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Achieving Dual Objectives of Maximizing Transmitted Solar Energy and Minimizing UV Transmission at Vertical Incidence

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Abstract. In northern China, exterior window glass significantly impacts heating energy consumption during winter by collecting heat and providing insulation. Additionally, it plays a crucial role in shading by attenuating ultraviolet rays. This paper presents an intelligent optimization algorithm based on genetic algorithms for optimizing the thickness of three-layer insulating glass to maximize solar radiation transmission and minimize ultraviolet radiation below 400nm wavelength, thereby enhancing the glass's heat collection and shading capabilities. The study utilizes MATLAB's genetic algorithm function, running 20 iterations to overcome local optima, achieving an optimal glass thickness configuration of 12mm for each layer. This configuration allows maximum solar energy transmission while substantially reducing UV radiation, balancing energy efficiency with health protection. Future research directions include examining different glass materials' effects on UV blocking, considering climate change impacts on glass performance, and scaling the optimization method for large-scale architectural applications to assess its practical and economic viability. The findings contribute to the development of energy-efficient and health-protective building materials.

Keywords: Insulating glass, genetic algorithm, optimization, heat collection, shading.

1. Introduction

Building exterior windows are essential for providing indoor lighting, ventilation, and scenic views, while also serving as primary conduits for heat exchange between a building's interior and the external environment. In northern regions, particularly during winter, these windows play a crucial role in heat collection and retention, significantly influencing heating energy consumption. Additionally, exterior windows are vital in reducing ultraviolet (UV) radiation, thus mitigating health risks such as skin erythema, pigmentation, sunburn, and even skin cancer [1]. These dual functions—heat conservation and UV protection—are critical to the design and functionality of energy-efficient windows.

Energy-saving windows, which aim to minimize heat exchange between indoor and outdoor environments while maintaining thermal insulation, have become increasingly prevalent. These windows are categorized into conventional types, such as heat-absorbing glass, double-layer, and multi-layer insulating glass, as well as Low-E glass. Newer innovations include aerogel-filled, phase-change, color-changing adjustable, and solar photovoltaic energy-saving windows. Among these, insulating glass windows stand out due to their low cost, simple manufacturing process, and widespread use [2].

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Current optimization methods for insulating glass primarily focus on enhancing the thermal properties of interlayer materials, such as replacing air with inert gases, incorporating aerogel, or creating vacuum glass [3-6]. However, these approaches often face challenges related to high costs and limited lifespan, and they have not fully explored the role of thermal and solar radiation in optimizing window performance.

This paper addresses the gaps in existing research by focusing on the optimization of three-layer insulating glass. An intelligent optimization algorithm based on genetic algorithms is proposed to maximize solar radiation transmission while minimizing the attenuation of ultraviolet rays with wavelengths below 400nm. This approach aims to enhance the glass's heat collection and shading capabilities without increasing costs or adding complexity to the manufacturing process. The study's methodology, results, and implications for improving energy efficiency and UV protection in building materials are discussed in detail [7].

2. Theoretical Framework

2.1. Optical modeling of triple-layer insulating glass

Assume that sunlight is incident vertically from air into three layers of insulating glass and transmits into air, and the interlayers of the insulating glass are all air. Assume that the solar spectrum is a Gaussian spectrum with half-width $FWHM$ = 500nm, central wavelength λ_0 = 580nm, and central intensity 1000 [8]. The refractive index of air n_0 = 1.0 and the refractive index of glass n = 1.5. At this time, the transmission and reflection relationship of sunlight between the three layers of insulating glass is shown in Figure 1, where the meanings of the symbols are shown in Table 1.

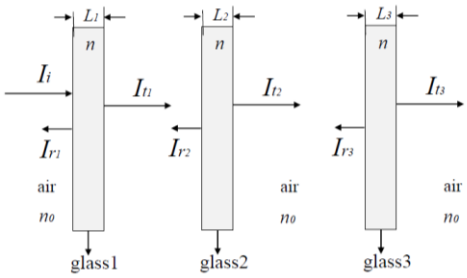

Figure 1. Relationship between transmission and reflection of sunlight between three layers of insulating glass (Photo credit: Original).

Table 1. Symbol meaning comparison table in Figure 1

Symbol	Meaning
n	Glass refractive index
n_0	Air refractive index
L_1	thickness of glass1
L_2	thickness of glass2
L_3	thickness of glass3
I_i	incident light intensity
I_{r1}	The reflected light intensity of the glass1 surface
I_{r2}	The reflected light intensity of the glass2 surface
I_{r3}	The reflected light intensity of the glass3 surface
I_{t1}	The intensity of transmitted light through glass1
I_{t2}	The intensity of transmitted light through glass2
I_{t3}	The intensity of transmitted light through glass3

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At this time, the transmittance.

$$T = \prod_{m=1}^{3} T_m = \prod_{m=1}^{3} \frac{I_{tm}}{I_{im}} = \prod_{m=1}^{3} \frac{(1-R)^2}{(1-R)^2 + 4R\, sin^2(kL_m)} \tag{1}$$

Among them, the reflectivity.

$$R = (\frac{n-n_0}{n+n_0})^2 \tag{2}$$

$$k = \frac{2\pi n}{\lambda} \tag{3}$$

$$\sigma = \frac{FWHM}{2\sqrt{2\, ln\, 2}} \tag{4}$$

$$I_{i1} = I_i = 1000e^{-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}} \tag{5}$$

$$I_{i3} = I_{t2} \tag{6}$$

$$I_{i2} = I_{t1} \tag{7}$$

2.2. Genetic algorithm configuration

The ga function of MATLAB R2021b is used for simulation. The thickness of the three-layer glass is set as variable x, ranging from 0.1mm to 12mm. The total intensity of sunlight in the full frequency band (wavelength 300nm to 2000nm) is recorded as I_total, and the intensity of ultraviolet light (wavelength below 400nm) is recorded as I_UV [9]. The difference between the two is used as the objective function f(x) of the genetic algorithm, in order to obtain the glass thickness that maximizes the transmission of solar radiation and maximizes the attenuation of ultraviolet light with a wavelength below 400nm. Considering that the genetic algorithm is prone to fall into the local optimum, it is run 20 times in a loop to obtain the optimal value [10].

3. Results

3.1. Optimal solutions and objective functions

Running the program obtains the optimal x = [0.012,0.012,0.012] and the optimal f(x) = 312086.0368. At this time, I_total = 3.8804×10^5 and I_UV = 7.5951×10^4.

3.2. Relationship between wavelength, incident light, and transmitted intensity

The relationship between wavelength and incident light and transmitted light intensity is shown in Figure 2.

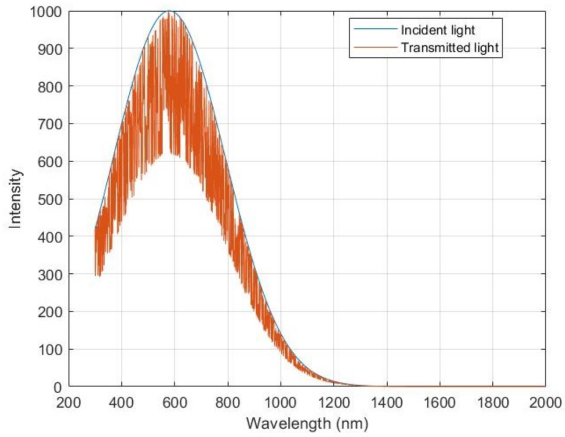

Figure 2. Relationship between wavelength and incident light and transmitted light intensity (Photo credit: Original).

It can be seen that the intensity of incident light and transmitted light is similar at this time, which is in line with the expectation of maximizing the transmission of solar radiation. At the same time, the intensity of ultraviolet rays with a wavelength below 400nm is low, which is in line with the expectation of maximizing the attenuation of ultraviolet rays with a wavelength below 400nm.

3.3. Iteration analysis: convergence and optimization efficiency

The relationship between the number of running times, f(x) and the optimal f(x) is shown in Figure 3.

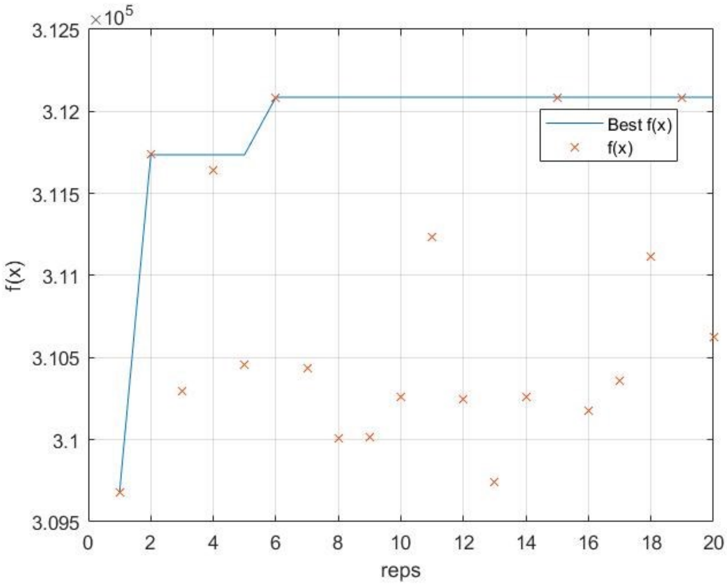

Figure 3. Relationship between running times(reps), f(x) and optimal (Best) f(x) (Photo credit: Original).

It can be seen that multiple runs to obtain the optimal value can effectively alleviate the problem that the genetic algorithm is prone to fall into the local optimum.

4. Conclusion and Challenges

This study successfully developed an intelligent optimization algorithm based on genetic algorithms to optimize the thickness of three-layer insulating glass. The primary objective was to maximize solar radiation transmission while minimizing ultraviolet (UV) radiation below 400nm, enhancing both the heat collection and shading capabilities of the glass. The optimal glass thickness configuration determined by the algorithm was 12mm for each layer, achieving a significant reduction in UV transmission while maintaining high solar energy throughput. This demonstrates the effectiveness of the genetic algorithm in optimizing complex multilayer structures for improved energy efficiency and health protection.

Future studies could explore the impact of non-vertical sunlight incidence on the performance of optimized glass structures, as this study was limited to vertical incidence scenarios. Additionally, investigating the use of different glass materials or incorporating transparent films with varying properties could further enhance the effectiveness of UV attenuation and solar energy transmission. Expanding the optimization approach to include these variables will provide a more comprehensive understanding of the potential applications and benefits of advanced insulating glass in diverse environmental conditions.

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