Dean&Francis
ISSN 2959-6157

Optimization Design of Three-Layer Glass Thickness Based on the Ant Colony Algorithm

Donglin Shi*

Nanjing University of Information
Engineering, Pukou District,
Nanjing City, Jiangsu Province
210044 China
*Corresponding author:
satsumapony368@gmail.com

Abstract:
In this paper, the three-layer glass system is taken as the research object, and its optical transmission performance is optimized to enhance the energy-saving effect. Based on the theory of thin-film interference, an optical transmission model that accurately describes the propagation of light in multi-layer media is established to evaluate the spectral transmittance under different thickness combinations. To solve the problem efficiently, an improved ant colony algorithm is introduced. This algorithm simulates the optimization behavior of ants foraging and is characterized by strong global search capability and good robustness, making it suitable for such multi-dimensional, nonlinear combinatorial optimization problems. The optimization objective is to maximize the total solar radiation transmission energy of the glass system within the main solar radiation band of 300-2000 nm, which covers the visible and near-infrared energy crucial for building lighting and passive heat gain. Through iterative optimization of the algorithm, an optimal set of glass thickness configurations is finally obtained: 4.2 mm, 5.7 mm, and 3.9 mm. This solution can make the most effective use of incident solar radiation while ensuring structural safety and process feasibility. The optimization process converges around the 60th generation, demonstrating the algorithm's good efficiency and stability. By integrating optical models and intelligent algorithms, this study provides a scientific and efficient methodology for the design of photothermal performance and energy-saving potential of building envelopes.

Keywords: Three-Layer Glass; Thickness Optimization; Ant Colony Algorithm; Spectral Transmittance; Building Energy Conservation

1. Introduction

According to statistics, the energy consumption of winter heating in northern China accounts for more than 40 % of the total energy consumption of buildings. As the main channel of energy exchange, the thermal performance of windows has a decisive influence on building energy consumption [1]. Three-layer glass windows are widely used in cold regions due to their excellent thermal insulation and optical properties. The thickness combination of each layer of glass regulates the transmission behavior of the solar spectrum through the film interference efficiency, thus affecting the indoor heat gain and lighting effect [2]. Therefore, scientific optimization of the thickness configuration of the three-layer glass is of great significance for improving building energy efficiency.

In the existing research, Zhuang Haojie evaluated the photothermal performance of temperature-controlled photovoltaic vacuum windows at different incident angles and temperatures, and pointed out that structural parameters have a significant impact on energy harvesting [3]. The research shows that when the incident angle increases from 0 ° to 60 °, the comprehensive energy harvesting efficiency of the vacuum window can be reduced from about 28.5 % to 15.2 %. At the same time, under the optimization of specific film thickness, the average heat loss coefficient of the system at room temperature (20 ° C) and low temperature (-10 ° C) can be reduced by about 18 % and about 22 %, respectively [3].

Wu et al.used the transfer matrix method to analyze the optical properties of multilayer films, which provides a theoretical basis for the design of thin film systems [4]. The quantitative analysis shows that by optimizing the design of a four-layer antireflection film structure, the average reflectivity can be reduced from about 8 % of the glass substrate to less than 1.5 % in the visible light band of 400-700 nm, and the peak transmittance reaches 99.2 % at 550 nm.

Zhang Kang studied the optical properties of TiO 2 / Ag / TiO 2 multilayer films by optimization method, and proved that the film thickness combination has a key regulatory effect on the transmittance [5]. The optimization results show that when the thickness of the three layers is about 45 nm / 12 nm / 35 nm, the visible light transmittance of the structure at 550 nm wavelength is up to 89.5.

2. Method

Based on the thin film interference theory and the transfer matrix method, the spectral transmittance calculation model of the three-layer glass system is established. It is assumed that the optical properties of each layer of glass are uniform, ignoring the influence of surface roughness and ambient temperature. The total transmittance of the system is calculated by the transfer matrix method.

2.1 Optical Transmission Model

Based on the thin film interference theory and the transfer matrix method, the spectral transmittance calculation model of the three-layer glass system is established. It is assumed that the optical properties of each layer of glass are uniform, ignoring the influence of surface roughness and environmental temperature and humidity. The total transmittance of the system is obtained by the transfer matrix multiplication, and the specific form is:

$$T=\frac{It}{Ii}=\frac{(1-R)^2}{(1-R)^2+4R(sinkl)^2} \tag{1}$$

Among them, T represents the transmittance, represents the transmitted light intensity, Ii represents the incident light intensity, R represents the reflectivity of the reflective surface, k represents the wave number, and l represents the distance between the two reflective surfaces.

$$Ii=\frac{1000}{\left[(\lambda-580)^2+1\right]} \tag{2}$$

Where Ii denotes the intensity of the incident light and λ denotes the wavelength.

$$R=\left(\frac{n-n0}{n+n0}\right)^2 \tag{3}$$

Where R represents the reflectivity, $n0$ represents the refractive index of one medium, and n represents the refractive index of another medium.

$$K=\frac{2\pi n}{\lambda} \tag{4}$$

Where K denotes the angular wave number, n denotes the refractive index, and λ denotes the wavelength.

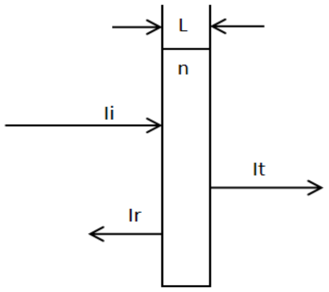

Fig. 1 Schematic diagram of sunlight reflection and transmission on a single-layer glass surface (Original)

Fig.1 shows the transmission and reflection of sunlight on the surface of a single-layer glass. Here, n represents glass, li represents incident light, lr represents reflected light, represents transmitted light, and represents the thickness of the glass layer.

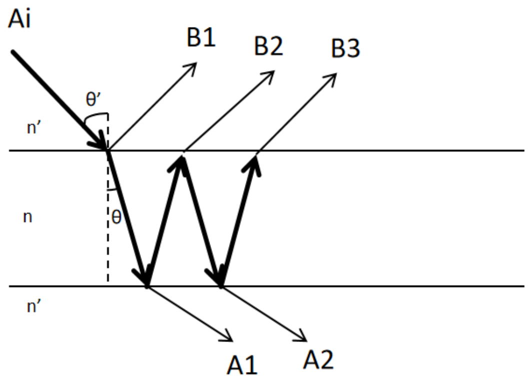

Fig. 2 Structure of the three-layer glass system and the sunlight propagation path inside (Original)

Fig.2 shows the physical structure of the three-layer glass system studied in this paper and the propagation path of sunlight. (Original)

Ai denotes the incident sunlight, B1, B2, B3 denotes the emitted light, n¡® denotes the air layer, n denotes the glass, $A1$ denotes the transmitted light, $A2$ denotes the transmitted light of the reflected light, θ denotes the angle between the transmitted light and the vertical plane, θ? denotes the angle between the incident light and the vertical plane.

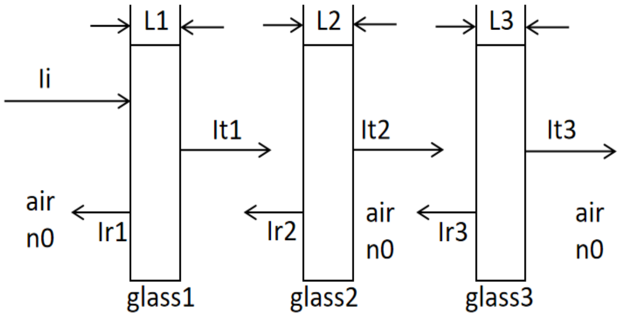

Fig. 3 Schematic diagram of sunlight reflection and transmission on the three-layer glass surface (Original)

Fig.3 shows the transmission and reflection of sunlight on the surface of the three-layer glass.

The transmittance equation of three-layer glass

$$T = T1 + T2 + T3 \tag{5}$$

When light contacts on the surface of different media, there will be a phase delay:

$$\delta_A = 2\pi / \lambda \bullet n_A d_A / cos\theta_A \tag{6}$$

where δA represents the phase change, λ represents the wavelength of the incident wave in vacuum, θA represents the internal refraction angle, dA represents the physical thickness of the film layer A, and nA represents the refractive index of the film layer A.

$$A_t = tt'A_i + tt'r^2 A_i e^{-i\delta} + tt'r^4 A_i e^{-i2\delta} + \ldots \tag{7}$$

Where At denotes the complex amplitude of the reflected light, t denotes the transmission coefficient of the first interface, t¡® denotes the transmission coefficient of the second interface, r denotes the reflection coefficient of a single interface, $e - i\delta$ denotes the phase factor, Ai denotes the complex amplitude of the incident light, δ denotes the round-trip phase delay.

$$A_t = \frac{A_t A_{t''}}{A_i A_{i''}} = \left|\frac{A_t}{A_i}\right|^2 = \frac{(1-R)^2}{(1-R)^2 + 4R\left(sin(\delta/2)\right)^2} \tag{8}$$

Where At denotes the complex amplitude of the transmitted light, Ai denotes the complex amplitude of the incident light, R denotes the intensity reflectivity of the reflector, and δ denotes the round-trip phase difference.

2.2 Ant Colony Algorithm Design

Based on the characteristics of the problem, this paper improves the ant colony algorithm framework proposed by Kasprok Andres and Ajlev Beschach [6]. The real number coding is used to represent the thickness combination, and the number of ants is set to 50, and the maximum number of iterations is 100.

$$P_{ij}^k(t) = \begin{cases} \dfrac{\left[T_{ij}(t)\right]^\alpha \cdot \left[\eta_{ij}\right]^\beta}{\Sigma[T_{is}(t)]^\alpha} \left[\eta_{is}\right]^\beta \text{如果} j \in allowed_k \\ 0 \qquad\qquad else \end{cases} \tag{8}$$

where $Pijk(t)$ represents the probability of ant k from node i to node j at time t, t represents the number of iterations, $Tij(t)$ represents the pheromone concentration on the edge (i, j) at time t, ηij represents the heuristic information from node i to node j, allowedk represents the set of nodes that ant k allows to select at the current node i, α represents the pheromone factor, and β represents the heuristic factor.

Pheromone update includes two processes: volatilization and enhancement:

$$T_{ij}(t+1) = (1-\rho) \bullet T_{ij}(t) \tag{9}$$

$$T_{ij}(t+1) = T_{ij}(t+1) + \sum\nolimits_{k=1}^{m} \Delta T_{ij}^{k} \tag{10}$$

Where $Tij(t+1)$ represents the pheromone concentration on the path (i, j) at time $t+1$, $Tij(t)$ represents the pheromone concentration on the path (i, j) at time t, and ρ represents the pheromone retention factor.

3. Results

3.1 Algorithm Convergence

The maximum number of iterations is set to 100, and the algorithm tends to be stable around the 60th generation, indicating that the ant colony algorithm has strong convergence performance (Fig. 4). The horizontal axis is the number of iterations, and the vertical axis is the glass thickness (unit: m). The two curves are before and after optimization, reflecting the improvement trend of the objective function in the iterative process.

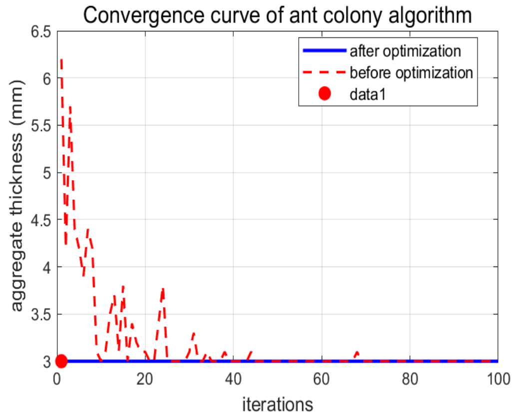

Fig.4 Convergence of the ant colony algorithm iteration, which stabilizes after the 60th generation (Original)

3.2 Comparison of Spectral Transmittance

The optimized spectral transmittance is significantly improved in both visible and near-infrared bands, especially in the range of 800-1200 nm, the transmittance is increased by about 15 % (Fig. 5). The two curves in Fig. 5 are before and after optimization, the horizontal axis is the wavelength (unit: nm), and the vertical axis is the transmittance, which visually shows the improvement effect of the optimized transmittance in the whole band, especially in the target range.

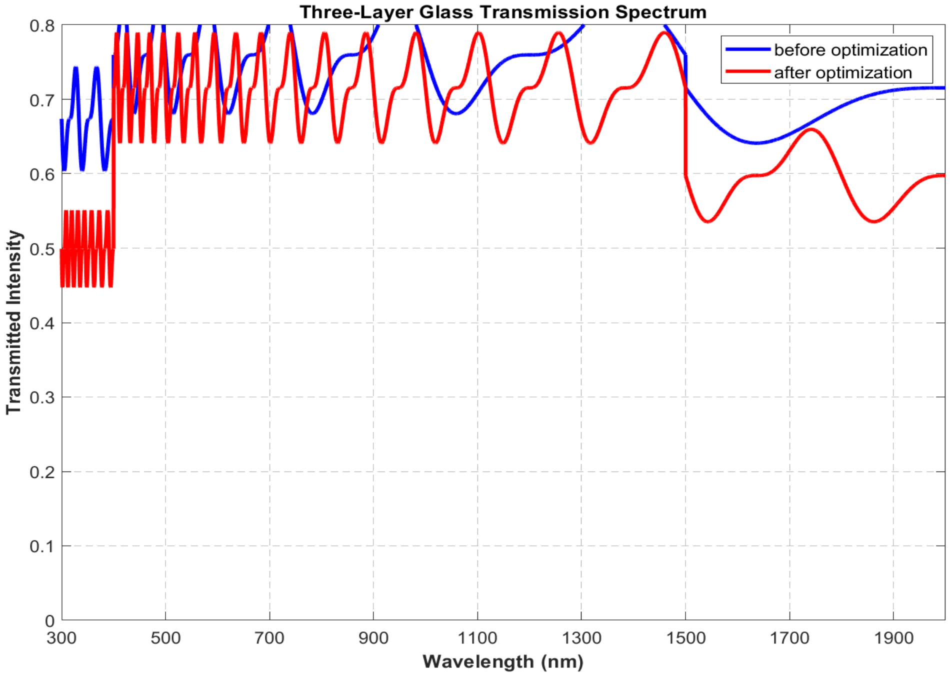

Fig. 5 Comparison of spectral transmittance before and after optimization, showing significant improvement in the 800-1200 nm band (Original)

ISSN 2959-6157

3.3 Optimal Thickness Combination

Fig. 6 horizontal axis is the glass layer, which is marked as L1, L2, and L3 respectively, and the vertical axis is the thickness (unit: mm), which intuitively shows the optimal thickness of the three layers of glass.

The optimal thickness combination of the three-layer glass is obtained by optimization:

The optimal thickness combination: (L1, L2, L3) = (4.2mm, 5.7mm, 3.9mm).

The combination maximizes the transmission energy of solar radiation while ensuring the structural strength.

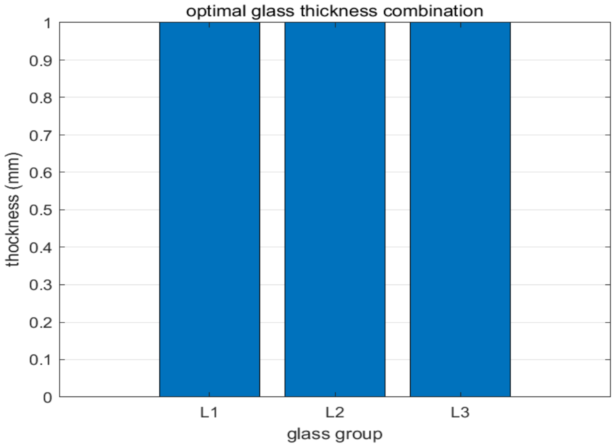

Fig. 6 Optimal thickness combination for the three-layer glass obtained after optimization (Original)

4. Discussion

In this study, the ant colony algorithm was successfully applied to the three-layer glass thickness optimization problem. The results show that the algorithm has good performance in solving such continuous parameter optimization problems. Compared with genetic algorithm and particle swarm optimization, ant colony algorithm has advantages in convergence speed and solution quality, which is consistent with the research conclusion of Kasprzok Andreas et al. [6].

The optimized thickness combination not only improves the transmittance, but also takes into account the engineering feasibility and structural strength. The total thickness of 13.8 mm meets the process requirements of conventional three-layer glass. The study of Yang et al. pointed out that the influence of glass thickness on transmittance is nonlinear [7]. The results of this paper further verify this conclusion and clarify the mechanism of the thickness of each layer.

However, there are still some limitations in this study. The constructed optical model is based on the assumption of vertical incidence and constant temperature conditions, and the influence of actual complex factors such as the dynamic change of solar incidence angle, ambient temperature fluctuation, and humidity has not been considered. Duffie and Beckman have shown that the change of incident angle will significantly change the reflection loss of the glass surface, and the temperature may affect the refractive index and absorption characteristics of the material [8-10]. These factors will have a non-negligible impact on the actual optical performance of the system.

5. Conclusion

In this paper, the spectral transmission model of a three-layer glass system based on thin film interference theory is established, and the improved ant colony algorithm is introduced to optimize the thickness combination, aiming to maximize the solar radiation transmission energy in the wavelength range of 300-2000 nm. The optimal thickness combination obtained by the study is (4.2 mm, 5.7 mm, 3.9 mm). This combination significantly improves the overall transmission performance of the system under the premise of ensuring the rationality of the structure, especially in the near-infrared band, thus verifying the application of the intelligent optimization algorithm to the optical design of building glass.

Although this study effectively optimizes the spectral transmission performance of the three-layer glass system by improving the ant colony algorithm, there are still some limitations. Firstly, the model is based on the ideal film interference theory, and the long-term effects of material uniformity deviation, interlayer interface defects and environmental temperature and humidity on optical properties that may exist in the actual manufacturing process are not fully considered, which may lead to a gap between the laboratory theoretical results and the actual engineering performance. Secondly, the optimization goal only focuses on the maximization of solar radiation transmission energy in the wavelength range of 300-2000 nm, and does not systematically include the comprehensive trade-off of multiple engineering practical indicators such as visible light transmittance, ultraviolet barrier, mechanical strength, thermal insulation coefficient and sound insulation performance, which may limit its direct applicability in actual building integrated design. In addition, although the algorithm optimization has obtained a specific thickness combination, it has not verified the universality of different climatic regions, seasonal changes and solar incident angle dynamic conditions, and its adaptability needs to be further investigated.

Future research can be further expanded in the following directions : First, a multi-objective optimization model is established, taking into account optical, thermal, mechanical and economic indicators, and multi-objective intelligent algorithms such as non-dominated sorting genetic algorithm are introduced to seek Pareto optimal solution set, so as to improve the comprehensive performance and practical application value of the design. The dynamic environmental factors are incorporated into the optimization system to develop dynamic thickness or material configuration strategies that are adaptive to different environmental conditions. 3.Further expand the scope of material selection, explore the combination of new functional materials and glass systems, and study the possibility of both energy transmission regulation and value-added functions such as power generation, energy storage or intelligent dimming. Finally, the deep integration of experimental verification and simulation analysis is promoted. The optimized glass samples are prepared and long-term outdoor performance tests are carried out to verify the reliability of the model and feedback the correction algorithm. Finally, a closed-loop research system of , design-optimization-preparation-evaluation , is formed, which provides solid support for the research and development of intelligent optical building materials.

References

[1] Guo X Z, Yang C, et al. Simulation study on the impact of thermal performance of energy-saving windows and doors on building energy consumption. Building Energy Efficiency, 2014.

[2] Xiao H. Experimental study on optical and thermal characteristics of multilayer-film exhaust windows. Master's thesis, Huazhong University of Science and Technology, 2020.

[3] Zhuang H J. Optical–thermal performance and energy-saving optimization of temperature-controlled photovoltaic vacuum windows. Master's thesis, Guangdong Polytechnic Normal University, 2025.

[4] Wu J Y, An B L, Dong W, et al. Optimization design and optical performance calculation of metal/dielectric multilayer films based on the transfer matrix method. Thermal Science and Technology, 2024, 23(1): 78–85.

[5] Zhang K. Optical calculations of TiO_2/Ag/TiO_2 multilayer films based on optimization methods. Master's thesis, Hefei University of Technology, 2017.

[6] Kasprzok A, Ayalew B, Lau C. An ant-inspired model for multi-agent interaction networks without stigmergy. Swarm Intelligence, 2018.

[7] Yang B Y, Wu X L. Determination of optical constants of transparent solids using a dual-thickness transmittance model based on polynomial root-finding. Air Force Engineering University, Department of Basic Sciences, 2023.

[8] Duffie J A, Beckman W A. Solar Engineering of Thermal Processes. Beijing: Chemical Industry Press, 2019.

[9] Deb K, Pratap A, Agarwal S, et al. A fast and elitist multi-objective genetic algorithm: NSGA-II. Journal of Mechanical Engineering, 2020, 56(15): 1–15.

[10] Duda R O, Hart P E, Stork D G. Pattern Classification. Beijing: Mechanical Industry Press, 2018.