Research on the Optimal Design of Indoor Environmental Control Equipment Based on Fluid Dynamics and Genetic Algorithm

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Abstract. With the improvement of living standards, the comfort and health of indoor environments are increasingly valued by people. Devices such as air conditioners, air purifiers, and humidifiers are crucial for improving indoor environments. However, their structural design and control strategies directly affect the regulation effect. This study aims to improve the comfort and health of indoor environments while reducing energy consumption and enhancing energy efficiency by optimizing the design of indoor environmental control devices. For air conditioners, based on fluid dynamics and heat transfer principles, genetic algorithms are used to optimize the shape of air conditioners to achieve the best airflow and temperature distribution. For air purifiers, a fluid dynamics model based on the Navier-Stokes equations is constructed, and optimization algorithms are used to adjust the airflow path and shape of the purifier to maximize the filtration contact area, indicating that streamlined air purifiers perform best. This study promotes technological development and industry innovation, and promotes health and sustainability by optimizing the design of indoor environmental control devices using fluid dynamics and genetic algorithms.

Keywords: Indoor Environmental Control Equipment, Optimal Design, Genetic Algorithm, Fluid Dynamics.

1. Introduction

Indoor environmental comfort and health issues have become a focus of public concern. With the change of modern lifestyles, people spend a significant amount of time in indoor environments, and the demand for indoor environmental quality has increased accordingly [1]. Indoor environmental equipment, such as air conditioners, air purifiers, and humidifiers, plays a crucial role in improving indoor environments. However, the design and performance of these devices significantly impact the regulation effect of the indoor environment. Air conditioning systems are one of the main devices for regulating indoor temperatures. Their placement, design of intake and exhaust ports, wind speed, and volume all significantly affect the efficiency of the air conditioning [2]. In the summer, air conditioners need to quickly reduce indoor temperatures, while in the winter, they do not need to provide a heating environment. Air conditioners of different shapes exhibit different efficiencies in air distribution and energy consumption. Therefore, optimizing the shape and size of air conditioners is key to achieving the best temperature regulation effects.

Air purifiers improve indoor air quality by filtering and purifying air pollutants. Their shape and design directly affect the efficiency of air movement and purification effects [3]. Different shapes of air purifiers have different efficiencies and coverage ranges when dealing with particles and gas pollutants of different sizes. Therefore, exploring the impact of the shape of air purifiers on purification effects and establishing optimization models is of practical significance for designing more efficient air purifiers.

Li Jingguang's team [4] developed a low operating resistance ventilation air conditioning purification system and optimized the structural form and multi-parameter dynamic control strategy, solving the traditional system's inability to balance temperature, pollutant concentration, and energy consumption, significantly improving ventilation efficiency and reducing energy consumption. Qu

Wentao, by studying the variation rules of various variables in the central air conditioning system, used multiple regression analysis methods to obtain the regression equations of the variables and established a dynamic optimization model based on multi-objective programming, effectively reducing the system's total power consumption. Through literature review, the problems in the design of indoor environmental control equipment mainly focus on the neglect of environmental parameter space distribution, the impact of information feedback on group subjective evaluation, the implementation challenges of intelligent building system optimization strategies, and the lack of data-driven intelligent indoor environmental control frameworks [5], as well as the implementation difficulties of personalized thermal comfort control. Especially in the research direction of fluid dynamics and genetic algorithms, these limiting factors affect the precise control and energy consumption optimization of indoor environmental control equipment, requiring more interdisciplinary research to consider fluid dynamics, genetic algorithms, sensor technology, and intelligent control comprehensively, to achieve a more efficient, comfortable, and sustainable indoor environment.

Through literature research, it has been found that using fluid dynamics and genetic algorithms [6] to study and improve these issues. Therefore, this study uses these two methods for optimization design. Fluid dynamics can accurately simulate indoor air flow and heat exchange processes in the field of indoor environmental control equipment optimization design, which is crucial for improving energy efficiency and indoor comfort. At the same time, the application of genetic algorithms [7] has shown great potential in optimizing control parameters and spatial layout, as it seeks the optimal solution to problems by simulating the process of natural selection, which is particularly effective in multi-objective optimization problems. Therefore, this study is based on fluid dynamics and genetic algorithms for the optimization design of indoor environmental control equipment.

In summary, the structural optimization design of indoor environmental control equipment is moving towards the direction of intelligence, automation, and energy-saving [8], by adopting advanced control strategies and optimization algorithms, not only can improve the system's energy efficiency but also enhance the comfort of the indoor environment.

2. Research Methods

Based on the dataset published by Wei Jiaze in the Scientific Data journal, which collected hourly indoor air quality data for one year from 100 households across 18 provinces in four different climate zones in China on home air purifiers, this article aims to construct a model based on fluid dynamics and genetic algorithms for the efficiency and design issues of air conditioners and air purifiers. By simulating air flow and analyzing design parameters, it seeks to reveal performance bottlenecks and propose improvements to enhance the efficiency and energy-saving effects of the equipment.

2.1. Foundation of the Model

To address these issues, this study has established several physical models, primarily for simulating the indoor temperature distribution and airflow under the influence of air conditioning systems. Below is a summary of these physical models and their corresponding equations:

2.1.1. Three-dimensional heat conduction model

This fundamental model takes into account the heat diffusion process within the room, simulating the temperature distribution. The basic formula is Equation (1):

$$T_{new}(i,j,k) = T(i,j,k) + \alpha \cdot \Delta t \cdot \left(\frac{T(i+1,j,k) - 2T(i,j,k) + T(i-1,j,k)}{\Delta x^2} + \frac{T(i,j+1,k) - 2T(i,j,k) + T(i,j-1,k)}{\Delta y^2} \right. \tag{1}$$

Where T represents the temperature field, α represents the thermal diffusivity, Δt represents the time step, and Δx, Δy, Δz represent the sizes of the spatial grid cells.

2.1.2. Convection Model

The convection model simulates heat transfer caused by the movement of air. The calculation formula is shown as Equation (2):

$$\begin{aligned} T_{new}(i,j,k) &= T(i,j,k) + \alpha \cdot \Delta t \cdot \left(\frac{T(i+1,j,k) - 2T(i,j,k) + T(i-1,j,k)}{\Delta x^2} \right. \\ &\left. + \frac{T(i,j+1,k) - 2T(i,j,k) + T(i,j-1,k)}{\Delta y^2}\right) \\ &= T_{new}(i,j,k) + \alpha \cdot \Delta t \cdot \left(\frac{\nu_x(i,j,k) \cdot (T(i+1,j,k) - T(i-1,j,k))}{2\Delta x} \right. \\ &\left. + \frac{\nu_y(i,j,k) \cdot (T(i,j+1,k))}{2\Delta y}\right) \end{aligned} \tag{2}$$

ν_x,ν_y,$\nu_z$are the components of the velocity field.

2.1.3. Boundary Conditions

Boundary conditions simulate the impact of room walls on temperature changes. The calculation formula is as shown in Equation (3):

$$\begin{gathered} T_{new}(1,:,:,:) = \text{outside temp}, T_{new}(N_x,:,:,:) = \text{outside}_{temp}, \\ T_{new}(:,1,:,:,:) = \text{outside}_t\text{emp}, T_{new}(:,N_y,:,:,:) = \text{outside}_{temp}, \\ T_{new}(:,:,1,:,:,:) = \text{outside}_{temp}, T_{new}(:,:,N_z,:,:,:) = \text{outside}_{temp} \end{gathered} \tag{3}$$

Nx, Ny, Nz are the dimensions of the grid.

outside_{temp} Represents the external temperature.

2.1.4. Pollutant Diffusion Model

The pollutant diffusion model is based on Fick's Law, which describes the diffusion process of pollutants in the air. The one-dimensional form of Fick's Law is as shown in Equation (4):

$$J = -D * \frac{\partial C}{\partial x} \tag{4}$$

Here, J represents the flux of a pollutant (in moles per square meter per second), D represents the diffusion coefficient (in square meters per second), C represents the concentration of the pollutant (in moles per cubic meter), and x represents the spatial coordinate.

In three-dimensional space, Fick's law can be extended to the formula as shown in (5):

$$\frac{\partial C}{\partial t} = D * \nabla^2 * C \tag{5}$$

∇^2 Is the Laplacian operator, representing the second-order derivative in space.

2.1.5. Size and Position Optimization Model

This optimization model is used to find the optimal size and location of an air purifier in order to minimize the variation in indoor pollutant concentration. This involves defining the objective function and constraint conditions.

The objective function is given by formula (6):

$$\text{variance} = \text{var}(T(:)) \tag{6}$$

Constraint conditions: The volume of the air purifier must not exceed 0.1 cubic meters. That is $\pi r^2 h \leq 0.1$.

r represents the radius of the air purifier, and h represents the height of the air purifier.

2.2. Model Analysis

2.2.1. Heat Transfer and Fluid Dynamics Model

(1) Heat Conduction Equation

The propagation of heat conduction in a three-dimensional, isotropic, and homogeneous medium can be expressed using formula (7):

$$\frac{\partial u}{\partial t} = \mathrm{div}(Uu) = k\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = k\left(u_{xx} + u_{yy} + u_{zz}\right) \tag{7}$$

In this equation, u = u (t, x, y, z) represents the temperature as a function of time variable t and spatial variables (x, y, z), ∂u/∂t denotes the rate of temperature change with respect to time at a point in space, u_{xx}, u_{yy}, u_{zz} are the second derivatives of temperature with respect to the spatial coordinates x, y, and z. k is the thermal diffusivity, determined by the material's thermal conductivity, density, and heat capacity.

(2) Navier-Stokes Equations

The Navier-Stokes equations describe the motion of fluids (such as air). Assuming an incompressible fluid, these equations can be simplified to formula (8):

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u + f \tag{8}$$

This equation takes into account the inertial forces, pressure gradient forces, and viscous forces of the fluid.

2.2.2. Pollutant Diffusion Model

The diffusion equation models the dispersion of pollutants in the air. In three-dimensional space, its equation is presented as in formula (9):

$$\frac{\partial C}{\partial t} + u \cdot \nabla C = D \nabla^2 C \tag{9}$$

This equation combines advection (the transport of pollutants caused by the wind velocity vector u) and diffusion (the molecular movement described by the diffusion coefficient D).

2.2.3. Optimization Model

(1) Optimization of Temperature Regulation:

The optimization objective of temperature regulation is to minimize the difference in indoor temperature distribution in order to achieve a uniform temperature field. The specific formula is given by formula (10):

$$\min \sigma_T^2 = \min \frac{1}{V} \int_V (T - \bar{T})^2 \, dV \tag{10}$$

This optimization problem seeks a configuration where the temperature at all points in the room is as close as possible to the target temperature $\bar{T}$.

(2) Optimization of Air Purification:

The optimization objective of air purification is to maximize purification efficiency, which means reducing indoor pollutant concentrations, as shown in formula (11):

$$\max \eta = \max\left(1 - \frac{C_{out}}{C_{in}}\right) \tag{11}$$

This optimization problem aims to maximize the efficiency of the air purifier by minimizing the pollutant concentration at the outlet relative to the inlet concentration.

3. Model establishment and solution

3.1. Research on Air Conditioning Efficiency

3.1.1. Model Establishment

(1) Iterative Solution Method

At each time step, the article uses an iterative solution technique to update the temperature field [9].

① Initialization: Set the initial temperature field based on the initial conditions of the room and the activation status of the air conditioning.

② Iterative process: For each time step, use the finite difference method to calculate the delayed new temperature distribution. This involves updating the temperature at each grid point and considering the heat conduction and advection effects from adjacent grid points.

③Convergence check: At the end of each time step, verify whether the change in the temperature field conforms to the predefined curve. If it does, proceed to the next time step; if not, repeat the iteration until convergence is achieved.

(2) Initial Conditions

① Room dimensions: Lx = 5 m, Ly = 8 m, Lz = 3 m.

② Initial temperature: The initial temperature in summer is 30°C, and in winter it is 10°C.

③ Outdoor temperature: The outdoor temperature in summer is 35°C, and in winter it is 5°C.

④ Target temperature: The target temperature is 22°C.

3.1.2. Model Solution

Based on the simulation results shown in Figure 1, the following conclusions are:

(1) Impact of AC shape and size: The simulation results indicate that air conditioners of different sizes have a significant impact on indoor temperature distribution. Among the three sizes provided, the smaller air conditioner (0.1 * 0.7 * 0.7 meters) exhibits lower temperature variations in both summer and winter, indicating that it can more effectively and uniformly distribute indoor temperature.

(2) Performance differences between summer and winter: For all tested air conditioner sizes, temperature variations are generally higher in winter than in summer. This may be due to the lower outdoor temperature in winter, which requires more energy for the air conditioner to heat the indoor space, resulting in a more uneven temperature distribution compared to summer.

(3) Optimization of air conditioner design: Based on the simulation results, the optimized air conditioner design is a rectangular unit with dimensions of (0.1 * 0.7 * 0.7) meters. This design results in lower temperature variations in both summer and winter, indicating that it can effectively regulate indoor temperature in different seasons and achieve a more uniform temperature distribution.

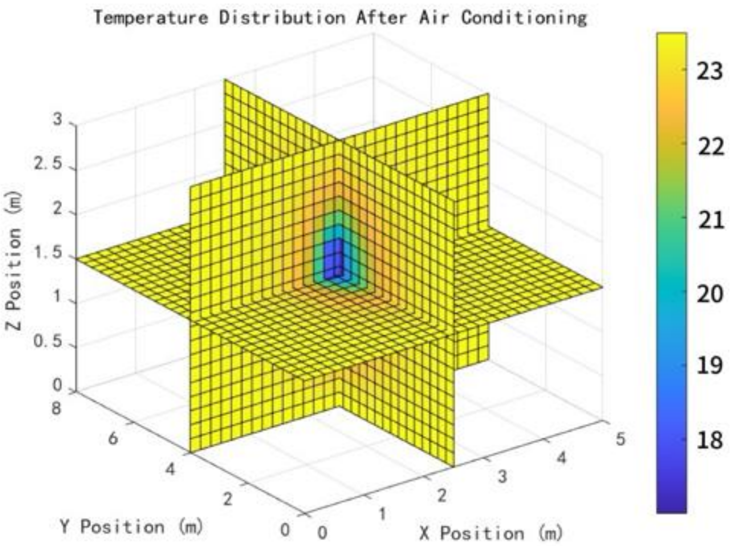

Figure 1. Temperature Distribution after Air Conditioning Treatment.

3.2. Study on the Purification Effect of Air Purifiers

3.2.1. Model Establishment

(1) Volume Constraint Model

Established through Equation (12):

$$V = \Pi * \text{ radius }^2 * \text{ height} \tag{12}$$

The constraint equation is established as Equation (13):

$$\text{ceq} = \Pi * \text{ radius }^2 * \text{ height } - 0.1 \tag{13}$$

Where ceq represents the equality constraint, and params: a vector containing the radius and height of the air purifier, used to ensure that the volume of the air purifier does not exceed 0.1 cubic meters.

(2) Air Purifier Mask Model

For a cylindrical air purifier: Create a boolean mask representing the location of the air purifier in the grid, with the specific formula as (14):

$$(i - cz)^2 + (j - cy)^2 + (k - cx)^2 \leq (\text{ radius } / dx)^2 \tag{14}$$

The parameters include (cx, cy, cz) as the grid coordinates of the air purifier's center, shape as the shape of the air purifier with current support for circles, size as the dimensions of the air purifier which for a circle are the radius and height, position as the central location of the air purifier, nx, ny, nz as the dimensions of the grid, and dx, dy, dz as the spacing of the grid.

(3) Pollution Concentration Simulation Model

Based on the iterative formula (15):

$$T_{\text{new}} = 0.9 \times T + \alpha \times (\text{ The sum of adjacent concentrations.-}6 \times T) \tag{15}$$

T is the current pollution concentration matrix, and T_new is the updated pollution concentration matrix, simulating the change in pollution concentration during the operation of the air purifier.

3.2.2. Model Solution

Firstly, the design parameters of two different shapes of air purifiers were optimized using a genetic algorithm, and the purification efficiencies of the streamline and cubic structures were compared. It was determined that the streamline air purifier had better performance under the given constraints.

Secondly, three-dimensional models of the air purifiers were created and presented, including their structures, components, and optimized designs, revealing the performance and characteristics of different designs. The visualization results are shown in Figures 2 to 4:

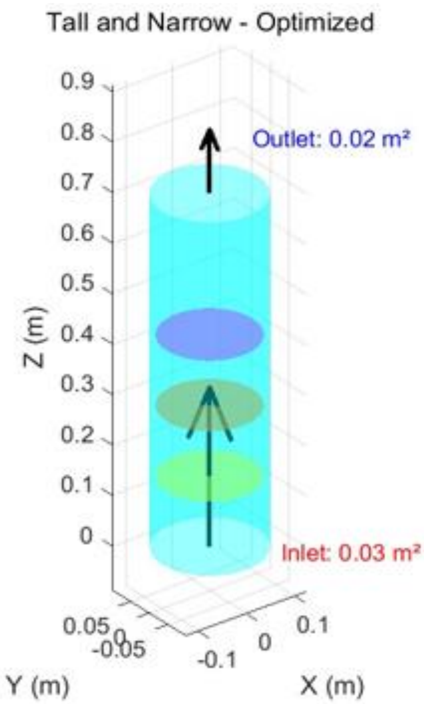

Figure 2. Effect of a tall and narrow type air purifier.

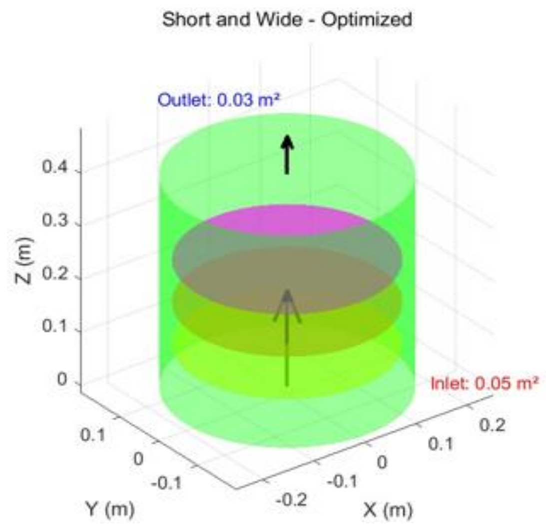

Figure 3. Effect of a short and stubby type air purifier.

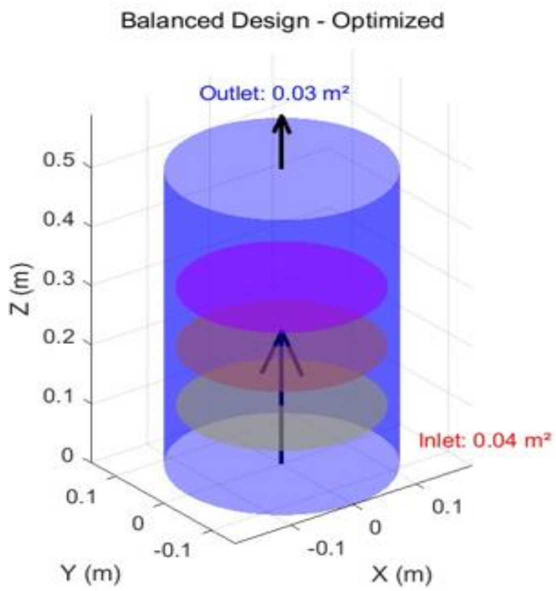

Figure 4. Effect of a moderately sized air purifier.

Based on the visualization results, the following conclusions are summarized in Table 1:

Table 1. Comparison of Air Purifiers of Different Shapes.

Design Type	Parameters	Advantages	Disadvantages	Applicable Scenarios
Tall and Narrow	Radius: 0.10m, Height: 0.70m	Rapid vertical airflow, high efficiency, small footprint	Less stable, limited purification range	Small rooms or elongated rooms
Short and Wide	Radius: 0.20m, Height: 0.40m	Strong stability, high airflow, full room coverage	Large footprint, weak vertical airflow	Medium to large rooms
Balanced Design	Radius: 0.15m, Height: 0.50m	Balanced design, adapts to various layouts	Overall performance is balanced but not extremely optimized	Common household environments

Finally, using the optimized execution model, we set an initial guess value initial guess to output the optimal results and maximum purification efficiency. The optimal air purifier dimensions and location were found through the optimization algorithm. The results are as follows:
The optimal air purifier size: radius of 0.36m, height of 0.25m, inlet position at 0.00m, and outlet position at 0.99m, with a maximum purification efficiency of 0.96.

4. Conclusions

In light of the escalating global climate change and energy crisis, indoor environmental control technology is playing a more critical role in enhancing energy efficiency and living comfort [10]. Traditional air conditioning and air purification devices have limitations in their design and performance, failing to fully meet the demands of modern homes and commercial spaces for efficiency, energy conservation, and a healthy environment.

This study, set against this backdrop, offers a novel perspective on the design of indoor environmental control devices through innovative modeling and optimization approaches. Utilizing mathematical modeling and genetic algorithms for optimization, the air conditioning units designed are capable of more effectively achieving uniform indoor temperature distribution throughout both summer and winter, significantly boosting energy efficiency. Moreover, the development of fluid dynamics models and the application of optimization algorithms have enabled the maximization of the air purifier's filtration contact area, thus enhancing air purification efficiency.

This research not only advances the field of indoor environmental control technology but also provides a scientific foundation and practical guidance for creating sustainable indoor environments, holding the potential to exert a profound influence on future indoor environmental control technologies.

In the future, by integrating artificial intelligence and machine learning technologies, intelligent control algorithms and adaptive optimization strategies can be developed to enable indoor environment control devices to automatically adjust operating parameters and control strategies based on real-time data of indoor and outdoor environmental changes, user behavior habits, and device operating states, thereby achieving intelligent and personalized environmental control.

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