Research on Optimization Model of Air Conditioners and Air Purifiers Based on Fluid Mechanics

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Abstract. This study focuses on the optimization model of air conditioners and air purifiers, which is conducted through in-depth exploration based on fluid mechanics and aerodynamics principles and genetic algorithm (GA) model. A physical model of the indoor environment including wall-mounted air conditioners and air purifiers is established. On the mathematical modeling level, the continuity equation, momentum equation, energy equation, and pollutant diffusion equation are comprehensively applied to rigorously control the laws of indoor airflow, temperature, energy transfer, and pollutant transport. This research provides a solid foundation for the scientific layout and precise parameter adjustment of air conditioners and air purifiers combined systems, and effectively guides the optimization of equipment operation strategies. It has crucial guiding value and practical significance for enhancing indoor environmental comfort, efficiently purifying the air, and safeguarding human health.

Keywords: Fluid Mechanics, Genetic Algorithm, Computational Fluid Dynamics.

1. Introduction

With the escalating demands for indoor environmental quality in modern society, air conditioners and air purifiers, as the crucial equipment for regulating indoor temperature and humidity and purifying the air, have garnered significant attention regarding their performance optimization. Conventional air conditioners and air purifiers often encounter numerous limitations during the design and operation processes [1].

This research is aimed at conducting a comprehensive and in-depth exploration of the optimization models for air conditioners and air purifiers in accordance with the principles of fluid mechanics, by means of the integrated utilization of various advanced technologies and approaches. The goal is to optimize the shape and size of air conditioners so as to maximize their temperature adjustment efficiency. The optimization results not only need to meet the constraints of volume and wind speed but also have to enhance the performance of air conditioners and guarantee high efficiency. In practical uses, selecting appropriate optimization algorithms and reasonable design parameter constraints can notably enhance the performance and energy efficiency of air conditioners. In this part, the genetic optimization algorithm is employed to optimize the design parameters of air conditioners for maximizing their temperature adjustment efficiency. This research is devoted to optimizing the design of air conditioners to improve the temperature adjustment effect. Under such circumstances, it is essential to construct a model based on factors like the shape, size, and airflow of air conditioners, and to search for the optimal solution through the genetic optimization algorithm.

In the optimization study of air conditioners, the placement, inlet and outlet design, and air speed and volume of air conditioners have significant impacts on their performance. The shape and size of air conditioners were optimized using the GA to achieve the goal of uniform temperature distribution and rapid reaching of the set temperature, while considering the volume and inlet and outlet area restrictions. The optimal shape was determined, which significantly reduced the temperature variance.

In the optimization process of air purifiers, the mechanism of the influence of shape on purification effect was deeply explored, the characteristics of axial airflow in cylindrical purifiers and their advantages and disadvantages, as well as the influence of shape change on the contact with pollutants and the stability of airflow. A genetic algorithm was used to construct an optimization model, and the purification efficiency, purification dead zone, and fan power consumption were integrated into the fitness function as multi-objectives [2]. After multiple generations of iterative evolution, the optimal design scheme including diameter, height, etc. was determined, effectively enhancing the performance of air purifiers and providing a more optimal solution for improving indoor air quality.

2. Genetic Algorithm Foundation and Adaptability

The Genetic Algorithm is a type of random search optimization algorithm that simulates the natural evolution process. It is based on Darwin's "survival of the fittest and elimination of the weak" evolutionary theory, and iteratively searches for the optimal solution by performing genetic operations (selection, crossover, mutation) on the population individuals [3]. In the context of optimizing the shape of air purifiers, its adaptability is significant: Traditional optimization methods often encounter bottlenecks when modeling and solving the complex, multi-variable, and non-linear relationship between the shape of air purifiers and their purification effects, while the genetic algorithm does not require a precise mathematical model to describe the complex relationship between the objective function and the constraints. It only evaluates the superiority of individuals based on the set adaptability function, which is well suited to the difficult problems of optimizing the shape of air purifiers, such as the ambiguity of the optimization goal and the constraints imposed by multiple factors (such as airflow, filter layout, and spatial positioning). It can flexibly search for the optimal solution in the vast shape design solution space [4].

3. Investigation of Fluid Field Distribution and Purification Efficiency through Experimental Measurements

3.1. The establishment of Air Conditioning simulation model

This section focuses on optimizing the shape and size of air conditioners to maximize their temperature adjustment efficacy. The optimization outcomes are required not only to satisfy the limitations of volume and wind speed but also to enhance the performance of air conditioners while guaranteeing high efficiency. In practical applications, choosing appropriate optimization algorithms and reasonable design parameter constraints can conspicuously improve the performance and energy efficiency of air conditioners. In this section, one intelligent optimization algorithms, namely GA, are employed to optimize the design parameters of air conditioners, thereby maximizing their temperature adjustment efficacy [5].

3.1.1. The Influence of Air Conditioner Placement

Boundary conditions:

(1) Wall boundary is adiabatic boundary: $\frac{\partial \mathrm{T}}{\partial \mathrm{n}} = 0$

(2) The air-conditioning outlet temperature is fixed as follows: T_{out}

(3) The air flow rate at the air-conditioning outlet is: v_{out}

Close to heat sources or cold sources: If an air conditioner is placed close to an indoor heat source, its cooling load will increase in summer as it needs to constantly counter the additional heat inflow[6]. Conversely, in winter, being close to a cold source (such as an uninsulated exterior wall or window) will reduce the heating efficiency as heat is prone to being lost to the cold source. The temperature change in the room is controlled by the heat conduction equation:

$$\frac{\partial T}{\partial \mathrm{t}} = \alpha \nabla^2 T + \frac{q}{\rho c_p} \tag{1}$$

Among:

①α: Thermal diffusion coefficient, k:The thermal conductivity, ρ:The air density, for the specific heat capacity:$\alpha = \frac{k}{\rho c_p}$

②Q: Strength of the heat source indicates the heat released by the air conditioner.

In the center of the room: Positioning the air conditioner in the center of the room theoretically enables the cold or hot air to be distributed more uniformly throughout the entire room. However, if the room layout is irregular or there are partitions, the effect might be influenced. For instance, in a long and narrow room, the center location may lead to suboptimal temperature regulation at both ends.

3.1.2. The influence of the Position, Quantity, Direction and Angle of the Intake and Exhaust Ports

The position, quantity, direction and angle of the intake and exhaust ports of the air conditioner need to be considered. If the intake port is close to a pollution source, more impurities will enter, affecting efficiency and air quality and increasing filter replacement frequency. The exhaust port should avoid blowing directly at people and valuable or temperature-sensitive items. Multiple intake and exhaust ports can contribute to more uniform air circulation, but for small household air conditioners, too many may increase costs and complexity and cause chaotic airflow. Horizontally, an adjustable angle of the exhaust port can adapt to different room shapes, and in summer and winter, blowing cold and hot air at certain angles can improve the indoor temperature effect. Vertically, for rooms with a higher floor height, increasing the installation height and adjusting the downward angle of the exhaust port can facilitate better vertical air circulation and avoid temperature differences between floors.

3.1.3. The Impact of Wind Speed and Air Volume

The airflow follows the Navier-Stokes equations.

$$\rho\left(\frac{\partial T}{\partial n} + (v \cdot \nabla)v\right) = -\nabla_p + \mu\nabla^2 v + F \tag{2}$$

Among:

μ:Air viscosity

(1) Wind Speed v_{out}:

A higher wind speed enables air to reach every corner of the room rapidly. However, an overly high wind speed might generate noise and, in summer, intensify the discomfort caused by the direct blowing of cold air on the human body. In winter, an excessively high wind speed may lead to the warm air being blown out before it has sufficient time for heat exchange, thereby reducing the heating efficiency.

(2) Air Volume Q_{out}:

Sufficient air volume is the foundation for an air conditioner to effectively adjust the temperature. In summer, a large air volume can rapidly lower the indoor temperature. However, when the temperature approaches the set value, appropriately reducing the air volume can maintain temperature stability and lower energy consumption. The same principle applies in winter. An appropriate air volume can ensure the even distribution and stability of indoor heat. The relationship between air volume, outlet area A, and wind speed v is:

$$Q_{out} = A \cdot v \tag{3}$$

High wind speeds can lead to increased energy consumption. A defined energy consumption target function can be used:

$$J_3 = P_{input} = \frac{1}{2}\rho v_{out}^3 A \tag{4}$$

Overall objective function:

$$J = J_1 + \gamma J_2 + \beta J_3 \tag{5}$$

3.1.4. Simulation of Indoor Temperature Changes over Time and Space under Different Conditions in Summer and Winter

Optimization of air conditioning placement:

① Define the air conditioning placement (x, y, z)

② Optimization objective: uniform distribution temperature, that is, minimize the objective function: $T_{(x,y,z)}$

$$J_1 = \int \left[T_{(x,y,z)} - T_{taret} \right]^2 dV \tag{6}$$

Among: T_{taret} is the target temperature.

$$J_2 = \int_v \left| v(x,y,z) \right|^2 dV + \lambda \int_v \left[T_{(x,y,z)} - T_{taret} \right]^2 dV \tag{7}$$

Among : λ is the weight coefficient.

(1) Summer Simulation:

Outside temperature:

$$T_{outdoor} > T_{target} \tag{8}$$

Modeling the conduction of heat through walls:

$$q_{wall} = -k_{wall} \frac{\partial T}{\partial t} \tag{9}$$

Suppose the initial external environment temperature is 35°C, the initial indoor temperature is 30°C, and the target temperature is 22°C. At the initial stage of air conditioner operation, the temperature in the area close to the air outlet drops rapidly, forming a low-temperature zone. The temperature distribution is shown in Figure 1. As time progresses, the cold air gradually diffuses to the surroundings. Due to the sinking of cold air, the temperature in the lower part of the room decreases relatively quickly, while the upper part of the room is affected by convection and the temperature drop is slightly slower. The temperature distribution is shown in Figure 2. After a certain period, the temperature of the entire room gradually approaches the set value. However, there might be situations where the temperature in corners or areas far from the air conditioner is slightly higher than the set value, such as the corners of the room. With the further passage of time, the air conditioner maintains the indoor temperature stable through intermittent operation and keeps it fluctuating around the set value.

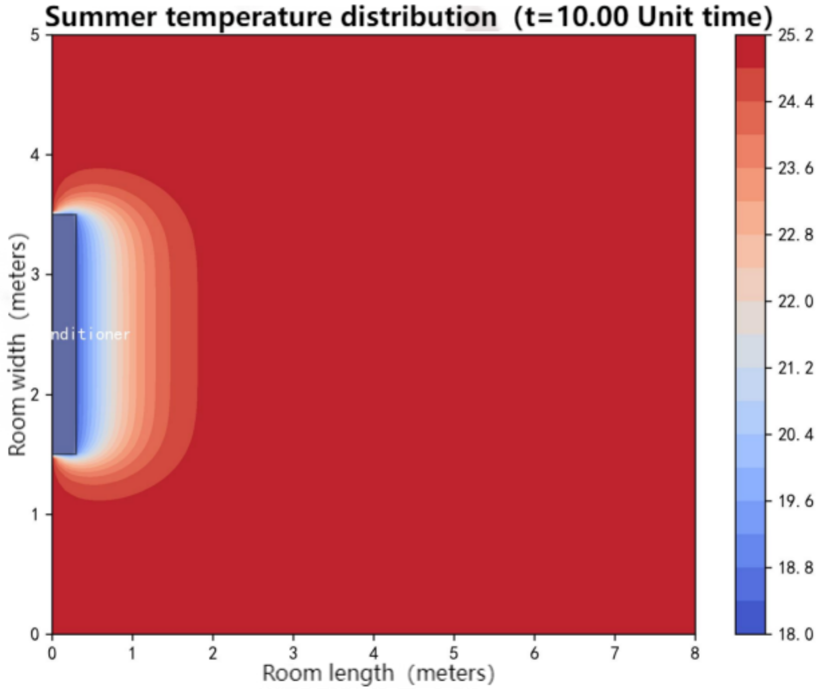

Figure 1. Two-dimensional temperature distribution

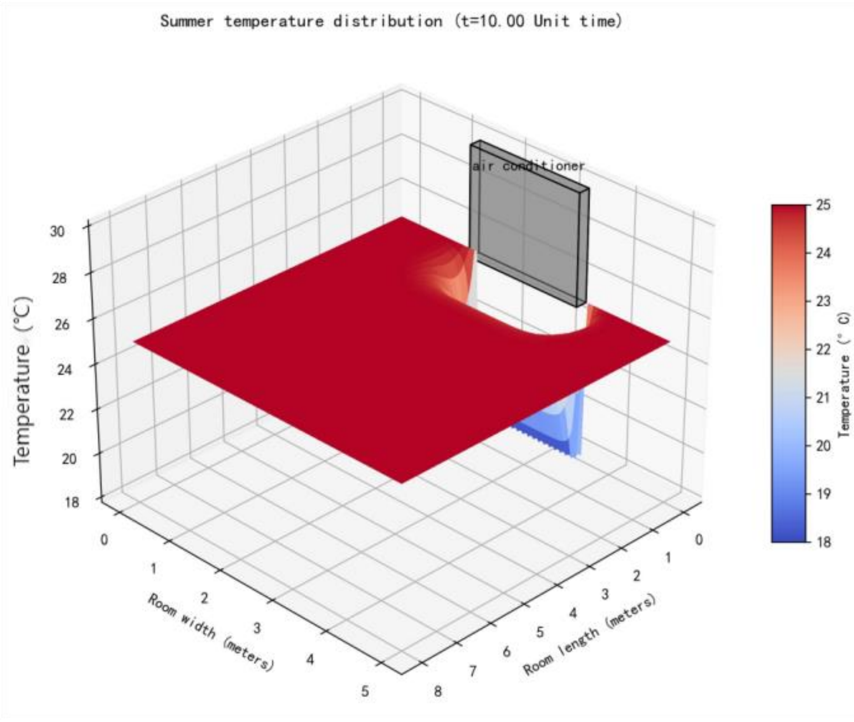

Figure 2. Three-dimensional temperature distribution

(2) Winter Simulation:

Outside temperature:

$$T_{outdoor} < T_{target} \tag{10}$$

The initial external environment temperature is 5°C, the initial indoor temperature is 10°C, and the target temperature is 22°C. After the heating is initiated, the hot air blows out from the air outlet of the air conditioner and ascends, causing the temperature in the upper part of the room to rise first and then gradually spreads downward. The temperature distribution is shown in Figure 3. However, as the hot air rises, it mixes with the surrounding cold air, resulting in certain heat transfer losses. Therefore, in the initial stage, there is a significant temperature difference between the upper and lower layers of the room. The temperature distribution is shown in Figure 4. As time elapses, the temperature in the lower layer gradually increases. When it approaches the set temperature, the air conditioner operates at a low power to maintain the temperature stable.

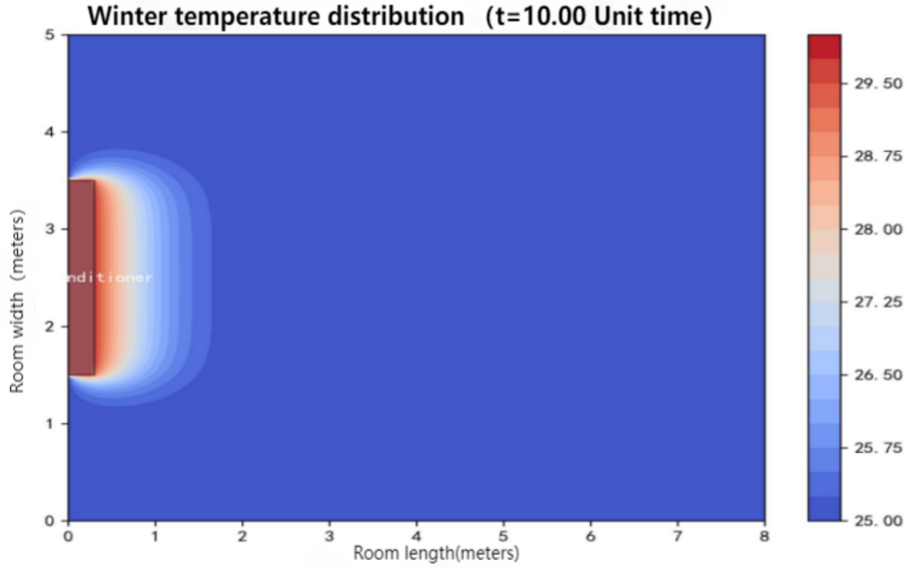

Figure 3. Two-dimensional temperature distribution

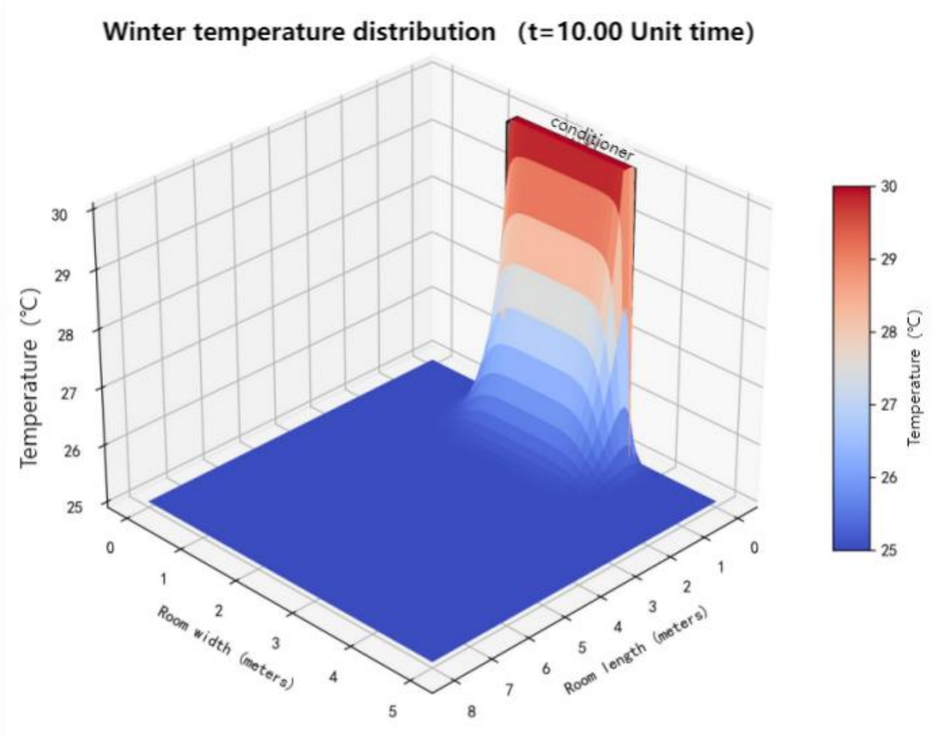

Figure 4. Three-dimensional temperature distribution

3.1.5. Establishment of Optimization Model for Air Conditioner Shape and Design of Optimal Shape and Size

The objective function is to achieve indoor temperature uniformity and minimize the time to reach the set temperature. The uniformity of temperature can be measured by calculating the variance of temperatures at different locations indoors. A smaller variance indicates a more uniform temperature. The time to reach the set temperature can be determined by simulating the difference between the average indoor temperature and the set temperature at different time points for various air conditioner shapes. The time when the difference first approaches zero is considered the time to reach the set temperature.

Based on market demands and installation space constraints, the volume range of the air conditioner is determined. For household wall-mounted air conditioners, the volume should not be overly large, as it would affect the indoor aesthetics and occupy excessive space. Also, it is necessary to ensure that the air inlet and outlet have sufficient areas to meet the air volume requirements. Simultaneously, the rational layout on the surface of the air conditioner should be considered to avoid affecting the smoothness of air intake and exhaust and the airflow distribution due to overly large or small areas.

By analyzing the above objective function and constraints, the optimal shape and size of the air conditioner can be determined using genetic algorithms. The 3D model of air conditioner is shown in Figure 5. The population distribution based on genetic algorithm is shown in Figure 6.

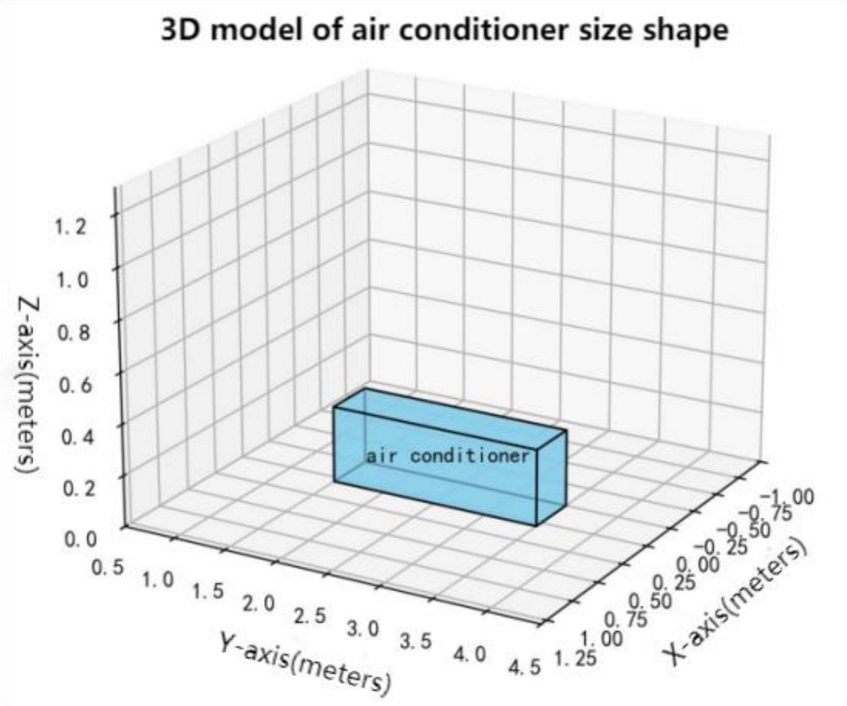

Figure 5. 3D_model

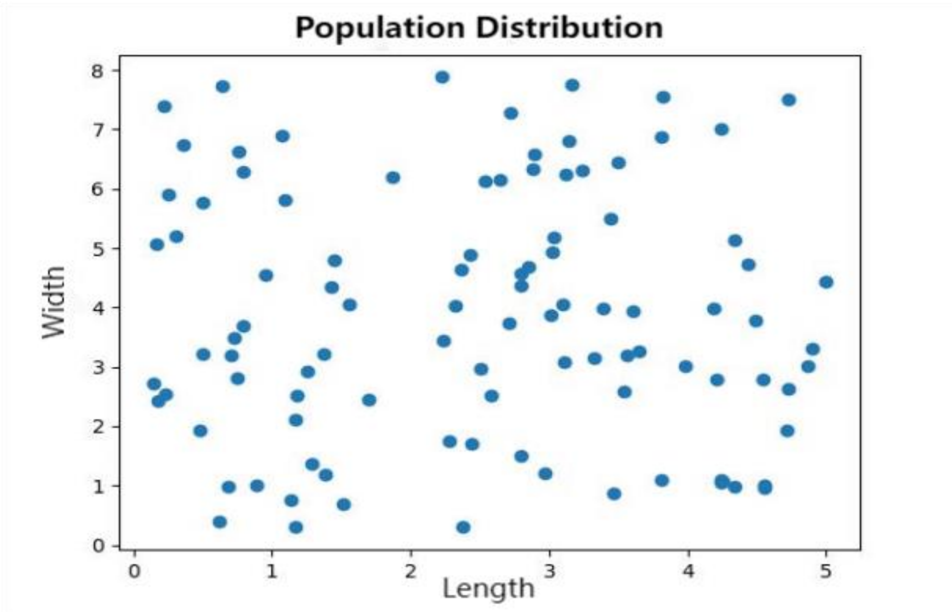

Figure 6. GA

3.2. The Establishment of Air Purifier simulation model

3.2.1. The Underlying Logic of How Shape Affects Purification Effect Airflow Guidance and Distribution Patterns:

Cylindrical purifiers mainly follow the axial airflow pattern. The intake port is usually located at the bottom or on the side. The airflow makes pollutants ascend vertically, and the purified air is discharged from the top outlet. This "vertical" flow pattern results in a considerable flow velocity in the central axis area, resembling a high-speed channel. However, the edge areas turn into "slow lanes", easily causing the surrounding air to stagnate and creating "grey zones" in the purification coverage. Nevertheless, its slender shape is suitable for being placed in corners and other recesses, effectively revitalizing the local air microcirculation and showing a specific preference for purifying the areas adjacent to the walls [7].

The concentration of pollutants in space is expressed as: C (x,y,z) to express, Unit is ppm. The purifier's shape is represented by the geometric function f(x,y,z), with the shape parameter set to express, Unit is pp. The inlet and outlet positions are respectively: (x_{in} , y_{in} , z_{in}) and (x_{out} , y_{out} , z_{out}). The airflow velocity is represented by the symbol v(x,y,z).The concentration of pollutants follows the advection - diffusion equation:

$$\frac{\partial T}{\partial n} + (v \cdot \nabla) C = D\nabla^2 C - R(C) \tag{11}$$

Among :

① D: diffusion coefficient:

② R(C): the rate of purification function.

The removal of pollutants by air purifiers follows the following relationship:

$$R(C) = \eta \cdot Q_{flow} \cdot C \tag{12}$$

Round and oval-shaped air purifiers, sharing the same cross-sectional specifications, exhibit a less pronounced boundary layer separation phenomenon compared to their polygonal counterparts. This enables air to flow freely, resembling a "smooth" passage. Such a feature ensures a stable air delivery to the purification chamber, laying a solid foundation for the continuous capture of pollutants. Nevertheless, the internal spatial regularity of these purifiers may, on occasion, be inferior to that of polygons, restricting the scale of filter deployment and influencing the overall "firepower" of the purifier [8].

3.2.2. An Air Purifier Optimized by Genetic Algorithm

Repeat the process of fitness evaluation and genetic operation for multiple generations (0-50 generations), and the average fitness of the population gradually increases and converges to the optimal solution [9]. This chart shows the changes in CADR (clean air delivery rate) during the genetic algorithm optimization process. The chart contains three curves, representing the maximum CADR (light blue), average CADR (orange), and standard deviation (light blue shaded area). At generation 0, the maximum CADR is approximately 0, the average CADR is approximately -200,000 m^3/h, and the standard deviation covers a wide range. As the generation increases, both the maximum CADR and average CADR generally increase, but with significant fluctuations, with peaks and troughs occurring around generation 10 and 20. The standard deviation also fluctuates, showing changes in the dispersion of CADR values. By generation 50, the maximum CADR and average CADR are approximately 200,000 m^3/h [10]. The changes in CARD during the genetic algorithm optimization process are shown in Figure 7.

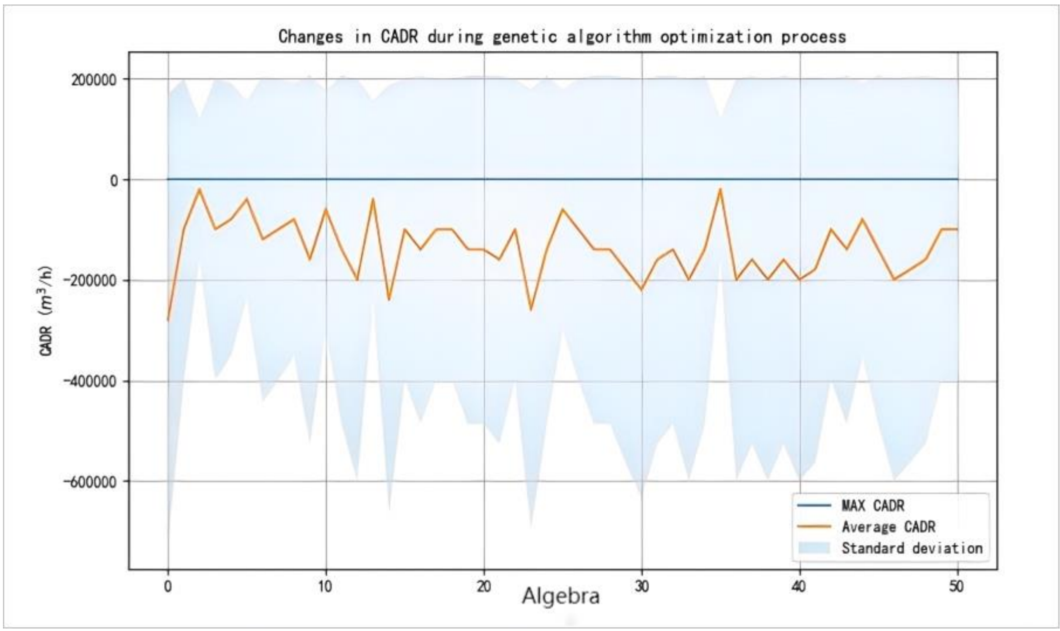

Figure 7. CARD Change

(1) Analysis of purification efficiency

Purification Coverage Γ: This refers to the proportion of the room's volume that is covered by the purification area:

$$\Gamma = \frac{\int_{v_{clean}} C(x,y,z,t)dV}{\int_{v} C(x,y,z,t)dV} \tag{13}$$

Maximize Γ, while minimizing the energy consumption P:

$$P = \frac{1}{2}\rho \mathrm{v}^3 A \tag{14}$$

Among: ρ is the density of air.

(2) Optimization of Shape Analysis:

The shape of the air purifier $f(x,y,z)$ determines the distribution of airflow $v(x,y,z)$. The uniformity of airflow is measured by the variance σ_v^2.

$$\sigma_v^2 = \frac{1}{V}\int_V [|v(x,y,z)| - \bar{v}]^2 dV \tag{15}$$

Therefore, our team used computational fluid dynamics (CFD) simulation software combined with regression analysis of experimental data to establish a quantitative relationship between geometric parameters and purification efficiency indicators and incorporated it into the objective function. After repeated simulations and optimizations, the model produced a more optimal shape similar to a "short and stout" cylinder [11].

4. Conclusions

In the comprehensive optimization study of air conditioners and air purifiers, an in-depth exploration was carried out to enhance their performance and functionality. The shape and size of air conditioners were meticulously optimized using genetic algorithms through an extensive array of simulations and experiments. This involved conducting numerous tests and analyses to ensure the best possible outcome. The primary objective was to achieve a uniform temperature distribution throughout the space, reach the set temperature accurately and promptly, strike a balance between the volume and the constraints imposed by the inlet and outlet, and significantly reduce temperature variance.

The optimization of air purifiers proved to be equally demanding and complex. The study delved into the mechanism of how shape influences the purification process and established an optimization model based on genetic algorithms. A comprehensive assessment was made by integrating multiple indicators to identify the most optimal solution, thereby significantly enhancing the overall performance. The research findings hold great practical value and can be effortlessly integrated into the manufacturing process, offering valuable guidance for installation and usage.

Looking ahead, the intention is to incorporate more real-time environmental factors, such as changes in humidity, air quality, and external temperature fluctuations. These will be combined with intelligent systems to broaden the scope of the research and explore the seamless integration of multiple advanced technologies. This will enable the development of even more efficient and intelligent air conditioning and purification systems that better meet the diverse needs of users.

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