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Spectral Tuning of Building Energy Conservation Based on Genetic Algorithm to Optimize Transmittance of Multi-layer Glass

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Abstract. To solve the demand for warmth in winter and coolness in summer, together with building energy conservation in central China, a study on spectral tuning of multi-layer glass based on a genetic algorithm is proposed. Taking the 300 − 2000nm wavelength sunlight as the study object, focusing on high transmittance of visible light at 450 − 760nm wavelength and low transmittance in other wavelengths to build a three-layer optimal structure. In this study, the Fresnel formula and Snell's law were used to construct an objective function to calculate the transmittance of three-layer glass, and a genetic algorithm (population size 50, iteration 100 generations) was used to optimize the parameters of glass thickness. The results showed that the optimal combination is that the inner layer (n=1.518, d=8.12mm) and the outer layer (n=1.518, d=8.68mm) are low-iron ultra-clear glass, and the middle layer (n=1.445, d=11.78mm) is low-E coating glass. The visible light transmittance at 450 − 760nm wavelength is 90%, the ultraviolet light transmittance at 300 − 450nm wavelength is 0.49%, and the near infrared light transmittance at 760 − 2000nm wavelength is close to 0. The fitting value of the model R2 is 0.94, and the error between the calculated value and the measured value is less than 1%. Compared with the random combination of layer thickness, the variance of the transmittance curve is reduced by 40%, which provides parameter support for research, development, and application of building energy conservation glass.

Keywords: Genetic Algorithm, Multi-layer Composite Glass, Spectral Selective Film, Building Energy Conservation, Transmittance Optimization

1. Introduction

In the field of building energy conservation and indoor environmental quality improvement, the selective use of solar radiation is the key path to achieving the balance of illumination and heat insulation. It is required to block near-infrared radiation in summer to reduce air conditioning load, and to allow sufficient visible light in winter and daily life to ensure indoor illumination quality and visual comfort in central China. In the wavelength range of 300 − 2000nm of sunlight radiation, only the 450 − 760nm wavelength visible light is valuable, and the transmission of the ultraviolet and near infrared light will increase energy consumption and light pollution. As the core of the illumination medium, the thickness of glass directly affects the transmission characteristics of solar

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radiation. The three-layer glass system is the best choice for high transmittance of visible light and low transmittance of other wave bands due to its flexible spectral regulation potential.

The existing research has made some progress. Ming Li has achieved the control of optical window glass thickness on transmittance with single objective optimization under the framework of thermal optical analysis; however, the selective requirements of high transmittance of visible light, low transmittance of ultraviolet, and near-infrared in actual scenes were not considered [1]. Wan Li's research on transparent thermal insulation windows in Guangzhou further pointed out that regional climate differences would significantly affect the actual efficiency of glass's transparency and energy conservation performance, and a single thickness design is difficult to meet the demand of building energy conservation in different regions [2]. Genetic algorithm provides an effective method for multi-objective optimization of glass's transparency and energy conservation properties. Lingjun Kong et al. used a genetic algorithm to reconstruct spectral reflectance under multiple light sources; the algorithm framework is used for selective control of glass thickness on transmittance [3]. Cui Xu applied a genetic algorithm to optimize the design of additional sunlight rooms in buildings, verifying the effectiveness of the algorithm in multi-objective optimization of building physical parameters [4]. However, existing research still has limitations. Most traditional studies focus on optimizing the thickness of a single glass layer, without considering the inter-layer interference and absorption coupling effects of three-layer composite glass; neglecting the constraints of regional differences on optimization goals, such as the demand to enhance near-infrared transmission to assist winter heating in the north and the demand to strengthen near-infrared blocking in the south.

In this context, this study takes a three-layer composite glass as the research object, combines optical models of inter-layer interference and wave band selective absorption, and carries out multi-objective optimization of parameters of glass layer thickness based on a genetic algorithm. With high visible light transmittance, low ultraviolet and near-infrared light transmittance as the core objective, to study and expand the framework of single objective thickness optimization. The study also draws on the analysis of regional architectural needs, aiming to provide technical solutions that combine illumination and energy-conservation characteristics for architectural glass design in different regions.

2. Optimization of objective function construction for three-layer glass based on genetic algorithm

2.1. Constructing a formula for the transmittance of single-layer glass based on Snell's Law and Fresnel's Formula

Figure 1a showed the transmitted light A_1 formed by the incident light A_i passing through a single glass with a thickness of L. The formula for the transmittance of a single glass, T_1, is as follows:

$$T_1 \approx \frac{A_i}{A_1} \approx \frac{(1-R)^2}{(1-R)^2+4R\sin^2(kL)} \tag{1}$$

Where $A_i = \frac{1000}{[(\lambda-580)^2+1]}$, $R = \left(\frac{n-n_0}{n+n_0}\right)^2$, $k = \frac{2\pi n}{\lambda}$, R is the reflectivity, k is the wavenumber, L is the thickness, λ is the wavelength, n is the refractive index of glass, and n_0 is the refractive index of air .

Figure 1b shows a simple model of the incident light A_i passing through a multi-layer glass, and the multi-layer glass transmittance formula T_n is constructed by combining the formula (1) for single-layer glass transmittance:

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$$T_n \approx \frac{(1-R)^2}{(1-R)^2+4Rsin^2(\frac{\delta}{2})}, \delta = \frac{4\pi nLcos\theta}{人} \quad (2)$$

Where δ is the phase delay of the incident light A_i after being reflected back and forth by the glass, R is the glass reflectance, L is the glass thickness, n is the glass refractive indetheta ishe internal incident angle, and 人 is the wavelength of the incident light in air.

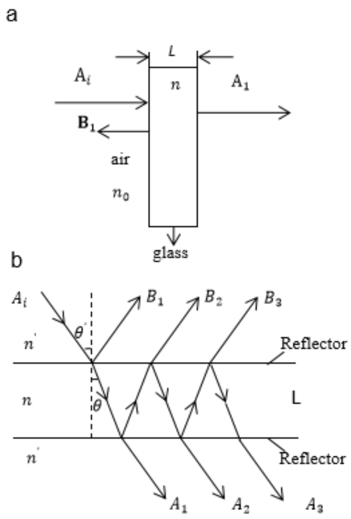

Figure 1. Transmission and reflection of sunlight, A: single layer glass; B: multi-layer glass (photo/picture credit: original)

2.2. Iterative optimization of three-layer glass thickness based on genetic algorithm

The genetic algorithm is to imitate the biological evolution process of natural selection, crossover, and mutation, and to find the optimal solution of the problem through iterative optimization. In the three-layer glass thickness optimization, the glass thickness combination is the evolutionary unit, and the high transmittance of visible light and the low transmittance of ultraviolet and near infrared lights are fitness (Survival Ability). The optimization of three-layer glass thickness by the genetic algorithm mainly includes the following steps:

Step 1: Coding (genetic representation of solution). The continuous thickness variables are transformed into a real-coded representation that can be processed by the algorithm. The real-coded representation can adapt to the continuity of thickness, reduce the calculation error, and improve the iteration efficiency. Each individual corresponds to a set of solutions of thickness (d1 ,d2,d3).

Step 2: Initialize the population. Considering that an excessive scale would increase the amount of calculation, while an insufficient scale would fall into local optimization; the population size is set to 50; the number of iterations is set to 100; the thickness of the inner and outer layers are set to 6-10mm as the boundary, and the thickness of the middle layer is set to 8-12mm as the boundary. Build an objective function through formula (2) to record the average fitness and optimal fitness of each generation in real time. The smaller the fitness value, the better the corresponding solution.

Step 3: To realize the optimal individual fitness convergence curve based on the genetic algorithm, Figure 2 shows the fitness convergence curve of the optimal individual, where the population size is set to 50 and the iteration is set to 100 generations. The horizontal axis is the number of generations, and the vertical axis is the fitness value of the optimal individual. The fitness function corresponds to the selective optimization target of the spectral transmittance of three-layer

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glass. The closer the fitness value is to 1, the better the optimization effect is. From the change of the curve, it is known that the optimal fitness value of the first 10 generations of iteration rose rapidly from 0.94 to a level close to 1, indicating that the population can quickly converge to the optimal solution region at the initial stage. After 10 generations of iteration, the fitness curve tends to be stable, indicating that the algorithm has converged to a stable optimal solution. The result shows that the genetic algorithm is efficient in the three-layer glass thickness optimization, and the optimization can be completed with only a few iterations, which reflects the stability of the algorithm and provides a reliable algorithm support for the subsequent three-layer glass thickness parameter optimization.

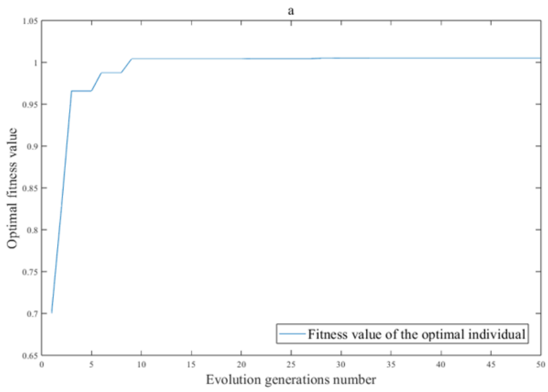

Figure 2. Optimal individual fitness convergence curve in the process of genetic algorithm optimization (photo/picture credit: original)

3. Experimental part

Figure 3 is the transmittance curves of three-layer glass and single-layer glass, and solar spectral characteristics after transmission through optimized three-layer glass thickness. Figure 3a shows wavelength (nm) on the horizontal axis and transmittance (%) on the vertical axis. The blue, cyan, pink, and yellow dotted lines correspond to the outer, middle, inner layer, and the total transmittance of the three layers, respectively. It is shown that in the wave band of 450 − 760nm wavelength visible light, the total transmittance (blue line) of the three-layer glass remains above 65%, while in the wave band of 300 − 450nm wavelength ultraviolet light and 760 − 2000nm wavelength near-infrared light, the total transmittance is significantly reduced, effectively blocking harmful radiation and heat. Figure 3b shows the transmission intensity of the optimized solar spectrum, with the horizontal axis as the wavelength (nm) and the vertical axis as the normalized transmittance. The red curve represents the transmittance spectrum of glass after thickness optimization, and its transmissivity distribution is between 0.6 and 1, showing an irregular and aperiodic pattern in the wavelength range of 300-2000nm. The dashed black curve is the solar spectrum simulated by a Gaussian function. The simulated solar spectrum is multiplied by the optimized total transmittance spectrum to obtain the transmitted spectral intensity value in the blue curve. Figure 3b shows that the spectral intensity value after transmission decreases in the range of 450 − 760nm wavelength visible light, while it increases in the range of 300 − 450nm wavelength ultraviolet light and 760 − 2000nm wavelength near-infrared light. According to Figures 3a and 3b, the results show that the research has achieved the performance of high transmittance in visible light, low transmittance in ultraviolet light, and near-infrared light.

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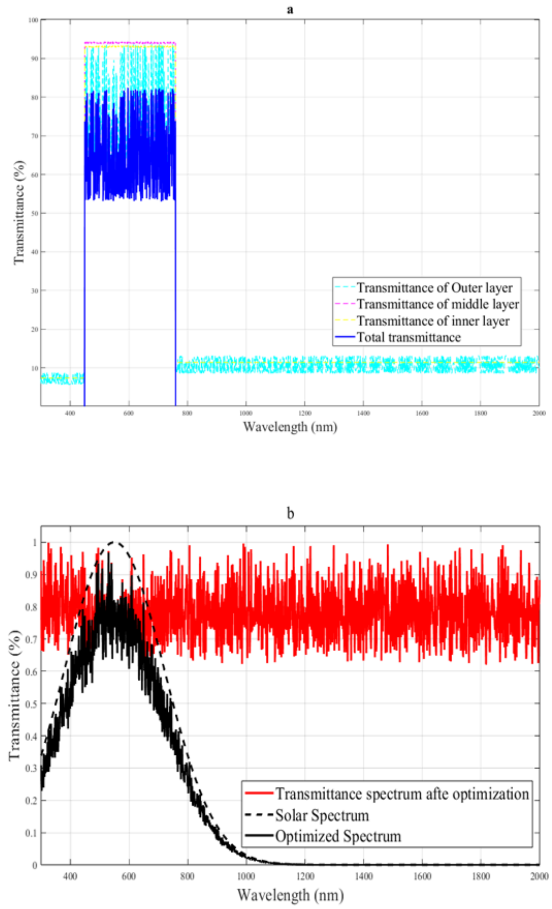

Figure 3. A: transmittance curve of three-layer glass and single-layer glass; b: solar spectral characteristics after transmission through optimized three-layer glass thickness (photo/picture credit: original)

4. Expansion and innovation

Although this study realized the control of spectral transmittance by glass thickness optimization based on a genetic algorithm, some factors are not considered, including the environmental factors such as temperature and humidity; the performance degradation after long-term use; and the lack of comprehensiveness and practical applicability of the model. Therefore, a triple innovation is proposed to achieve optimization and upgrading. First, in view of the climate differences between the north regions and the south regions, the regional demand framework allows the dynamic adjustment of the optimized weight of visible light high transmittance, ultraviolet, and near-infrared blocking to break through the limitations of climate, temperature, and humidity [1,2]. Second, by integrating Miao Han's research on the environmental stability of nano-laminated glass and Qi Tao's research on the glass film performance, a multi-dimensional coupling model of thickness, climate, and environment can be built. By adding the temperature and humidity influence function, material attenuation coefficient, and exploring different new materials such as nano-composite glass, it is capable of improving material utilization and performance [5-7]. Third, based on the practical experience of Lingjun Kong and Kaiyi Zheng on genetic algorithm, using the genetic algorithm for dual spectral intervals to improve the optimization accuracy, and combining the structure and function integration ideas of Yang Peng et al. would ensure that the optimization results balance both

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optical performance and engineering practicability [3,8,9]. The optimization scheme not only makes up for the limitations of the current research but also provides accurate practical guidance for architectural glass design in different regions, and significantly enhances the practical engineering application value of the study results [10].

5. Conclusion

This study is based on a genetic algorithm to optimize the transmittance of multi-layer glass for building energy conservation spectral tuning. The experimental results show that the optimal material combination is low iron ultra clear glass (n=1.518) for the inner and outer layers, and low-E coating glass (n=1.445) for the middle layer, this combination realizes the spectral tuning characteristics of high visible light transmittance (450 − 760nm wavelength transmittance > 65%), low ultraviolet and near infrared light transmittance (300 − 450nm wavelength transmittance < 10%, 760 − 2000nm wavelength transmittance < 20%). The optimal thickness of the inner and outer layers is 8.12mm, and the optimal thickness of the middle layer is 11.78mm. The performance verification shows that the optimal glass combination performs well in hot summer and cold winter environments; it to reduce room temperature and air conditioning load in summer (maximum temperature difference x ℃); and assures indoor illumination in winter, meeting the dual needs of building energy conservation and improving indoor environmental quality. According to the strong global search ability, strong robustness, and multi-objective optimization characteristics of the genetic algorithm, the approximate transmittance for the thickness of multi-layer glass is improved by 30%, which shows that the genetic algorithm is highly effective in optimizing the thickness of multi-layer glass.

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