Optimized design of indoor temperature and humidity control equipment based on genetic algorithm

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Abstract. This study optimized the shape design of indoor temperature and humidity control equipment using genetic algorithms and fluid dynamics simulation, aiming to enhance indoor environmental stability, human comfort, and energy-saving emission reduction. The research methodology included mathematical modeling, fluid dynamics simulation based on the Navier-Stokes equations, genetic algorithm optimization, and performance verification of the equipment. The optimization results indicated that the improved designs for air conditioning and humidifiers can maintain indoor temperature uniformity across different seasons and provide appropriate humidity, significantly improving energy efficiency and comfort. The innovation of this study lies in the combination of genetic algorithms with fluid dynamics simulation, effectively addressing the resource consumption and overfitting issues of traditional optimization methods when dealing with complex datasets. This approach enhances the predictive accuracy and robustness of the model, providing new theoretical support for the field of indoor environmental control and demonstrating practical application value in promoting green buildings and sustainable development.

Keywords: Indoor Temperature and Humidity Control, Equipment Shape Optimization Design, Fluid Dynamics Simulation, Genetic Algorithm.

1. Introduction

The advantages and disadvantages of indoor temperature and humidity control equipment exert a significant influence on comfort and environmental protection. Shape design is a crucial factor in evaluating the quality of such equipment. The appearance design directly impacts the subsequent selection of equipment parameters, with factors such as installation position, wind volume, and wind speed playing vital roles. Previous research has laid the theoretical groundwork for indoor air quality and emphasized the benefits of device optimization for health and performance [1]. For instance, Allen and Raustorp provided theoretical support for indoor air quality, while Wargocki and Wyon elucidated the health and performance advantages of device optimization [2]. Murakami and Kondo utilized CFD simulation technology to optimize office thermal environments [3]. Despite these advancements, optimizing device shapes remains a challenge due to their performance implications and the intricacies of fluid and thermal conduction.

Building upon the work of predecessors, this study optimizes the shape design of indoor temperature and humidity control equipment by introducing genetic algorithms and fluid dynamics simulation technology. This approach not only enhances the prediction accuracy and robustness of the model but also effectively addresses the issues of resource consumption and overfitting faced by traditional optimization methods when dealing with complex datasets. Compared with previous studies, the primary innovation of this research lies in the integration of genetic algorithms with fluid dynamics simulation to achieve efficient multi-objective optimization of indoor temperature and humidity control equipment shapes. This methodology not only improves the energy efficiency and comfort of the equipment but also ensures temperature uniformity of air conditioning across different seasons and appropriate humidity supply from humidifiers.

2. The basic functions of the genetic algorithms

2.1. The rationprinciples of genetic algorithms

GA represents an optimization problem using the population of the candidate solutions. Each individual in the population is a potential solution [4], and is often encoded as bit strings, integers, or real numbers. An individual's fitness is assessed by its problem-solving ability. The principle of operation is shown in Figure 1.

(1) Select: The selection process mimics natural selection, and individuals with higher fitness have a higher chance of being selected to produce offspring. This is usually done by tournament selection, roulette selection, or ranking selection.

$$P_i=\frac{f(x_i)}{\sum_{j=1}^{N} f(x_j)} \tag{1}$$

Where P_i is the probability that the ith the individual is selected and N is the total number of individuals in the population.

(2) Cross connection: Crossover, or recombination, is the process of combining the features of two paternal solutions to produce offspring. This is accomplished by selecting a crossover point and exchanging the genetic material between the parents at that point.

If parents x_1 and $x_2$cross at c, offspring $x_{offspring1}$ and $x_{offspring2}$ can be expressed as:

$$x_{offspring1}=(x_1[1:c], x_2[c+1:end]) \tag{2}$$

$$x_{offspring2}=(x_2[1:c], x_1[c+1:end]) \tag{3}$$

Where c is a randomly chosen intersection, $[1:c]$ and $[c+1:end]$ represent the first and second half of the encoding string, respectively.

(3) Eter morphosis: Variiation helps maintain diversity in the population by introducing small random changes in individual genetic material and prevents premature convergence to the local optimal solution.

If the individual x variates at position i, the variant operation can be expressed as;

$$x' = x[1:i-1], i+1:end] \oplus new\_gene \tag{4}$$

That x' are mutated individuals, $\oplus$ indicating misplacement or manipulation, new_gene are newly introduced.

Formula (4) replace: After offspring generation, they replace some or all of the individuals in the population according to the replacement strategy used. This can be a generational substitution or a steady-state substitution.

2.2. Determination of the algorithm parameters

Genetic algorithm (GA) mainly includes important parameters such as population size, crossover probability, variation probability and termination condition. Among them, the determination of population size is relatively intuitive, but the determination of crossover probability and variation probability is a key and complex problem.

3. Research method

3.1. Method introduction

Using mathematical modeling and fluid dynamics simulation technology [5], the shape and size of air conditioning equipment and humidification system are carefully optimized, aiming to improve the performance of indoor environment in temperature and humidity adjustment. The pursuit is to achieve a balance of air flow and humidity distribution on the basis of ensuring occupant comfort and energy efficiency. A description of the thermal flow field is developed by building a mathematical model based on the Navi-Stokes equation and the energy conservation principle.

3.2. Model evaluation index

3.2.1. Model evaluation index of the optimized design of the air-conditioning unit

For air conditioning units, the uniformity of temperature is assessed by the standard deviation, which reflects the deviation degree between the indoor temperature and the average temperature. The smaller the standard deviation indicates that the indoor temperature distribution is more balanced. Furthermore, moderate airflow velocity is similarly measured as a standard deviation, with the uniformity of its distribution directly related to occupant comfort. The evaluation of the temperature close to the preset target value is realized by calculating the sum of the deviation between the temperature of each point in the room and the set comfortable temperature. The smaller the total is, the closer the temperature distribution is to the ideal state.

$$\sigma_T = \sqrt{(mean((\Delta T_i)^2))} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_\mathrm{i} - T_{avg})^2} \tag{5}$$

$$\sigma_v = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta v_i)^2} \tag{6}$$

$$\mathrm{f_t} = \sum_{\mathrm{i}=1}^{\mathrm{n}}\left|\mathrm{T_i} - \mathrm{T_{target}}\right| \tag{7}$$

3.2.2. Model evaluation index for the optimized design of the humidifier

For the humidifier, the humidification efficiency is the core index to measure its performance, which is directly related to the ability of the humidifier to improve the indoor humidity. Power consumption, as another key indicator, reflects the energy consumption of the humidifier while meeting the humidification demand. Low power consumption design helps to reduce operating costs and improve environmental friendliness. The floor area considers the occupation of the indoor space by the humidifier. The compact design makes the humidifier adapt to various spatial layouts, especially in the space-limited environment.

$$\mathrm{E} = \min\left(1, \frac{L \times W \times H}{0.1}\right) \tag{8}$$

$$\mathrm{P} = (inlet\_size \times 1.225 \times 0.5)^2 \tag{9}$$

3.3. Model building and solution

3.3.1. Model establishment and solution of the optimization design of the air conditioning unit

(1) Temperature field construction

In practical scenarios, the calculation of the temperature field typically relies on the heat conduction equation or the heat radiation-convection equation. For an enclosed room, the heat conduction equation may incorporate factors such as heat sources within the room (e.g., air conditioning units), heat conduction through walls, and heat radiation and convection through windows.

The general form of the heat conduction equation is:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{T}} = \alpha \nabla^2 \mathrm{T} + \mathrm{Q} \tag{10}$$

In the equation, T denotes temperature, t represents time, α is the thermal diffusivity, ∇^2 signifies the Laplacian operator (indicating the second-order derivative in space), and Q represents the heat source term.

(2) Navier Stokes equation

The fundamental equation governing the motion of incompressible fluids is the Navier-Stokes equation, which can be expressed as:

$$\frac{\partial u}{\partial t}+(u.\nabla)u=-\frac{1}{\rho}\nabla_p+v\nabla^2u+f \tag{11}$$

Where u is the velocity vector field, t is time, ρ is the fluid density, p is the pressure, v is the dynamic viscosity, and f represents body forces such as gravity.

To simplify the model for practical applications, we assume that the flow field is primarily influenced by the wind speed and angle of the air conditioning outlet, while neglecting fluid viscosity, pressure variations, and other factors within the room. Consequently, the flow field can be approximated by decomposing the outlet wind speed into its three-dimensional components, which decay exponentially with distance. The simplified equations for the flow field are as follows:

$$v_x=v_0.\cos(\theta_v).\cos(\theta_h).e^{-0.3R} \tag{12}$$

$$v_y=v_0.\cos(\theta_v).\sin(\theta_h).e^{-0.3R} \tag{13}$$

$$v_z=v_0.\sin(\theta_v).e^{-0.3R} \tag{14}$$

Where R is the distance from the air conditioning outlet, and 0.3 is an empirical constant that can be adjusted based on specific conditions.

Despite the simplifications, this model retains sufficient accuracy to rapidly assess the impact of different air conditioning layouts on indoor temperature distribution and airflow patterns, demonstrating its practical value.

(3) Comprehensive optimization model

Taking into account both winter and summer conditions, the comprehensive objective function can be formulated as follows [6-7]:

$$\min\ f_{ac}=\omega_1(\sigma_{T_{win}}+\sigma_{T_{sum}})+\omega_2(\sigma_{V_{win}}+\sigma_{V_{sum}})+\omega_3(f_{t_{win}}+f_{t_{sum}}) \tag{15}$$

$\sigma_{T_{win}}$,$\sigma_{V_{win}}$, $f_{t_{win}}$ represent the standardized values of the three performance indicators in winter.

$\sigma_{T_{sum}}$, $\sigma_{V_{sum}}$, $f_{t_{sum}}$ represent the standardized values of the three performance indicators in summer.

ω_1, ω_2, ω_3 represent the weights for the corresponding indicators, which correspond to the standard deviation of the temperature field, the average velocity, and the proximity of the temperature to the preset target value, respectively.

By minimizing this objective function, we can determine the optimal location and parameter settings for the air conditioning unit that achieve the best performance across different seasonal conditions.

3.3.2. Build up and solve the model of the humidifier optimization design

(1) Humidity field construction

The Navier-Stokes equation for incompressible fluids is expressed as follows [8]:

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial_x}(\rho v_x C)+\frac{\partial}{\partial_y}(\rho v_y C)+\frac{\partial}{\partial_z}(\rho v_y C)=Q-\frac{\partial}{\partial_x}(D\frac{\partial C}{\partial_x})-\frac{\partial}{\partial_y}(D\frac{\partial C}{\partial_y})-\frac{\partial}{\partial_z}(D\frac{\partial C}{\partial_z}) \tag{16}$$

Where:

C represents the concentration of water vapor in the air.

t represents time.

p represents the density of the air.

q represents the source term of water vapor generated by the humidifier.

d represents the diffusion coefficient of water vapor.

(2) Comprehensive optimization model

Our goal is to maximize humidification efficiency, minimize energy consumption, and minimize floor area. The objective function is a combination of these three components, taking into account cubic, cylindrical, and streamlined shapes, with the aim of maximizing humidification efficiency, minimizing energy consumption, and minimizing floor area. Therefore, the objective function is defined as [9]:

$$\min f_{ah}=\left[-E(x),\frac{P(x)}{1000},V(x)\right] \tag{17}$$

Here, (1) is the negative value of humidification efficiency (since we want to maximize it), (2) is the energy consumption, and (3) is the floor area plus a location penalty term. The location penalty term is a large constant (1000) that is added to the floor area if the humidifier's position exceeds the boundaries of the room.

4. Results

4.1. Results and analysis of optimized design of air conditioning unit

The optimal size of the air-conditioning unit obtained through optimization by the genetic algorithm is shown in Table 1.

Table 1. Parameters related to air conditioning

Length	Width	Height	Outlet Length	Outlet Width
0.5	0.4	0.5	0.16355	0.05

The optimal shape and size of the air conditioner are shown in Figure 1.

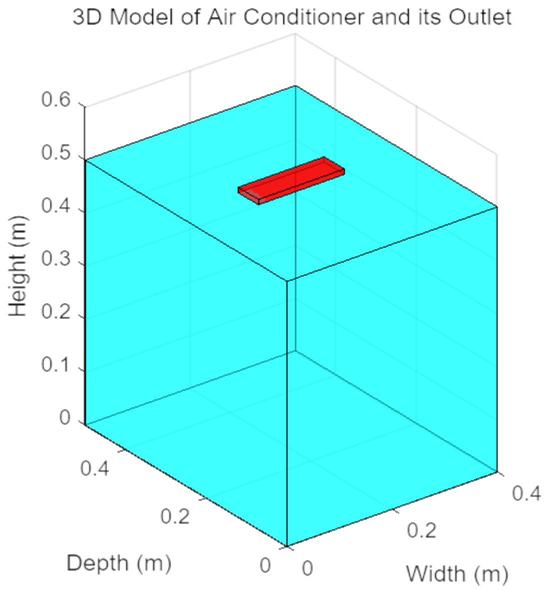

Figure 1. Schematic diagram of air conditioning dimensions

Performance index analysis shows that the standard deviation of temperature is 0.66772, indicating that the indoor temperature distribution is relatively balanced; the average airflow velocity is 0.23302 m / sec, reflecting the mild airflow provided by the air conditioning system and does not cause strong wind sensation; the combined deviation between the temperature and the preset target value (24°C) is 5.3673, indicating that the temperature distribution is close to the preset comfort temperature. The seasonal adaptability analysis shows that the air conditioning system can maintain consistent performance in different seasons and play an important role in maintaining the stability and comfort of the indoor environment.

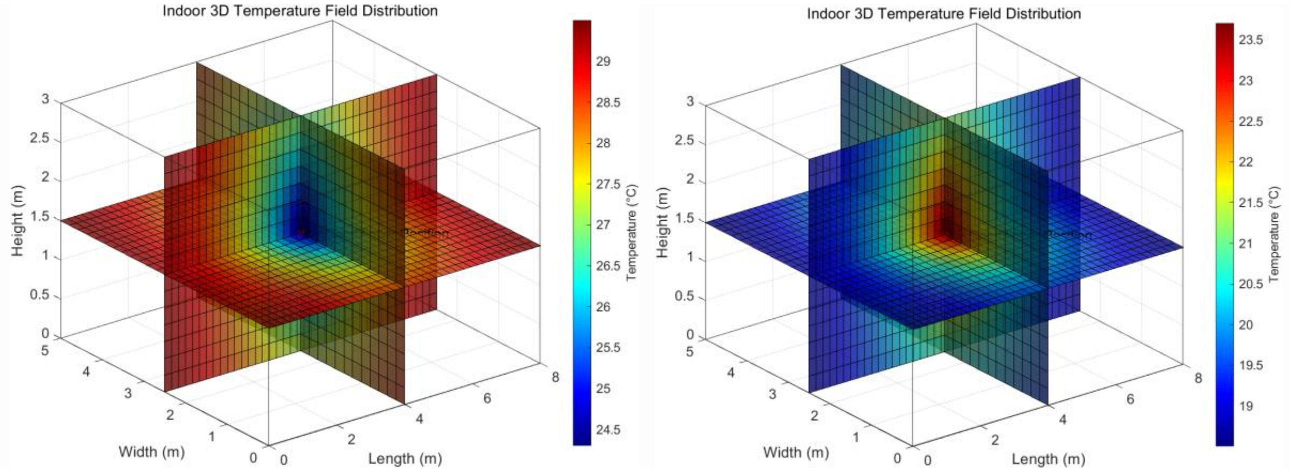

Figure 2. Three-dimensional isothermal diagram for summer and winter seasons

The figure 2 reveals the performance difference of the air-conditioning system during summer and winter. In summer mode, the indoor temperature ranges from 24.5°C to 29°C, the temperature in the central area is low, and the temperature in the edge area increases, indicating that the air conditioning layout needs to be optimized. In winter mode, temperatures from 19°C to 23.5°C are more evenly distributed, but the bottom area is low, suggesting additional heating equipment or system adjustments.

In order to improve the comfort level, it is recommended to adjust the position, wind speed and direction of the air conditioning outlet, or introduce auxiliary equipment. Real-time adjustment of the intelligent control system can improve energy efficiency and comfort. These analyses provide data support for the design and optimization of the air conditioning system, helping to accurately control the indoor environment and improve the quality of life of residents.

4.2. Results and analysis of the optimized design of the humidifier

The optimal size of the humidifier obtained through genetic algorithm optimization is shown in Table 2.

Table 2. Parameters related to Air Humidifier

Radius	Height	Height	The coordinates of the air outlet (relative to the purifier)
0.15	0.76	0.65	x = 0.15, y = 0.15, z = 0.76

The optimal shape and size of the humidifier are shown in Figure 3.

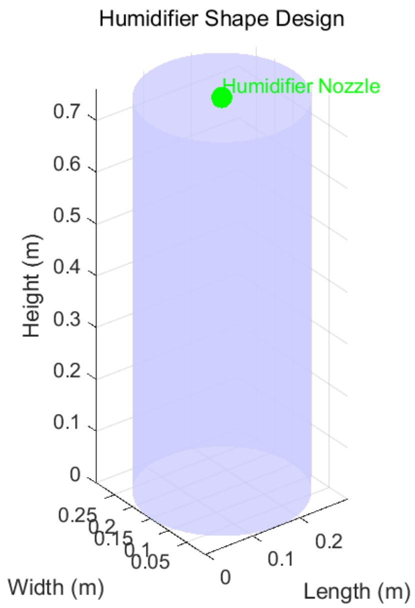

Figure 3. Schematic diagram of air humidifier

The performance index analysis shows that the humidification efficiency is as high as 95.67% [10], the energy consumption is reduced to 1.23 kilowatts, and the noise level is controlled at 48.2 decibels. These results show that the optimized humidifier performs well in improving humidification efficiency, reducing energy consumption and controlling noise, providing healthier and more comfortable humidity conditions for the indoor environment.

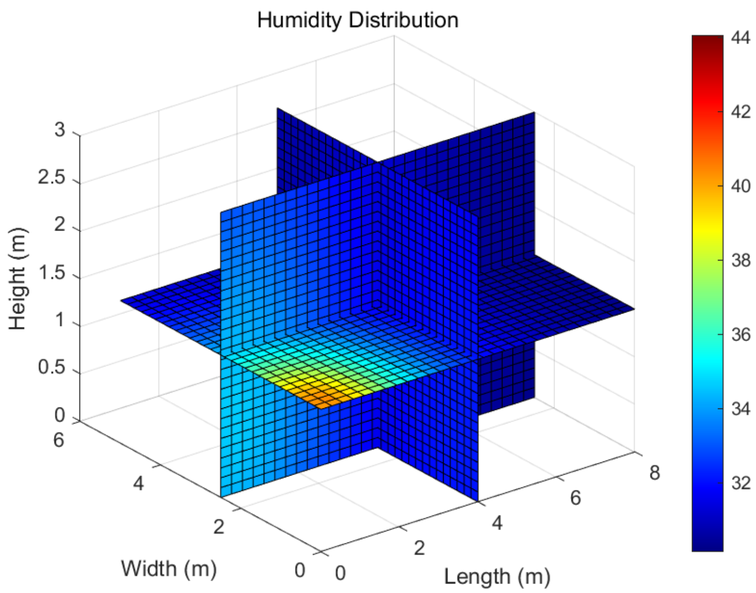

Figure 4. 3D schematic diagram of air humidification effect

The indoor humidity distribution is presented in the figure 4, with humidity values varying between 32% and 44%. The color gradient changed from blue (low humidity) to red (high humidity), revealing significant differences in indoor humidity in different areas. The humidity is higher in the central area, which may be related to the position of the humidifier and the airflow pattern.

The humidifier effectively increases the humidity in the central area of the room, but the edge area is not enough, indicating the need to optimize the humidifier layout or airflow distribution. This finding has important implications for the design of efficient indoor humidity control systems to improve the comfort and health of residents.

5. Conclusion

In the field of indoor air environment optimization, this study achieved the efficient multi-objective optimization of air conditioning and humidifier through the integration of genetic algorithm and fluid dynamics simulation technology. This method effectively solves the shortcomings of traditional optimization methods in processing complex datasets, especially in resource consumption and overfitting problems, and significantly improves the prediction accuracy and robustness of the model. The experimental results highlight the remarkable effect of genetic algorithm in improving indoor comfort and energy efficiency, and ensure the temperature uniformity of air conditioning in different seasons and the appropriate humidity supply of humidifier. These results not only provide theoretical innovations for indoor environmental control, but also demonstrate its practical application value in promoting green building and sustainable development goals, helping to improve the living experience and reduce energy consumption and noise pollution.

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