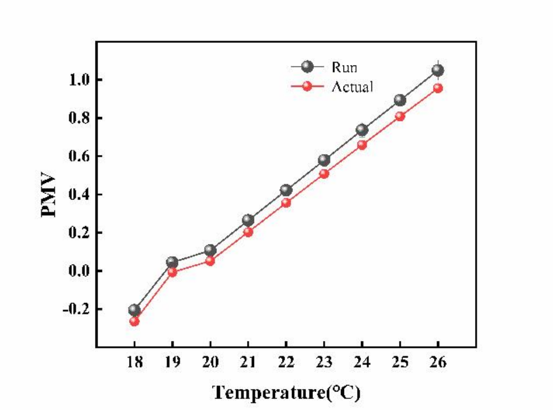


Fig. 2 Run VS Actual.

2.2 Box-Benhnken scheme design.

According to the air supply influencing factors of air conditioning design and the results of single-factor experiments, supply air temperature, supply air humidity, air supply volume and air supply angle are selected as experimental factors. The experimental value range is selected as shown in Table 1.

Table 1. Experimental data and scope

Factor	Unit	Center point	Design scope	Experiment scope
Supply air temperature	℃	19	18~28	12~26
Supply air humidity	%	0.05	-	0~0.1
Air supply volume	$m^3 \cdot h^{-1}$	570240	30 $m^3 \cdot h^{-1}$·person＜	103680~1036800
Supply air humidity	%	0.05	-	0~0.1

The experimental plan design is generated by Design Experts 13 software, which designed 29 groups of plans for four factors. The response surface Box-Benhnken method plan design is shown in Table 2.

Table 2. Response surface experimental design

Run	(A) Supply air temperature(℃)	(B) Supply air humidity(%)	(C) Air supply volume(m³·h-1)	(D) Air supply angle(°)
1	26	0.05	103680	0
2	26	0	570240	0
3	12	0.05	570240	-60
4	19	0	570240	60
5	12	0.05	103680	0
6	26	0.05	570240	-60
7	19	0	103680	0
8	19	0.05	103680	-60
9	19	0.05	570240	0
10	12	0.05	1036800	0
11	19	0.1	570240	60
12	19	0.05	1036800	60
13	12	0.05	570240	60
14	19	0.05	570240	0
15	12	0	570240	0
16	26	0.1	570240	0

17	26	0.05	570240	60
18	19	0.05	570240	0
19	19	0	1036800	0
20	12	0.1	570240	0
21	26	0.05	1036800	0
22	19	0.1	103680	0
23	19	0	570240	-60
24	19	0.05	1036800	-60
25	19	0.05	103680	60
26	19	0.05	570240	0
27	19	0.1	570240	-60
28	19	0.05	570240	0
29	19	0.1	1036800	0

The indoor conditioning effect of each solution is evaluated using PMV values: PMV=-1, slightly cool; PMV =+1, slightly warm; PMV =0, comfortable. Due to indoor conditions and somatosensory range, the average PMV value of the area below two meters is usually selected to reflect the overall indoor environmental change effect [18, 19]. The accuracy of the fit between the simulation results and the response surface prediction results was evaluated by the variance analysis table provided by Design Experts 13 software.

3. Response surface simulation and results discussion

3.1 Simulation results

According to the designed experimental plan, Airpak was used to conduct numerical simulation. The indoor PMV results of each scheme are shown in figure 3.

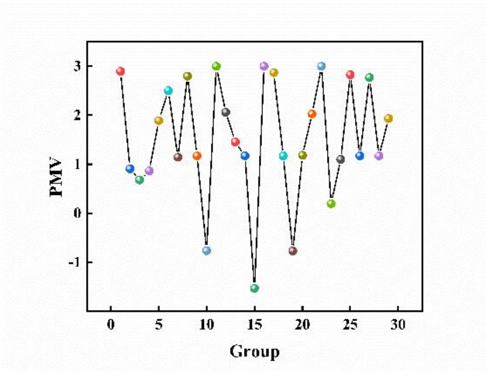


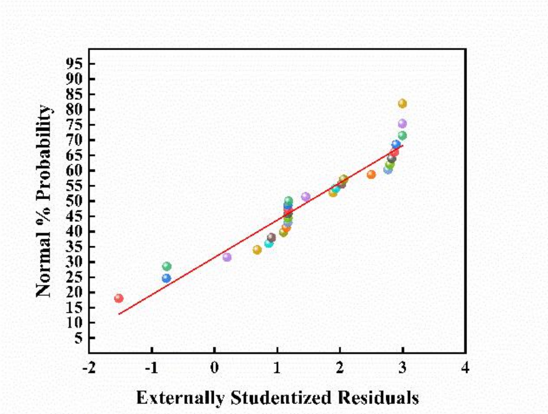
Fig. 3 Simulation Results

According to Design Experts 13 software, the experimental results show a quadratic multiple regression trend. The quadratic multiple regression equation between the independent variables of supply air temperature (*A*), supply air humidity (*B*), supply air volume (*C*), supply air angle (*D*), and indoor comfort PMV (*Y*) is as follows:

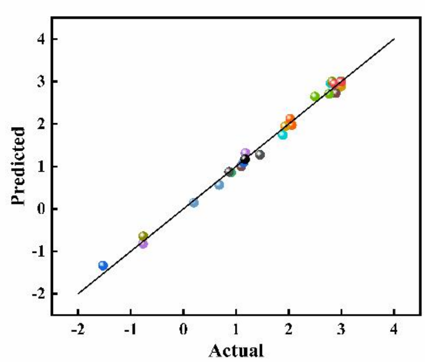
$$\begin{aligned} Y = & -0.240162 + 0.102698A + 34.97572B \\ & -6.46223\times10^{(-6)}C + 0.005895D - 0.442054AB \\ & +1.36468\times10^{-7}AC - 0.000242AD \\ & +9.11127\times10^{-6}BC - 0.036592BD \\ & +8.30877\times10^{-9}CD - 0.000635\times A^2 \\ & -83.65320B^2 + 1.59132*10^{-12}C^2 + 0.0002D^2 \end{aligned} \quad (1)$$

3.2 Fitting effect judgment

In order to judge the fitting effect of the equation, the fitting effect is judged based on the precision and accuracy of the regression equation. A normality test is performed on the residuals, and the results satisfy the normal distribution, indicating that the residual results are random. To visualize the normal probability, plot Figure 3, where all the points are scattered near the straight line. The data fits a normal distribution well, indicating a good overall fit of the model to the random errors. This also implies that the regression equation has a high level of accuracy in Figure 4(a). By using Design Experts 13 software for calculations, the model's precision reached 40.851, which is significantly higher than the ideal value of 4. The accuracy of the regression equation is determined by the fitting curve between the predicted values and the simulated values obtained from PMV. In Figure 4(b), the simulated values are similar to the predicted values, with a small experimental error, indicating a high level of accuracy in the simulation. Furthermore, the calculated R^2 value of 0.9569 from Design Experts 13 software for prediction is close to the actual R^2 value of 0.985, with a difference within the specified range of 0.2. This suggests a high degree of agreement between the predicted and actual values, indicating a good fit for the regression equation.



4(a)



4(b)

Figure 4. Normal Probability Plot in left. Fitting Curve of Predicted PMV Values and Simulated Values in right

In conclusion, the regression equation model established has shown good performance in terms of both precision and accuracy. Therefore, the model can be utilized for analyzing indoor thermal comfort variations.

3.3 Analysis of Multi-Factor Interactions

The regression equation's fit variance table is obtained by comparing the predicted values from the multivariate regression equation with the actual values. By evaluating the experimental results from the perspective of single-factor and two-factor angles, it can provide assistance in exploring the influence of multiple factors on indoor airflow conditions. The fit variance of the regression equation is shown in Table 3. In the table, the F-value represents the degree of influence, where a larger F-value indicates a higher degree of influence. The P-value reflects the variable's effect on the equation's fit. A smaller P-value implies a more reliable result.

Table 3. Variance analysis of fitted regression equations

Source	Sum of Squares	df	Mean Square	F-value	P-value	
Model	40.65	14	2.90	132.66	<0.0001	significant
A-Supply air temperature	10.60	1	10.60	484.41	<0.0001	
B- Supply air humidity	16.43	1	16.43	751.06	<0.0001	
C-Air supply volume	6.67	1	6.68	305.15	<0.0001	
D-Air supply angle	0.7645	1	0.764	34.93	<0.0001	
AB	0.095	1	0.0957	4.375	0.0552	
AC	0.794	1	0.7945	36.31	<0.0001	
AD	0.0413	1	0.0413	1.887	0.1911	
BC	0.1807	1	0.1807	8.257	0.0123	
BD	0.0482		0.0482	2.20	0.1599	
CD	0.2164	1	0.2164	9.888	0.0072	

Residual	0.3064	14	0.02188			
Lack of Fit	0.3064	10	0.0304			
Cor Total	40.95	28	Cor Total	40.95	28	

According to Table 3, the regression model has an F-value of 132.66, with a significance level of P<0.0001, indicating that the model is significant and has a good fit with high reliability. Based on the fitting results of the F-value and P-value in the single-factor analysis, we can determine the degree of influence of the four factors under investigation in the following order: humidity of the supply air > temperature of the supply air > air supply volume > air supply angle. This aligns with the actual control scenario. Regarding the interaction effects between the factors, the interaction between supply air temperature and supply air humidity shows the largest effect, while the interaction between supply air temperature and supply air angle shows the smallest effect.

To visually illustrate the impact of each factor on PMV, response surface plots are generated. The contour shapes in the response surface plot indicate the degree of interaction between two factors. When the contours are elliptical or saddle-shaped, it indicates a more significant interaction between the factors. On the other hand, when the contours are circular, it suggests that the interaction between the factors is less pronounced. The two-dimensional view of the response surface plot is shown in Figure 5.

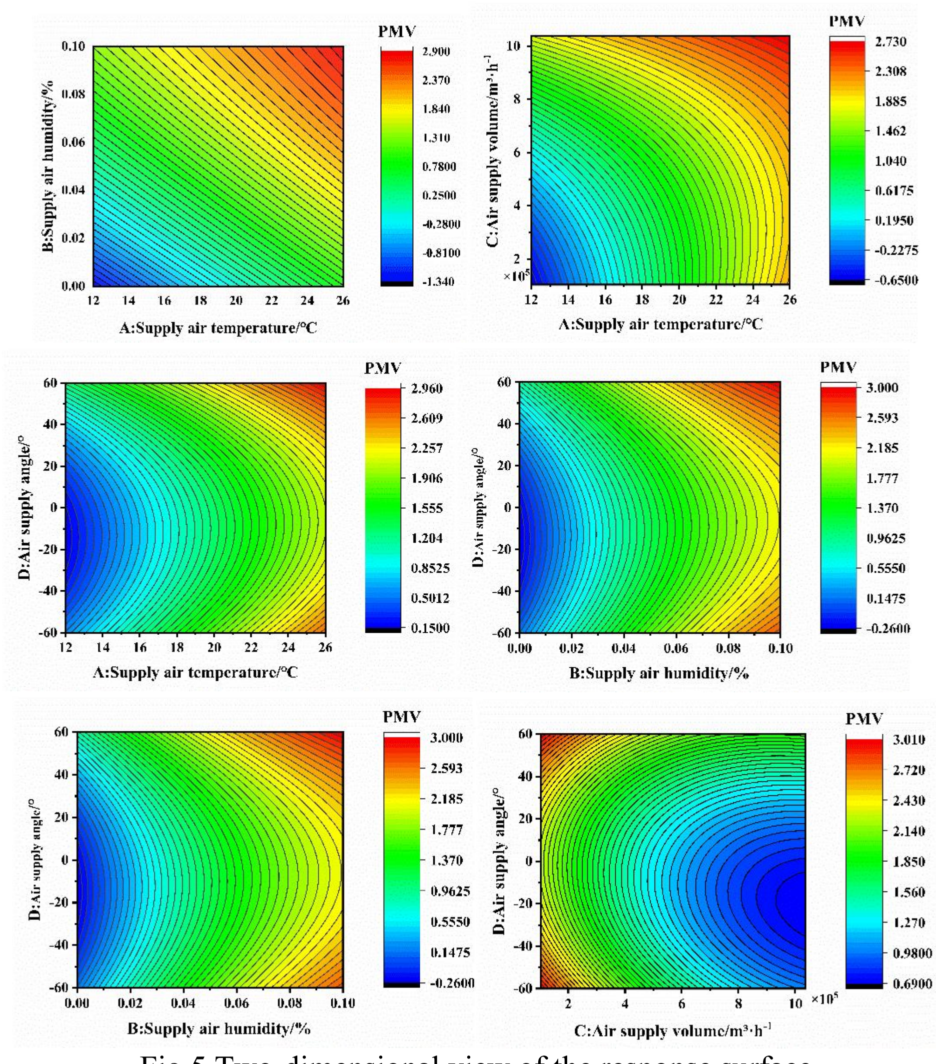


Fig.5 Two-dimensional view of the response surface

According to the numerical values in Table 3, it can be observed that supply air humidity and supply air temperature have the most sensitive impact on PMV. However, the contour lines in Figure 5, depicting the interaction between these two factors, appear smooth and the interaction is not significantly pronounced. The contour lines for supply air volume and supply air temperature, as well as supply air volume and supply air humidity, form circular patterns, indicating that the interaction between these factors is not significant. On the other hand, the contour lines between supply air angle and the other three factors form elliptical shapes, suggesting a significant interaction between them. Based on the trend of the contour lines, setting the supply air angle slightly below the horizontal position would result in better cooling effects. Range of factors influencing PMV: The higher the supply air humidity in summer conditions, the higher the PMV value. The PMV performs better within the range of 0.001% to 0.023% for supply air humidity. The supply air angle in the range of -10° to 10 °has a better impact on the results. The supply air temperature is an important influencing factor, with a range of 18°C to 20°C. The Air supply volume is inversely proportional to the supply air temperature.

In conclusion, the response surface analysis method can be used for sensitivity analysis of influencing factors, and the degree of influence of each factor on PMV can be determined to identify the optimization direction for the supply air scheme.

3.4 Analysis of Multi-Factor Interactions

Since supply air temperature and supply air humidity have an intuitive impact on PMV adjustment but have no interaction effect, both are simulated using the design range. On the other hand, supply air direction has a significant interactive effect on indoor comfort regulation with other factors. Therefore, the selection conditions for supply air direction are based on the experimental range to consider the overall impact. As for the air supply rate, it only has a strong interaction effect with the supply air direction and does not have a significant effect with the other two factors. Thus, no range specification is made for the air supply rate.

Based on the above, using Design Experts 13 for air supply scheme recommendation, the recommended scheme is to select the configuration that yields a simulated PMV value of 0. There are a total of 4 sets of recommended air supply schemes in Table 4.

Table 4. RSM decision-making air supply plan

	Supply air temperature （℃）	Supply air humidity（%）	Air supply angle （$m^3 \cdot h^{-1}$）	Air supply angle （°）
1	18.563	0.012	636413.591	2.398
2	18.310	0.002	449472.4625	-9.081
3	20.411	0.011	883858.2126	7.073
4	19.431	0.023	986775.7634	-11.959

Simulations are conducted in Airpak to validate the eight experimental schemes, and the results showed that the predicted scenarios are consistent with the results obtained from the experimental simulations. Therefore, when dealing with practical air conditioning supply environments, the response surface analysis method can be employed to provide the optimal air supply scheme.

4. Summary

This study combines the response surface Box-Behnken design with air conditioning comfort airflow design. Taking into account the influence of interaction effects, a linear regression equation model is established to provide universal airflow parameters for further optimization of radiant air conditioning. The experimental results of the study show that controlling the air supply humidity has the most significant impact on indoor air comfort compared to variations in air supply volume, air supply temperature, and air supply angle. The optimized air conditioning ventilation scheme through response surface design can effectively improve indoor comfort in large spaces. It provides valuable references for future research on radiant air conditioning supply and lays a solid foundation.

In the actual operation and control process, appropriate air supply design parameters can be selected according to different indoor conditions to further optimize air conditioning ventilation performance and provide better indoor comfort. Future research can also use energy consumption as an evaluation criterion for program optimization to further improve the practical application value of the research. At the same time, the application of this research in the field of radiation refrigeration and air conditioning can provide new ideas and methods for related research.

References

[1] Shan Peng, Yu Jinghua, Gang Wenjie, et al. Study on Load Characteristics of Different Air Conditioning Systems in Large Space Railway Station. IOP Conference Series. Earth and Environmental Science, vol. 238, no. 1, 2019, p. 12038.

[2] K.J. Chua, S.K. Chou, W.M. Yan, et al. Achieving Better Energy-Efficient Air Conditioning – A Review of Technologies and Strategies. Applied Energy, vol. 104, 2013, pp. 87–104.

[3] OHSHIRO, Masatoyo. AN AIR-CONDITIONING SYSTEM FOR LARGE SPACE: DEVELOPMENT OF AIR-CONDITIONING SYSTEM(Part2). Technical Papers of Annual Meeting the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 1995, pp. 1509–1512.

[4] Zhao Kang, Liu XiaoHua, Jiang Yi. Application of Radiant Floor Cooling in Large Space Buildings – A Review. Renewable & Sustainable Energy Reviews, vol. 55, 2016, pp. 1083–1096.

[5] YU Di Qi, Xue Shiwei, WU Xiaozhou, et al. Sensitivity analysis of indoor air distribution characteristics of radiant air conditioning. Jian Zhu Ke Xue, vol. 38, no. 6, 2022, pp. 188–196.

[6] Halawa Edward, van Hoof Joost, Soebarto Veronica. The Impacts of the Thermal Radiation Field on Thermal Comfort, Energy Consumption and Control—A Critical Overview. Renewable & Sustainable Energy Reviews, vol. 37, 2014, pp. 907–918.

[7] Shan, Xiaofang, LU Weizhen. “An Integrated Approach to Evaluate Thermal Comfort in Air-Conditioned Large-Space Office.” Science & Technology for the Built Environment, vol. 27, no. 4, 2020, pp. 436–450.

[8] LI Hongmin, QU Zong-Hao, Zhang Jia Rui, et al. Research on control strategy of variable air volume air conditioning system based on PMV value. Computer Ear, 2022, 7, 84–93.

[9] CHEN Jiong-De, Wang Zi-Xuan, ZHAO ye, et al. Research on nonlinear model predictive control method for variable air volume air conditioning system. ZHI LENG XUE BAO，2019，40(06):62-69.

[10] Raymond H. Myers, Douglas C. Montgomery, Christine M. Anderson-Cook. Response surface methodology (4th ed). Wiley, 2016.

[11] Bezerra Marcos Almeida, Santelli Ricardo Erthal, Oliveira Eliane Padua. Response Surface Methodology (RSM) as a Tool for Optimization in Analytical Chemistry. Talanta (Oxford), vol. 76, no. 5, 2008, pp. 965–977.

[12] Khuri, André I. Response Surface Methodology & Related Topics. 1st ed., World Scientific Publishing Co. Pte. Ltd, 2006.

[13] Liu Li Yao, Mao Jinfeng, Yun Changjiang, et al. Experimental study on cooling performance of separated heat pipe storage air conditioner. ZHI LENG XUE BAO, 2020, 41(2), 100–143.

[14] Zhang Bo Yue. Research on Air Distribution Design of Underground Powerhouse of Pumped Storage Power Station Based on Multi-objective Optimization Theory. Master's Theses, Tianjin University, 2020.

[15] Chen Huijuan, Moshfegh Bahram, Cehlin Mathias. Computational Investigation on the Factors Influencing Thermal Comfort for Impinging Jet Ventilation. Building and Environment, vol. 66, 2013, pp. 29–41.

[16] Mao Ning, Song Mengjie, Pan Dongmei, et al. Comparative Studies on Using RSM and TOPSIS Methods to Optimize Residential Air Conditioning Systems. Energy (Oxford), vol. 144, 2018, pp. 98–109.

[17] Xu Wei, ZHOU Yu, CHEN Xi, et al. National Standard Energy-saving Design Standard for Public Buildings GB50189-2015. Construction Technology, 2018(16):39-45.

[18] LU Yaoqing. Practical Heating and Air Conditioning Design Manual. Beijing: China Construction Industry Press, 2008.

[19] W.P. Jones, and Engineering Information, Inc. Air Conditioning Engineering. 5th ed., Butterworth-Heinemann, 2001.