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Optimization of Solar Transmittance of a Three-Layer Glass Structure Based on the Ant Colony Algorithm

***Bowen Deng**

School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai, 201620, China
*Bowen Deng,dengbowen@sues.edu.cn

Abstract:

Currently, high temperatures occur frequently in summer, and the overall duration of summer has been prolonged. Glass that reduces sunlight transmittance is an economical and effective passive energy-saving measure to lower indoor energy consumption. The structural parameters and types of glass have a significant impact on their solar transmittance. In this study, the optimization of the solar transmittance of three layers of ordinary glass by the thickness of the glass was carried out. The radiant energy of sunlight passing through Windows mainly exists in the near-infrared band, while ultraviolet radiation is harmful to the human body. Therefore, under the premise of ensuring lighting, minimizing the transmittance of the near-infrared and ultraviolet bands as much as possible can effectively reduce solar radiation and thereby lower energy consumption. The research achieves multi-objective optimization by establishing a spectral transmission model ranging from 300 to 2000nm and combining the ant colony algorithm to minimize the near-infrared and ultraviolet bands while ensuring daylighting. The research results show that when the thickness of the three-layer glass is 5.103mm, 5.724mm, and 5.310mm, it can minimize solar radiation energy to the greatest extent and ensure lighting. In this case, the total solar radiation transmission energy of the three-layer glass decreased from 1267.81 W/m2 before optimization to 997.37 W/m2, a reduction of 21.33%.

Keywords: Ant Colony Algorithm, Triple-pane glass,Solar transmittance,Optimization

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1. Introduction

Currently, high temperatures occur frequently in summer, and the overall duration of summer has been prolonged. The heat generated by solar radiation through the exterior Windows of buildings is the main factor causing the indoor temperature to rise. Reducing the transmittance of sunlight through Windows is the key to achieving lower indoor energy consumption. Optimizing the structural parameters of glass is an economical and effective passive energy-saving measure. Solar radiation covers a broad spectrum ranging from 300 to 2000nm, and its transmission process in different glass layers is complex, making seeking the optimal thickness combination to minimize indoor heat gain a challenging nonlinear optimization problem.

Many advancements have been made in the relevant research on energy-saving optimization of Windows. Jiang et al. combined the Topsis method with the G1 method to establish an evaluation system for the energy-saving characteristics of Windows, providing a reference standard for the actual evaluation of the energy-saving effects of various Windows [1]. Jin et al. simulated through Ecotect software and found that the window-to-wall ratio of south-facing Windows should be 0.45, and the window-to-floor ratio should be between 0.1 and 0.25. This ratio can achieve a better comprehensive balance among lighting, energy consumption, and thermal comfort [2]. Fu's research found that hydrogel composite glass can reduce energy consumption by 0.03MJ/m2 throughout the year compared to ordinary glass, making it an economical and energy-saving new type of material [3]. Ma optimized the model establishment of thermal insulation phase change multi-layer glass Windows. Compared with buildings with double-glazed Windows, its annual energy-saving rate can reach 19.38% [4]. Qi et al. found through research that when the window-to-wall ratio of photochromic glass is above 0.6, and the building area is large, the annual energy-saving rate can exceed 10% at most [5]. Zheng et al. established a "climate-parameter-function" selection model and found that the comprehensive energy-saving rate of Low-E glass was ≥28% and the lighting compliance rate was ≥85% [6]. Mi research found that when applying Vacuum-structured electrochromic glazing windows (VEC) in clear weather, under the working state of 1.5V, the effective daylighting illuminance during working time can be increased by 39%. In the panchromatic state, it can reduce the peak indoor air temperature by 3.1℃, achieving building energy savings of 12% to 16% in five different climate zones in China [7]. Wang et al. studied CdTe photovoltaic glass in tropical island areas and found that compared with the traditional insulated glass unit (IGU), CdTe SPVG and Insulated SPVG (SPVG-IGU) reduce heat gain by 24.7%, HVAC energy consumption by 4.4%, and total energy consumption by 3% [8]. However, most of the existing optimization studies are based on specific window types or from the perspective of actual simulation, and have failed to deeply integrate full-band spectral analysis with advanced algorithms suitable for combinatorial optimization. Ant colony algorithm is renowned for its excellent global optimization ability in discrete Spaces, but it remains a blank in solving local specific problems [9, 10].

In view of this, this paper proposes an integrated framework that combines a high-precision 300-2000nm full-spectrum transmission model with an ant colony algorithm, specifically designed to optimize the thickness combination of three-layer glass to achieve the lowest transmittance, thereby realizing energy-saving purposes. The innovation of this paper lies in the combination of ant colony algorithm and multi-objective optimization, and it is not limited to a specific type of window. It studies the influence of the thickness of three layers of glass on the solar transmittance.

2. Research Methods

2.1 Introduction to the ACO Algorithm

The ant colony algorithm uses the walking paths of ants to represent the feasible solutions of the problem to be optimized, and all the paths of the entire ant colony constitute the solution space of the problem to be optimized. Among them, in the shorter path, ants release a greater number of pheromones. Therefore, as time goes by, the concentration of pheromones accumulated on the shorter path will gradually increase, resulting in more and more ants choosing this path. Ultimately, the entire ant colony will concentrate on the best path under the effect of positive feedback. At this point, the corresponding path is the optimal solution to the problem to be optimized.

In the ant colony algorithm, the feasible solutions independently constructed by artificial ants in the solution space are jointly determined by pheromone concentration and heuristic information. Specifically, the probability of an ant transitioning from one state to another is usually described by the following formula:

$$P_{ij} = \frac{{\tau_{ij}}^{\alpha} \cdot {\eta_{ij}}^{\beta}}{\sum l \in allowed[\tau_{il}]^{\alpha} \cdot [{\eta_{il}}^{\beta}]} \tag{1}$$

Among them, τ_{ij} represents the pheromone concentration on the （i, j） edge, η_{ij} is the heuristic factor, α and β respectively controls the influence degree of pheromones and heuristic information. After all the ants have completed the construction of their solutions, the algorithm enhances the paths corresponding to the high-quality solutions through pheromone update rules. First, the global pheromone is volatilized to reduce the influence of the old path and prevent the algorithm from falling into a local optimum too early. Subsequently, pheromones are added to the excellent path based on the quality of the solution, thereby generating a positive feedback effect and making the high-quality path easier to select in subsequent iterations.

2.2 ACO Algorithm Design

2.2.1 Relevant parameter settings

The optical parameters are set as follows: define the refractive index of air n_0=1.0, refractive index of glass n_1 =[1.5,1.5,1.5], and load the AM1.5 solar spectral data (wavelength 300-2000 nm) as input.

The algorithm parameters are set as follows: the number of ants num=50 and the number of iterations gen=150, which are used to balance the exploration and convergence speed. Avoid the algorithm taking too long a single run. The pheromone volatility coefficient rho=0.08 and the pheromone intensity Q=50, which are used to control the pheromone update intensity. Set $\alpha = 1$ and $\beta = 3$ respectively apply the influence of weight pheromones and heuristic information.

2.2.2 Discretization and pheromone initialization

Each thickness variable is discretized into 30 nodes, generating uniformly distributed points. Set the pheromone matrix $tau = 0.1$ independently for each variable to prevent the algorithm from converging prematurely.

2.2.3 Iteration of ACO algorithm

First, the objective function and transmittance function are designed. In the transmittance function, the solar spectrum is segmented by wavelength, with 300-450nm defined as the ultraviolet band, 450-750nm as the visible light band, and 750-2000nm as the near-infrared band. Then, the transmittance of each segment is calculated in segments to facilitate the multi-objective optimization of the objective function. The Fresnel reflection coefficient is applied in the calculation of transmittance:

$$R = \left(\frac{n_i - n_0}{n_i + n_0}\right)^2 \tag{2}$$

Here it is assumed that all sunlight is incident perpendicularly. Then apply the single-layer transmittance calculation formula:

$$T_{\mathrm{j}} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\Delta/2)} \tag{3}$$

Here, delta represents the phase thickness. Assuming that the air between the three layers of glass does not cause loss, the transmittance of the three layers of glass can be obtained by multiplying the transmittance of the single layer of glass three times. Define the objective function as:

$$F = (1 - T_1) + w \times (T_2 + T_3) \tag{4}$$

Among them, T_1, T_2, T_3 are the transmittances of the 300-450nm, 450-750nm, and 750-2000nm bands respectively. w is the penalty factor, set to 1.0.

Secondly, a design is carried out where each ant selects values for three thickness variables in sequence. The first variable is randomly chosen to increase diversity. The subsequent variables are selected using the roulette wheel method, and the probability formula is:

$$P = \frac{\tau_{\dim}(j)^{\alpha} \cdot \eta^{\beta}}{\sum \tau_{\dim}(k)^{\alpha} \cdot \eta^{\beta}} \tag{5}$$

Among them, $\tau_{\dim(j)}$ represents the pheromone concentration on the path between the target node j and the current node. The higher the concentration, the better the path. $\tau_{\dim}(k)$ represents the pheromone concentration on the path between all optional nodes k and the current node, η which is heuristic information and is defined as:

$$\eta = \frac{1}{fitness + 10^{-6}} \tag{6}$$

It represents the reciprocal of the fitness of the current partial solution. The smaller the fitness, the higher the probability, thereby achieving the design of minimizing the value of the objective function.

Finally, the pheromone update method is designed so that all pheromones decay proportionally. $tau\{i\} = (1 - rho) \times tau\{i\}$, $tau\{i\}$ is the pheromone array of the dim dimension, used to store the pheromone concentration of all paths in this dimension. At the same time, increase the pheromones of excellent solutions. $tau\{i\}(idx) = tau\{i\}(idx) + delta_{tau}$, Here, $delta_{tau}$ is the pheromone increment, which is calculated based on the fitness of the ant. The calculation method is:

$$delta_{tau} = \frac{Q}{(fitness(ant) + 1e - 6)} \tag{7}$$

After the design is completed, run the algorithm for multiple loop iterations and converges until the optimal three-layer glass thickness is obtained that minimizes the

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transmittance of the near-infrared and ultraviolet bands while ensuring light transmission.

3. Result and Discussion

Fig. 1 shows the iteration curve of the ant colony algorithm, with the horizontal axis representing the number of iterations and the vertical axis representing the optimal fitness value. The convergence curve of the ant colony algorithm exhibits typical convergence characteristics of optimization algorithms. In the early stage of iteration, the fitness value drops rapidly, indicating that the algorithm conducts effective global exploration at this stage and quickly approaches the optimal solution region. After approximately 50 generations, the curve becomes very gentle, and the optimal fitness value fluctuates within a small range of around 1.766. This indicates that the algorithm has found a relatively stable optimal solution region, and the subsequent iterations mainly involve conducting local fine searches. It is demonstrated that in this optimization problem, it can effectively search for the thickness combination that reduces the total transmissive energy of solar radiation.

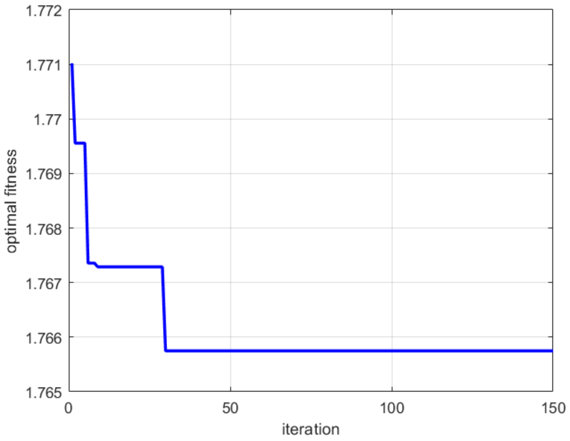

Fig. 1 Iterative curve of ant colony algorithm (Photo/Picture credit: Original).

Fig. 2 shows the optimal transmittance-wavelength curve graph, where the horizontal axis represents wavelength and the vertical axis represents transmittance. The transmittance in the visible light region (400-750 nm) after optimization is generally high (>90%), especially reaching a peak (about 95%) around 550 nm, indicating that this glass has an excellent transmission effect on visible light. The transmittance in the near-infrared region (750-2000 nm) fluctuates significantly, but overall it shows a suppression effect, with low points (about 70%) around 1100 nm and 1600 nm, demonstrating the infrared blocking ability and excellent light transmission capacity of the optimized three-layer glass.

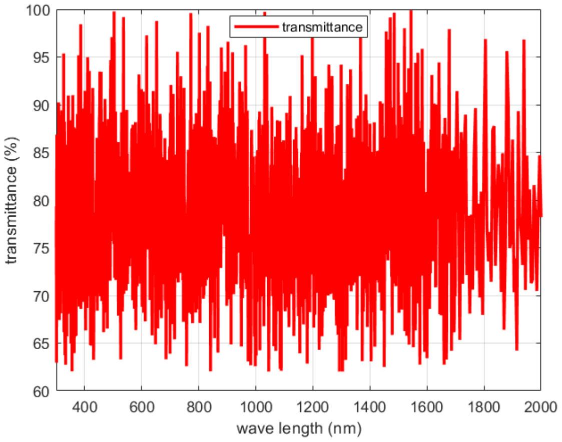

Fig. 2 Optimal transmittance - wavelength curve graph (Photo/Picture credit: Original).

Fig. 3 shows a comparison of the transmittance between the optimized glass and ordinary single-layer glass, with the horizontal axis representing the wavelength and the vertical axis representing the transmittance. Across the entire wavelength range, the transmittance of the optimized triple-pane glass is significantly lower than that of single-pane 5mm glass. The near-infrared transmittance of ordinary glass is generally above 85%, while the optimized triple-pane glass can reduce it to a minimum of around 65% in some areas. It is indicated that the optimized triple-pane glass has a significant weakening effect on the radiation of the sun entering the room through the Windows.

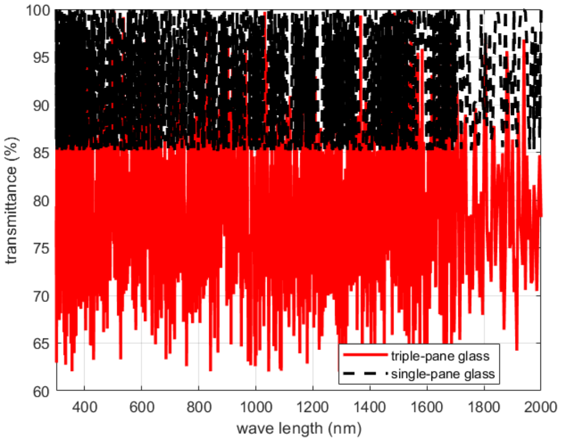

Fig. 3 Comparison chart of transmittance between optimized glass and ordinary single-layer glass (Photo/Picture credit: Original).

Fig. 4 shows a comparison of the transmittance between the optimized glass and the ordinary three-layer glass, with the horizontal axis representing the wavelength and the vertical axis representing the transmittance. The solar transmittance of the optimized three-layer glass has decreased across the entire spectrum compared to the ordinary three-layer 5mm glass, with a particularly significant reduction in the 750nm-2000nm band, that is, the near-infrared band. It indicates that the optimized triple-pane glass has superior optical performance compared to ordinary triple-pane glass.

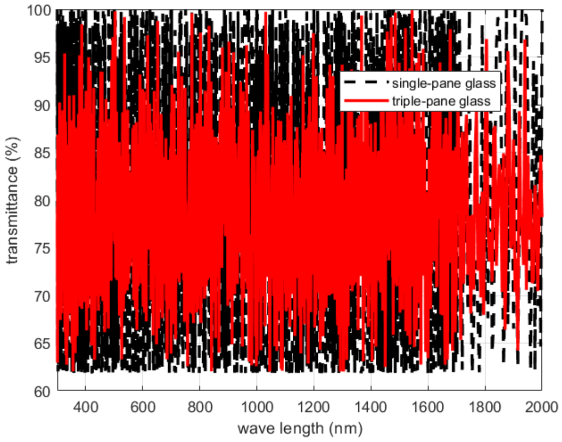

Fig. 4 A comparison chart of the transmittance between the optimized glass and ordinary triple-pane glass (Photo/Picture credit: Original).

Fig. 5 shows a comparison of the transmission spectrum of the optimized glass with the original solar spectrum, where the horizontal axis represents wavelength and the vertical axis represents solar irradiance. The solar irradiance of the optimized three-layer glass across the entire spectrum is lower than that of the original am1.5 solar spectrum. Among them, the decline in the visible light band is relatively small, indicating that the optimized three-layer glass can meet the normal lighting requirements. The decline in the near-infrared band is significant, and the ultraviolet band also shows a decrease. This indicates that the optimized three-layer glass has achieved the optimized goal of reducing the energy of sunlight entering the room.

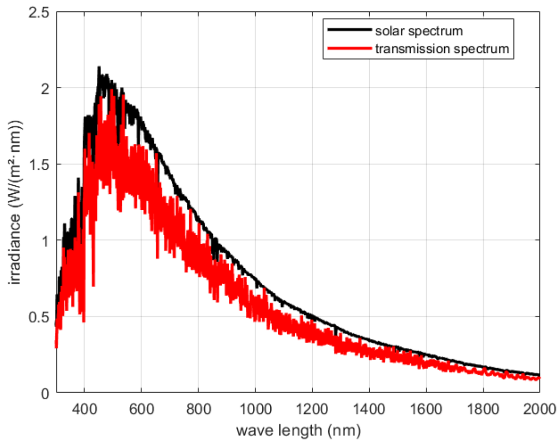

Fig. 5 Comparison chart of the transmission spectrum of the optimized glass with the original solar spectrum (Photo/Picture credit: Original).

Fig. 6 shows a comparison chart of the original solar spectral energy and the optimized three-layer glass solar spectral energy, with the horizontal axis representing the band and the vertical axis representing the transmission energy per unit area. The original solar spectrum is 181.57W/m^2 in the ultraviolet band, 510.17 W/m2 in the visible light band, 576.07 W/m2 in the near-infrared band, and the total energy is 1267.81 W/m2. The optimized spectral energies in the three bands are 140.02 W/m2, 404.87 W/m2 and 452.47 W/m2 respectively, and the total energy is 997.37 W/m2. The reduction ratios are 22.68%, 20.64%, 21.45% and 21.33% respectively. It directly demonstrates the effectiveness of the optimized three-layer glass in reducing solar radiation.

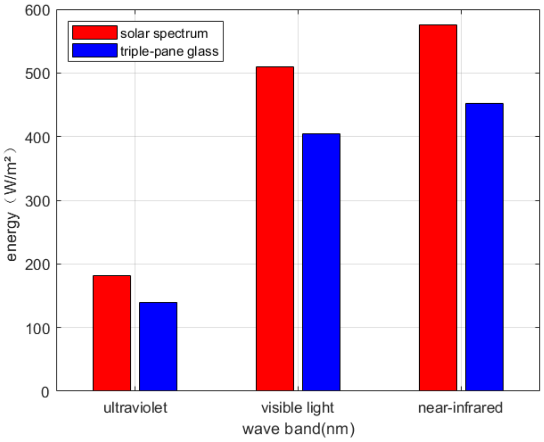

Fig. 6 Comparison chart of the original solar spectral energy and the optimized three-layer glass solar spectral energy (Photo/Picture credit: Original).

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4. Conclusion

The multi-layer glass optical model constructed in this paper can accurately obtain the full-band transmittance and transmission energy. The thicknesses of the three layers of glass obtained after optimization by the ant colony algorithm are 5.103mm, 5.724mm, and 5.310mm respectively. In this case, the total solar radiation transmission energy of the three-layer glass decreased from 1267.81 W/m2 before optimization to 997.37 W/m2, a reduction of 21.33%, and it was effective across the entire wavelength range. It also ensures the transmittance of visible light. The goal of reducing the solar radiation entering the room has been successfully achieved, and the energy-saving effect is relatively significant. It provides a reference for the relevant research on the transmittance of triple-pane glass. The deficiency of this study lies in the assumption of the incident Angle of sunlight when establishing the model, and only the common material glass was discussed. The type of gas between the glass interlayers was not discussed either. Based on the existing achievements, the research can introduce more optimization objectives and more different condition constraints in the future, such as removing the simplification of the incident Angle of sunlight and considering the incident Angle of sunlight in various situations. Not only is ordinary glass used, but also the application of different materials of triple-pane glass is discussed and analyzed. Meanwhile, on this basis, the pheromone update mechanism of the ant colony algorithm is updated, so as to make the results more in line with the requirements of practical applications.

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