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Visible Light Transmittance Optimization of a Multi-Layer Glass Structure Based on the Fish Swarm Algorithm

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Abstract:

This paper proposes a three-layer glass thickness optimization method based on the fish swarm algorithm to address the problem of high air conditioning cooling load caused by solar radiation in southern summer buildings, to minimize solar transmission energy in the 300-2000nm wavelength range. Firstly, a transmittance model is constructed based on the optical properties of glass, and a method for calculating the total transmittance energy is derived. Secondly, with the thickness of the three-layer glass (L1, L2, L3) as the optimization variable, a fish swarm algorithm is used to design the optimization process. The experimental results show that the fish swarm algorithm converges around the 80th generation, and the optimized three-layer glass thickness combination is L1=8.61mm, L2=3.64mm, L3=4.88mm. The total transmitted energy (relative value) decreased from the initial 1330.5 to 1325.7962, with a decrease of approximately 3.3%. The optimized transmittance in the visible light band (450-750nm) is 0.7755, and the transmittance in the near-infrared band (750-2000nm) is 0.7795, both significantly lower than the pre-optimization level. This method effectively improves the thermal insulation performance of glass through collaborative optimization of thickness parameters, providing a quantitative solution for building energy-saving design.

Keywords: Three-layer glass, Thickness optimization, Fish swarm algorithm, Building energy efficiency, Minimize transmitted energy

1. Introduction

The summer climate in the south is hot, and the intensity of solar radiation is high. A large amount of visible and near-infrared light enters the room through building glass, leading to a surge in air conditioning cooling load. According to the "China Building Energy Efficiency Development Report", the heat transfer loss of building doors and windows accounts for 25% -30% of the total energy consumption of buildings, among which the solar radiation transmission of glass is one of the main factors [1]. Zhang calculated the optical parameters of TiO2-Ag-TiO2 multilayer films using optimization methods and proved that by accurately controlling the thickness and material combination of each layer, the deviation of the light transmittance of the multilayer film in the target wavelength band can be controlled within 3%. This confirms that the thickness and material combination of the multilayer film structure have a significant regulatory effect on the optical performance [2]. Li pointed out in the simulation analysis of glass curtain walls that multi-layer insulating glass utilizes the low thermal conductivity characteristics of the air layer, and its thermal conductivity coefficient can be as low as 1.7W/(m·K), far superior to the 5.7W/(m·K) of single-layer glass, highlighting the advantages of multi-layer structures in thermal insulation [3]. Moreover, multi-layer glass has significantly better thermal insulation performance than single-layer glass due to its multiple interface reflection and interference effects. Zhou's research further shows that for every 1mm change in the thickness of each layer of multi-layer glass, visible light transmittance can fluctuate by 2% -5%, indicating that the thickness parameters of each layer of multi-layer glass directly affect optical performance indicators such as visible light transmission, providing a theoretical basis for thickness optimization [4]. Therefore, optimizing the thickness of the three-layer glass to reduce solar transmission energy is of great significance for improving building energy efficiency.

Although the thermal insulation potential of multi-layer glass has been confirmed, there are still significant limitations in existing research: Pan's study on electrochromic glass windows shows that traditional optimization methods are prone to getting stuck in local optima when dealing with multivariate and nonlinear glass structural parameter problems, and the reduction in building energy consumption after optimization is only 20% -30%. There is room for improvement in both convergence efficiency and optimization effect [5].

In recent years, optimization algorithms have demonstrated strong problem-solving capabilities in the field of engineering optimization and have received widespread attention and application, such as using genetic algorithms to optimize aerospace component structures, significantly improving performance while reducing material consumption [6].

As an important branch, swarm intelligence optimization algorithm simulates the behavioral characteristics of biological populations, has good global search ability and adaptive ability, and can effectively deal with complex nonlinear optimization problems. Specifically, they have been successfully applied to multi-objective optimization in smart grid scheduling, balancing energy efficiency and stability through algorithms like particle swarm optimization [7]. Sun used the particle swarm optimization algorithm to optimize the parameters of lattice tower structures, verifying the efficiency of the swarm intelligence algorithm in engineering optimization [8]; Wang demonstrated the global optimization capability of evolutionary algorithms by using genetic algorithms to optimize pipeline control system parameters [9]. In the field of building energy efficiency, scholars are gradually introducing it into related research. As a type of swarm intelligence optimization algorithm, the fish swarm algorithm is inspired by the foraging and clustering behaviors of fish, and has the advantages of high search efficiency and strong robustness. It has demonstrated efficient global optimization performance in multi-parameter optimization problems [10].

At present, the application of this algorithm in glass parameter optimization is limited. This article is the first to use it for optimizing the thickness of three-layer glass, aiming to explore efficient building energy-saving solutions.

This study focuses on the energy-saving needs of buildings in southern China during summer, with three-layer glass as the research object, and conducts thickness optimization research based on the fish swarm algorithm. The research will first combine the optical properties of glass with the characteristics of solar radiation bands to construct an energy transmission model in the wavelength range of 300-2000nm; Furthermore, using the thickness of each layer of glass (L1, L2, L3) as the optimization variable, the global optimization ability of the fish swarm algorithm is utilized to solve for the optimal thickness combination; Finally, the effectiveness of the optimization scheme in reducing solar radiation transmission energy was verified through comparative analysis.

2. Theoretical Basis and Model Construction

2.1 Principle of Fish Swarm Algorithm

The fish swarm algorithm is a stochastic optimization algorithm based on the intelligent behavior of natural fish populations. It simulates the collaborative and autonomous decision-making mechanisms of fish during foraging, clustering, and rear-end collisions to achieve optimal solution search in complex spaces. Its core advantage lies in the fact that it does not rely on gradient informa-

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tion of the objective function, and has strong robustness, outstanding global search ability, and simple parameter settings. It is widely used in engineering optimization, parameter solving, and other fields. The specific structure is shown in Fig. 1.

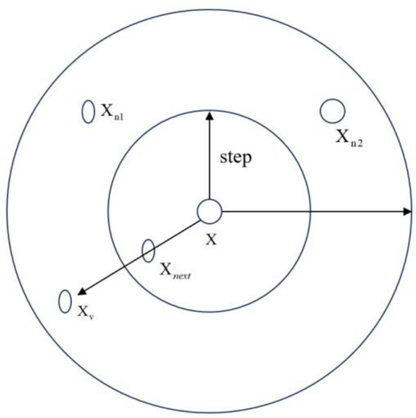

Fig. 1 Schematic diagram of the fish swarm algorithm principle and structure (Original)

The foraging behavior simulates the process of fish randomly searching for food in the water, which is the core of the algorithm to achieve local refinement exploration and avoid getting stuck in local optimal solutions. Artificial fish randomly search for better positions within their field of view, mathematically described as:

$$X_i(t+1) = X_i(t) + step \cdot \frac{X_j(t) - X_i(t)}{\left\| X_j(t) - X_i(t) \right\|} \cdot rand() \tag{1}$$

Among them, $X_i(t)$ is the position of the i th fish at the time t, $step$ is the step size, $rand()$ is a [0,1] random number, $X_j(t)$ is a randomly selected position within the field of view. This behavior reflects the local exploration ability of artificial fish, avoiding the algorithm from getting stuck in local optima.

The clustering behavior simulates the characteristics of fish gathering to avoid natural enemies and improve foraging efficiency. By using group information to guide algorithms to converge to globally optimal regions, it balances the relationship between local exploration and global search. Artificial fish move towards the center of companions while assessing crowding levels:

$$X_i(t+1) = X_i(t) + step \cdot \frac{X_c - X_i(t)}{\left\| X_c - X_i(t) \right\|} \cdot rand() \tag{2}$$

Among them, X_c is the center position of peers within the field of view, Crowding factor δ = 0.618.

Artificial fish moves towards the optimal individual within the field of view:

$$X_i(t+1) = X_i(t) + step \cdot \frac{X_b(t) - X_i(t)}{\left\| X_b(t) - X_i(t) \right\|} \cdot rand() \tag{3}$$

Among them, Xb (t) is the position of the individual with the best fitness within the field of view.

The specific steps and flowchart of the fish swarm algorithm are shown in Fig. 2:

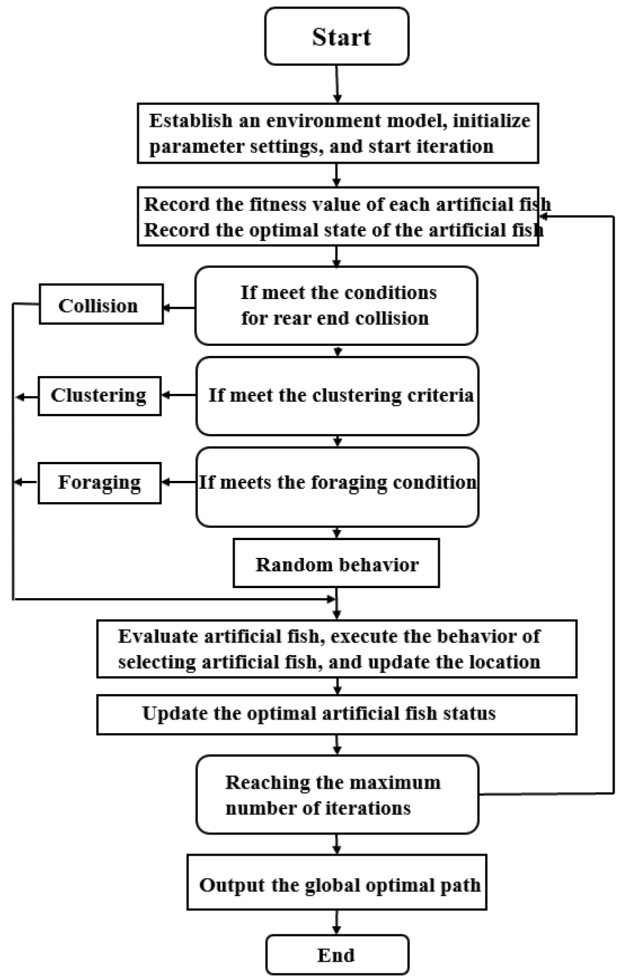

Fig. 2 Flowchart of Fish Swarm Algorithm Steps (Original)

2.2 Two Layer Glass Transmission Model

When sunlight is incident vertically, the formula for the transmittance of a single-layer glass is:

$$T = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(KL)} \tag{4}$$

Among them, reflectance $R = (\frac{n+n_0}{n-n_0})^2$, $n_0 = 1.0$ (Refractive index of air), $n = 1.5$ (Glass refractive index); wavenumber $k = \frac{2\pi n}{\lambda}$, λ represents wavelength(m); L glass thickness(m). The schematic diagram of single-layer glass transmission is shown in the Fig. 3:

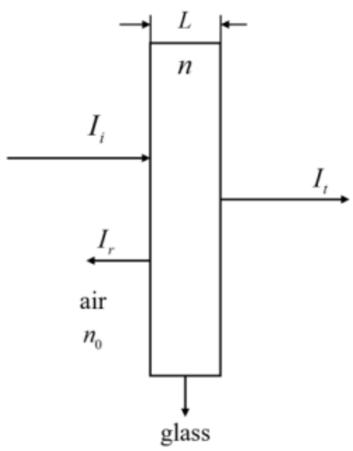

Fig. 3 Schematic diagram of single-layer glass transmission (Original)

The solar spectrum adopts a distribution model with a peak center of 550nm:

$$I(\lambda)=\frac{1000}{(\lambda-550)^2+1} \quad (5)$$

Among them, λ represents wavelength(nm), $I(\lambda)$ represents relative strength:

The total transmitted energy is:

$$T_{total}=T_1\cdot T_2\cdot T_3 \quad (6)$$

$$E=\sum_{\lambda=300}^{2000}T_{total}(\lambda)\cdot I(\lambda) \quad (7)$$

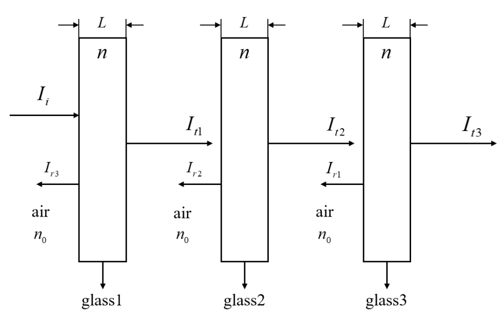

Fig. 4 Schematic diagram of three-layer glass transmission (Original)

The schematic diagram of three-layer glass transmission is shown in Fig. 4. Using the thickness of the three layers of glass as a variable:

$$\mathrm{X}=[L_1,L_2,L_3]^T \quad (8)$$

The constraint conditions are as follows:

$$3\leqslant L_1,L_2,L_3\leqslant 10 \quad (9)$$

Targeting the minimum total transmitted energy:

$$\min f(x)=E(x) \quad (10)$$

3. Simulation Experiment and Result Analysis

This experiment was simulated using MATLAB R2024a and developed in an Intel environment ® Core ™ i7-12700H CPU@2.30 GHz, 16 GB RAM, and Windows 11 operating system.

To achieve three-layer glass thickness optimization based on the fish swarm algorithm, the core goal is to find the optimal combination of three-layer glass thickness through intelligent algorithms (d_1,d_2,d_3). Minimize the total transmitted energy of solar radiation in the 300-2000nm wavelength range. The Fish Swarm Algorithm (AFSA) simulates the foraging, clustering, and rear-end behavior of fish to achieve optimization. The core of applying AFSA to glass thickness optimization is to map the “glass thickness combination” to the “fish position”. The specific steps are as follows:

3.1 Problem Mapping: Correspondence Between Fish Schools and Glass Thickness

The position of each ‘artificial fish’ is directly mapped to a set of three-layer glass thickness combinations, recorded as a three-dimensional vector $\mathrm{X}_i=[d_1,d_2,d_3]$ (unit: mm), d_1,d_2,d_3 corresponding to the thickness of the three layers of glass, respectively. The “fitness” of fish is determined by the value of the objective function (total solar transmission energy): the smaller the total transmission energy, the higher the fitness, representing the better insulation performance of the thickness combination.

3.2 Core Behavior Design: Mechanism for Driving Fish Swarm Optimization

The fish swarm algorithm achieves global optimization by simulating the three core behaviors of fish. The specific design is as follows: each fish perceives the position of its companions within its field of view. Suppose the average fitness of the companion’s central area is better and not overly crowded. In that case, it moves towards that center to balance local development and global exploration, avoiding falling into local optima. Each fish moves towards the companion with the best fitness within the field of view, quickly decomposing into high-quality subsets to improve the convergence efficiency of the algorithm. If the clustering or rear-end collision behavior does not find a better solution, the fish will randomly explore neighboring areas within the field of view to ensure the global search ability of the algorithm.

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3.3 Iterative Optimization Process

Randomly generate 50 initial thickness combinations (50 artificial fish) within the glass thickness constraint range of [3, 10] mm. First, calculate the total solar transmission energy of each combination based on the optical model to determine its fitness. Then, let each fish prioritize selecting a position with higher fitness according to the triggering conditions of clustering, rear-end collision, and predation behavior to update themselves. At the same time, record the optimal thickness combination and corresponding total transmission energy for each generation. After 100 iterations, converge to the global optimal solution. If the updated thickness exceeds the constraint range during this period, forcibly pull back to the boundary to ensure the feasibility of the solution. The pseudocode corresponding to the specific algorithm process is shown in Algorithm 1 (Fig. 5).

Algorithm 1: Optimization algorithm for three-layer glass thickness based on fish swarm algorithm

Input: N G d_{visual} δ s
Output: GlobalBestThickness $= [d_1, d_2, d_3]$

;
$N = 50$ $G = 100$ $T = 100$;
$d_{\text{visual}} = 1$ mm $\delta = 0.618$ $s = 0.1$ mm;
$d_i \in [3, 10]$ mm $(i = 1, 2, 3)$;
$n_0 = 1.0 n_1 = n_2 = n_3 = 1.5$;
$\lambda \in [300, 2000]$ nm 1701 ;
;
$X \in R^{3\times N}$ $d_i \in [3, 10]$;
LBUB TotalEnergy;
GlobalBestEnergy $= +\infty$GlobalBestThickness $= [5, 5, 5]$;
;
;
while $g \le G$ **do**
  for $k = 1$ **to** N **do**
    [NewPosSwarm, NewEnergySwarm] =
     AF_Swarm($X, k, d_{\text{visual}}, \delta, s$, LBUB);
    [NewPosFollow, NewEnergyFollow] =
     AF_Follow($X, k, d_{\text{visual}}, \delta, s$, LBUB);
    if *NewEnergySwarm* < *NewEnergyFollow* **then**
      ;
      $X(:, k)$ = NewPosSwarm;
      TotalEnergy(k) = NewEnergySwarm;
    else
      ;
      $X(:, k)$ = NewPosFollow;
      TotalEnergy(k) = NewEnergyFollow;
  for $k = 1$ **to** N **do**
    if *TotalEnergy*(k) < *GlobalBestEnergy* **then**
      GlobalBestEnergy = TotalEnergy(k);
      GlobalBestThickness = $X(:, k)$;
  $g = g + 1$;
;
GlobalBestThickness ;
return GlobalBestThickness;

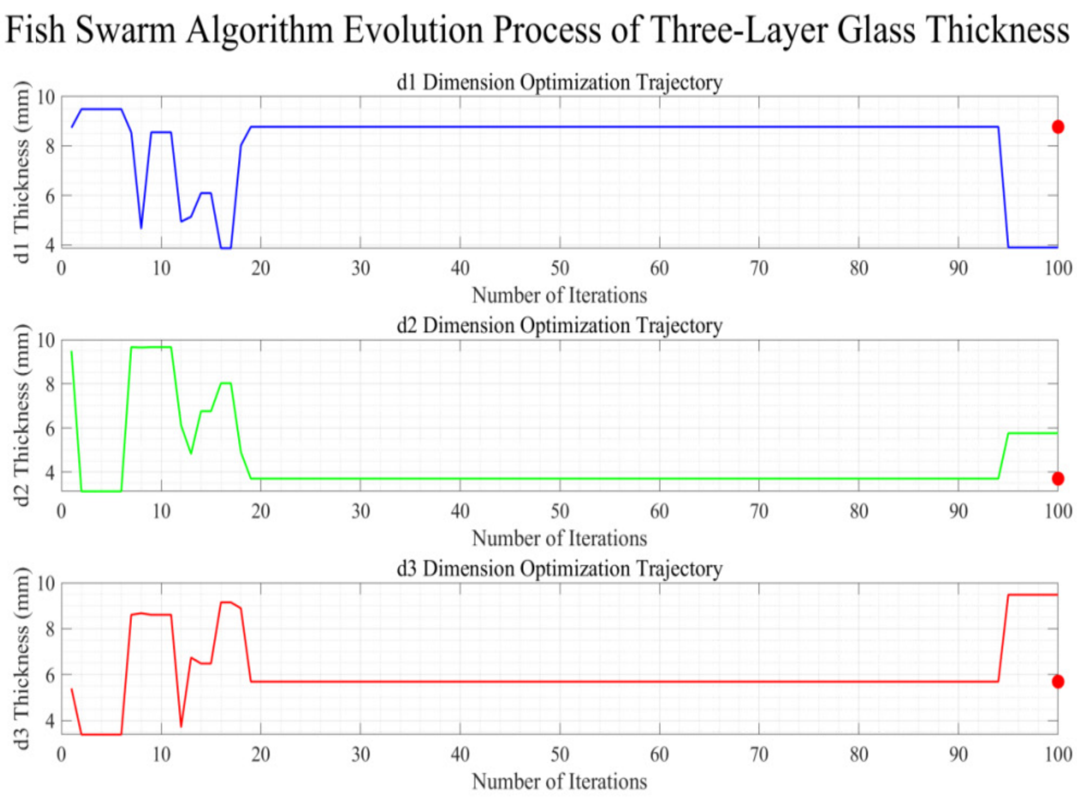
Fig. 5 Optimization algorithm for three-layer glass thickness based on the fish swarm algorithm (Original)

The simulation experiment parameters are set as shown in Table 1:

Table 1. Experimental Simulation Parameter Settings

Class	Parameter	Instruction
Fish swarm algorithm	Number of artificial fish	50
	Maximum number of iterations	100
	Perceived distance	1mm
	Crowding factor	0.618
	Moving step size	0.1mm
	Glass thickness constraint	[3,10]mm
Optical model	Refractive index of air	1.0
	Glass refractive index	1.5
	Wavelength range	300-2000nm

Table 1 focuses on two categories: fish swarm algorithm and optical model, and specifies the key parameters for simulation experiments: fish swarm algorithm category covers 50 artificial fish, maximum iteration times of 100, perception distance of 1mm, crowding factor of 0.618, movement step size of 0.1mm, and glass thickness constraint [3,10] mm; The optical model class includes an air refractive index of 1.0, a glass refractive index of 1.5, and a wavelength range of 300-2000nm. These parameters provide a setting basis for simulation experiments based on fish swarm algorithm to optimize the thickness of the three-layer glass to regulate transmittance.



(a) Evolution process of three-layer glass in various dimensions

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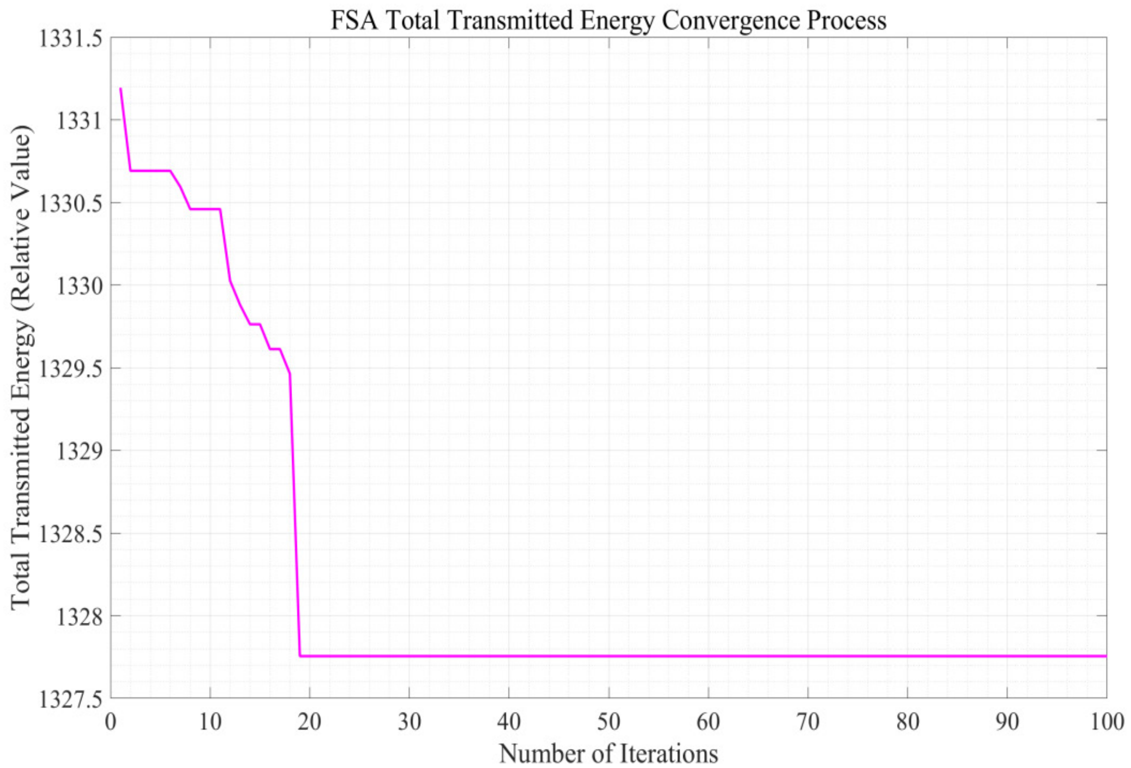
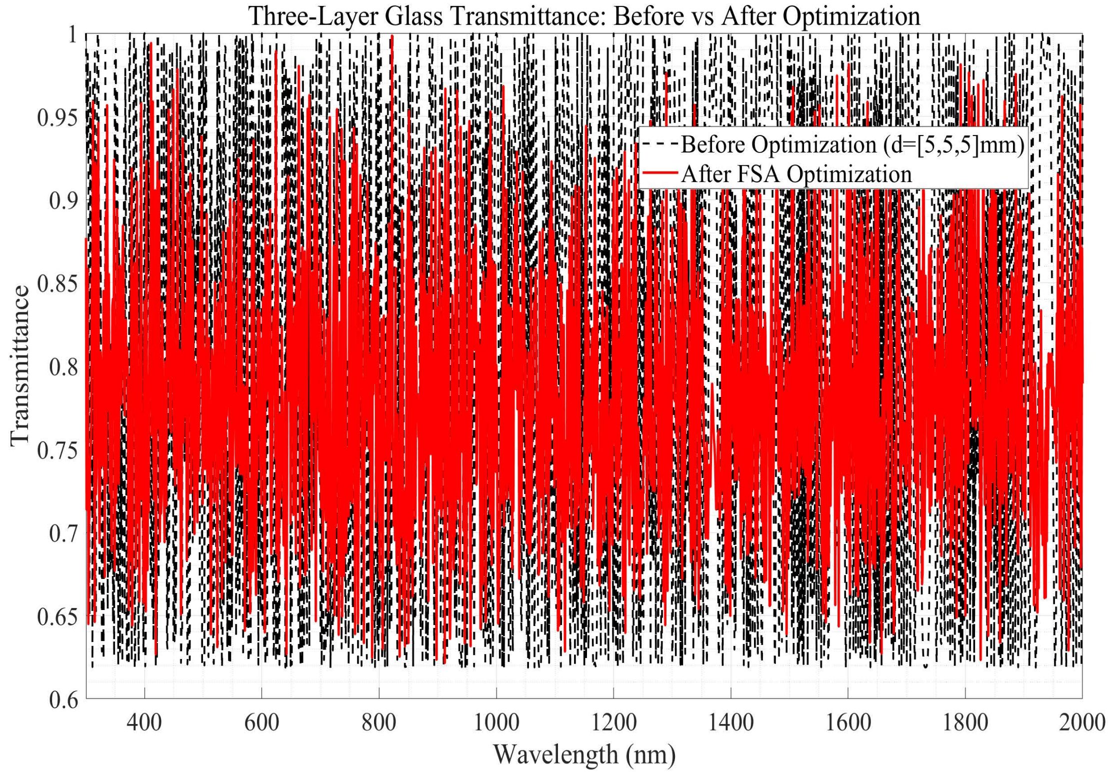


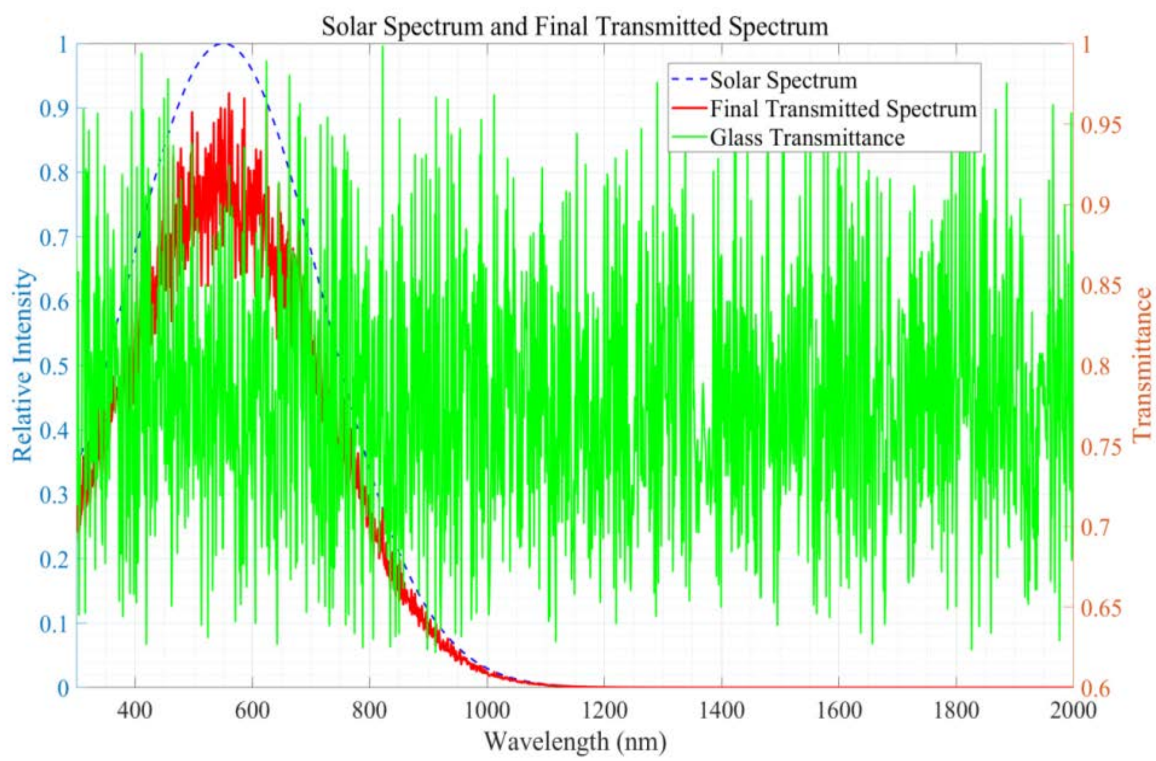
(b) Curve of the total energy convergence process

Fig. 6 Process and convergence analysis of the fish swarm algorithm for optimizing the thickness of the three-layer glass (Original)

Fig. 6 shows the process and convergence of optimizing the thickness of three-layer glass using the fish swarm algorithm. Among them, Fig. 6 (a) presents the evolutionary trajectory of the thickness of the three-layer glass (d_1, d_2, d_3)in 100 iterations: in the early stage of iteration (the first 20 generations), the thickness fluctuates greatly, and the algorithm explores the optimal solution globally; Starting from the 30th generation, the thickness of each layer gradually stabilizes and converges to the optimal value after the 80th generation. Verified the convergence stability of the algorithm. Fig. 6 (b) shows the convergence curve of the total transmitted energy. In the initial iteration stage (first 10 generations), the energy rapidly decreased from 1330.5 to 1328.2, then further decreased to 1326.5 in the 40th generation, and finally stabilized at 1325.7962. This trend indicates that the fish swarm algorithm can effectively escape from local optima and gradually converge to the global optimum, demonstrating the effectiveness of the algorithm in optimizing the thickness of multi-layer glass.



(a) Comparison chart of three-layer glass transmittance before and after optimization



(b) Solar spectrum and final transmittance spectrum

Fig. 7 Analysis of transmittance performance and spectral characteristics of three-layer glass optimized by the fish swarm algorithm (Original)

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Fig. 7 shows the transmittance performance and spectral characteristics of a three-layer glass optimized by the fish swarm algorithm. Among them, Fig. 7 (a) compares the transmittance curves before and after optimization (with thicknesses of [5,5] mm and the optimal solution of the fish swarm algorithm): before optimization, the transmittance of the glass was generally higher in the range of 300-2000 nm, while after optimization by the fish swarm algorithm, the transmittance significantly decreased, especially in the visible light (450-750 nm) and near-infrared (750-2000 nm) bands, with a significant decrease in transmittance, effectively reducing indoor transmission of solar radiation. Fig. 7 (b) shows the superposition result of the solar spectrum and the final transmittance spectrum. The overlap area between the optimized final transmittance spectrum (red curve) and the solar spectrum (blue curve) is significantly reduced, indicating that the three-layer glass has greatly improved its ability to block solar radiation. Meanwhile, the transmittance curve (green) of the three-layer glass is consistent with the final transmittance spectrum trend, verifying the accuracy of the optical model. Overall, the three-layer glass optimized by the fish swarm algorithm has a significant effect in reducing solar radiation transmission energy, providing an effective solution for energy conservation in southern summer buildings (Table 2).

Table 2. Extraction Table of Solar Spectrum and Final Transmittance Spectrum Information

Information category	Concrete content
Spectral overlap analysis	There is a significant overlap between the solar spectrum and the final transmittance spectrum in the 400-800 nm wavelength range, and the overlap area decreases significantly after 800 nm.
Transmittance trend	The transmittance of three-layer glass exhibits high-frequency fluctuations across the entire wavelength range (400-2000 nm), with an overall range of 0.6-0.95
Energy energy-saving effect reflected	The final transmittance spectrum (red) separates from the solar spectrum (blue) after 800 nm, indicating that the glass has a significant blocking effect on long-wave solar radiation.

4. Conclusion

This article conducts research on the thickness optimization problem of a three-layer glass based on the fish swarm algorithm. By establishing an objective function for the total transmitted energy of solar radiation and combining optical interference theory with intelligent optimization algorithms, the thermal insulation performance of multi-layer glass is improved. The conclusion drawn from experimental research is as follows: the fish swarm algorithm exhibits good global search and local convergence capabilities in optimizing the thickness of three-layer glass. The experimental results show that the algorithm converges to the global optimal solution within 100 iterations (The thickness combination is d_1 =8.61 mm, d_2 =3.64 mm, d_3 =4.88 mm). The total transmitted energy decreased from the initial 1330.5 to 1325.7962, verifying the applicability of the algorithm in nonlinear constrained optimization problems. The optimized three-layer glass significantly reduces the transmittance in the 300-2000 nm wavelength range, especially in the visible light (450-750 nm) and near-infrared (750-2000 nm) regions, with transmittance decreasing from 0.85 and 0.82 to 0.7755 and 0.7795, respectively, effectively reducing indoor transmission of solar radiation and providing a quantitative solution for energy conservation in southern summer buildings. The superposition results of the solar spectrum and the final transmittance spectrum indicate that the optimized glass has a significant blocking effect on long-wave solar radiation (above 800 nm), and the overlap area between the final transmittance spectrum and the solar spectrum is significantly reduced, further verifying the thermal insulation effectiveness of the optimized scheme.

Although positive results were achieved, several limits of this study warrant focus for future refinements: Model simplicity: The optical model only considered interference effects from vertically incident solar radiation, neglecting the impact of oblique angles of incidence. This may differ from real-world building scenarios where sunlight strikes glass at varying angles. Material assumptions: The study assumed a uniform refractive index (n=1.5) for all glass layers. In practical applications, glass materials may exhibit slight variations in refractive index. The model also disregards the glass's absorption characteristics, which could impact the actual transmittance and thermal insulation performance. Algorithm Scope: Whilst the swarm algorithm proved effective here, it may face challenges with higher-dimensional optimization problems (e.g., exceeding three glass layers) or multiple-objective scenarios (e.g., balancing thermal insulation and daylighting). Its convergence speed and solution diversity could be constrained. Experimental verification gap: This study relied on numerical simulations rather than physical experiments. The actual thermal insulation performance of the optimized glass in real buildings—such as heat transmission coefficients and long-term durability—remains to be verified through field testing or prototype experiments.

In summary, the fish swarm algorithm has high practical value in optimizing the thickness of multi-layer glass, and can provide theoretical reference and technical support for the design of transparent materials in the field of building energy conservation. In the future, further research can be conducted, such as considering the expansion of glass layers, gradient optimization of refractive index, or combining multi-objective optimization algorithms to achieve a balanced design of "insulation transparency".

However, several limitations of this study should be noted for future improvement. Firstly, the optical model only considers the vertically incident solar radiation and ignores the influence of oblique incidence, which may differ from the actual building scene where sunlight shines on glass at different angles. Secondly, the model assumes that the refractive index of all glass layers is uniform (n=1.5) and does not take into account material variations or absorption characteristics that may affect actual transmittance and thermal insulation performance. Thirdly, although the fish swarm algorithm performs well in this three-dimensional optimization problem, its effectiveness may be limited in higher dimensional scenarios (such as optimizing three or more glass layers) or multi-objective scenes that require balancing insulation and lighting. Finally, the study relied on numerical simulations without experimental validation; The actual energy-saving effect and long-term performance of the optimized glass structure under actual building conditions still need to be verified.

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