Optimal Design of Triple-Layer Glass Thickness Based on Quantum Genetic Algorithm and Its Influence on Solar Energy Transmission

Jinghe Ye [1, a)] and Ruijie Yang[2]

[1] *College of International Collaboration (Houston International Institute), Dalian Maritime University, Dalian, Liaoning, 116026, China*
[2] *School of Computer Science, Xi'an Shiyou University, Xi'an, Shaanxi, 710399, China*

[a)] Corresponding author: jye14@cougarnet.uh.edu

Abstract. As China's urbanization process accelerates, the problem of building energy consumption becomes increasingly prominent. As one of the main sources of building energy consumption, the optimized design of glass windows is crucial to energy conservation and emission reduction in the construction industry. This study innovatively introduces the quantum genetic algorithm (QGA) to optimize the layer thickness parameters of the three-story building glass structure, designed to maximize solar transmission energy in the 300-2000 nm band. The experiment uses smoothing splines to fit the real solar spectrum, simulate different incident angles, optimize the initial population size to 100, the chromosome length to 20, and obtain the optimal thickness combination: L1=5.5692 mm, L2=7.2072 mm, L3=3.5401 mm. The transmittance reaches 98.186%. Compared with single-layer glass, the energy gain of the optimized triple-layer glass is increased by 12%, providing a more efficient solution for building energy conservation and indoor thermal comfort in cold northern regions, and has significant practical application value. In the future, it can further explore new materials and structures on this basis and expand application scenarios.

INTRODUCTION

In recent years, with the acceleration of China's urbanization process, the problem of building energy consumption has become increasingly prominent. In 2018, the total energy consumption of the entire construction process in China was 2.147 billion Tons of Coal Equivalent (TCE), of which 1 billion TCE was consumed in the building operation stage, accounting for 21.7% of the total energy consumption in China. In 2018, the total carbon emissions from the entire construction process in China were 4.93 billion tons of carbon dioxide (tCO2), accounting for 51.3% of the country's carbon emissions. Carbon emissions during the building operation phase are 2.11 billion tons of tCO2, accounting for 21.9% of the national carbon emissions. The energy exchange of building envelopes, especially glass windows, accounts for more than 30% of the total energy consumption of buildings and is the main source of building energy consumption [1].

Glass curtain walls are widely used in modern buildings due to their good lighting, lightweight weight and high strength, especially in cold northern regions. Their design optimization is of great significance for improving indoor thermal comfort in winter and reducing heating energy consumption. As an exterior window structure with superior performance, the triple-glazed system is superior to the traditional double-glazed structure in terms of thermal insulation, but its optical performance is greatly affected by multi-layer interference and thickness parameters. If it is not designed properly, the solar energy transmission efficiency will be reduced. Therefore, improving the light transmittance of glass while ensuring thermal insulation performance is one of the key technical paths to achieve the goal of low-carbon buildings.

Existing research mainly starts from the two aspects of structural optimization and material performance, and uses numerical simulation or intelligent algorithms to analyze and improve the thermal-optical properties of multi-layer glass. For example, Kim studied the structure of triple-glazed windows and exhaust windows, proving that increasing the exhaust flow rate will reduce the heat absorption of the space [2]. Basok et al. investigated the differences in heat transfer between different gases in triple-glazed windows and proved that argon has better thermal resistance than air [3]. In recent years, it has gradually become a trend to optimize the parameters of multilayer membrane structures by combining intelligent optimization algorithms. For example, Zang Nan and Li Jian optimized the parameters of double-layer coated photovoltaic glass using the Firefly optimization algorithm, effectively improving the transmittance and reducing the reflectivity, significantly improving the power generation efficiency of the double-glass monocrystalline silicon photovoltaic system [4]. Hua will apply the improved quantum genetic algorithm to the optimization of building energy models, better manage the over-discharge of energy storage devices and reduce the peak-valley difference on the grid side, optimize the energy distribution on the supply side, and achieve better economic results [5]. These achievements provide theoretical and methodological support for the intelligent design of architectural glass.

Combining the above research background and technological development trends, this paper innovatively introduces the Quantum Genetic Algorithm (QGA) to optimize the layer thickness parameters of three-layer architectural glass, aiming to maximize the transmitted energy of sunlight in the 300–2000 nm band, providing an efficient and intelligent design method for improving the photothermal performance of architectural glass.

METHOD

Quantum genetic algorithm is a new probabilistic evolutionary algorithm that combines quantum computing ideas with genetic algorithm mechanisms. It has strong global search capabilities and good convergence performance, and is suitable for solving complex optimization problems such as nonlinear and multi-peak problems. Compared with the traditional genetic algorithm's solution-by-solution search, it reduces the risk of falling into the local optimum [6].

The algorithm process first uses quantum bit encoding to initialize the population, and each individual represents a set of glass layer thickness parameters. The population initialization operation is shown as follows. Where P_j^t is the quantum representation of the jth chromosome in the tth generation， α is the probability amplitude of the quantum bit being in state 0, and β is the probability amplitude of the quantum bit being in state 1. m represents the number of quantum genes, that is, the length of the chromosome.

$$P_j^t = [\alpha_1^t, \alpha_2^t, \alpha_3^t, \dots, \alpha_m^t; , \beta_1^t, \beta_2^t, \beta_3^t \dots, \beta_m^t] \tag{1}$$

Quantum coding enables the initial population to have a wide coverage of the solution space. Subsequently, the individual quantum states are observed and decoded, converted into specific thickness values and substituted into the optical model. The corresponding transmittance is then calculated as the fitness value in combination with the real sunlight data. The calculation formulas for interface reflectivity and transmittance are as follow： R represents reflectivity, T represents transmittance. N represents the number of medium layers in the system, k represents the current number of layers， and n represents the refractive index of each layer of medium.

$$\mathrm{R_k} = \left(\frac{\mathrm{n_k} - \mathrm{n_{k+1}}}{\mathrm{n_k} + \mathrm{n_{k+1}}}\right)^2, \mathrm{k} = 1,2, \dots, \mathrm{N} - 1 \tag{2}$$

$$\mathrm{T} = (1 - \mathrm{R_k})^2 \tag{3}$$

But at the same time, the phase delay of light on each layer of glass must be taken into account. The phase delay formula is as follows, where θ is the incident angle, d is the thickness of the glass layer, and λ is the wavelength.

$$\delta_k = \frac{2\pi n_k d_k cos\theta}{\lambda} \tag{4}$$

Therefore, the transmittance is iteratively updated as:

$$T \leftarrow \frac{T}{(1 - R_k)^2 + 4R_k sin^2(\delta_k)} \tag{5}$$

Finally, the weighted integral transmittance of the solar spectrum is calculated as the fitness function of the population:

$$F(d1,d2,d3)=\int_{\lambda_2}^{\lambda_1} T(\lambda;d_1,d_2,d_3)\cdot I(\lambda)d\lambda \tag{6}$$

Based on the fitness evaluation, QGA updates the population by simulating the quantum revolving door mechanism to guide the search direction. Its core is to dynamically adjust the quantum bit state based on the comparison results between the current individual and the optimal individual, thereby increasing the probability of retaining excellent solutions and suppressing inferior solutions. The operation of updating the population of the quantum rotating gate can be expressed as follows [7]. Where i is the current number of quantum bits.

$$\begin{bmatrix}\alpha_i\\ \beta_i\end{bmatrix}=\begin{bmatrix}cos(\Delta\theta_i) & -sin(\Delta\theta_i)\\ sin(\Delta\theta_i) & cos(\Delta\theta_i)\end{bmatrix}\begin{bmatrix}\alpha_i\\ \beta_i\end{bmatrix} \tag{7}$$

The optimization process continues to iterate until the preset maximum number of generations is reached.

EXPERIMENTAL DESIGN

To more accurately simulate the actual energy distribution of sunlight entering the room, the experiment referenced real data of sunlight [8]. By adopting the smoothing spline fitting method, it constructed an approximate real solar spectrum curve (Figures 1, 2). This curve not only captures non-periodic trends such as the broad peak characteristics of the solar spectrum and slowly changing background radiation, but also better simulates actual conditions such as low-angle incidence, atmospheric scattering, and cloud attenuation in winter. The horizontal axis in Figure 1 is the wavelength range of the solar spectrum (300-2000nm), and the vertical axis is the radiation intensity of sunlight at different wavelengths (W/m²/nm). Its distribution characteristics intuitively reflect the concentrated radiation of short-wave visible light (380-780nm) and the continuous attenuation characteristics of the near-infrared band (780-2000nm).

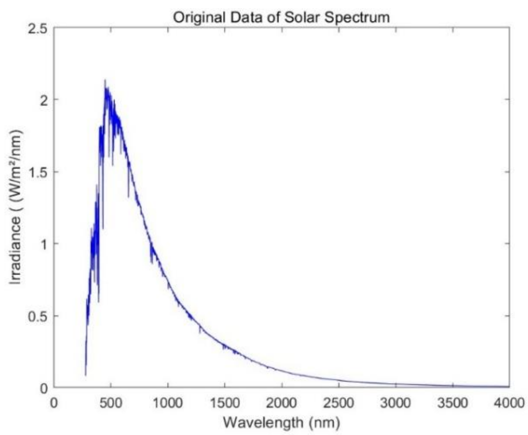

FIGURE 1. Solar spectrum raw data image (Photo/Picture credit: Original).

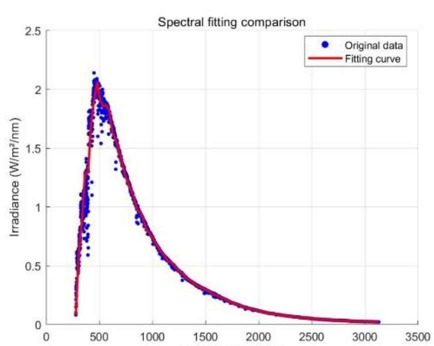

FIGURE 2. Comparison of smoothing spline fitting solar spectrum before and after (Photo/Picture credit: Original).

To truly reflect the changes in the sun's position, the experiment also simulated the situation of sunlight entering three layers of glass at different incident angles (Table 1). The multiple sets of data obtained showed that the closer the incident angle is to vertical incidence, the higher the final total transmittance (Figure 3). The horizontal axis in Figure 3 represents the incident angle, and the vertical axis is maximized as the angle approaches zero, and the vertical axis represents the transmittance.

TABLE 1. Maximum transmittance at different incident angles of sunlight

Angle of incidence	L1	L2	L3	Transmittance
0°	5.5692	7.2072	3.5401	0.9818
15°	4.9743	8.3745	5.8196	0.9783
30°	5.9264	6.7217	3.7638	0.9788
45°	7.5268	8.2324	3.7997	0.9742
60°	7.7616	7.9002	4.9602	0.9745
75°	4.2353	6.3530	3.3020	0.9719

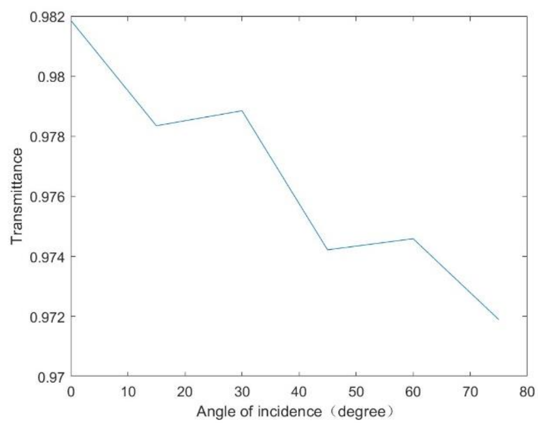

FIGURE 3. Trend of the impact of incident angle on transmittance (Photo/Picture credit: Original).

Considering that the initial population size and chromosome length may be important factors affecting the final transmittance, the experiment tested multiple parameter combinations with different population sizes and chromosome lengths. When testing parameters, fewer evolutionary generations are used to measure which set of parameters can converge faster and achieve better fitness. The final results show that the parameter combination of initial population size 100 and chromosome length 20 can achieve the highest fitness after 100 evolutionary generations (Table 2).

TABLE 2. Different population size and chromosome length parameter combinations and their fitness

Population size	Chromosome length	Population fitness after 100 generations of evolution
50	10	0.9579
50	20	0.9641
50	30	0.9608
100	10	0.9619
100	20	0.9701
100	30	0.9636
150	10	0.9600
150	20	0.9610
150	30	0.9579

RESULT

Based on the above optimization scheme, the experiment used a parameter combination of an initial population size of 100 and a chromosome length of 20 for testing. Considering the probabilistic characteristics of the quantum genetic algorithm, to ensure the stability of fitness convergence, the evolutionary generation is set to 300 generations to fully observe the optimization process. Figure 4 shows the changing trend of fitness during the algorithm evolution process, where the horizontal axis is the evolutionary generation (0-300 generations) and the vertical axis is the fitness of the optimal individual in each generation (i.e., transmittance). From the results, it can be seen that the transmittance of the algorithm has increased to more than 97% at about 100 generations, and it has reached a peak at around 200 generations and then stabilized.

After multiple independent experimental verifications and comparison of the obtained data records (Table 3), the system finally obtained a maximum transmittance of 98.1856%, and the corresponding optimal glass thickness combination was: L_1=5.5692 mm, L_2=7.2072 mm, L_3=3.5401 mm. This result verifies the effectiveness and stability of the algorithm in solving multi-layer medium optical optimization problems.

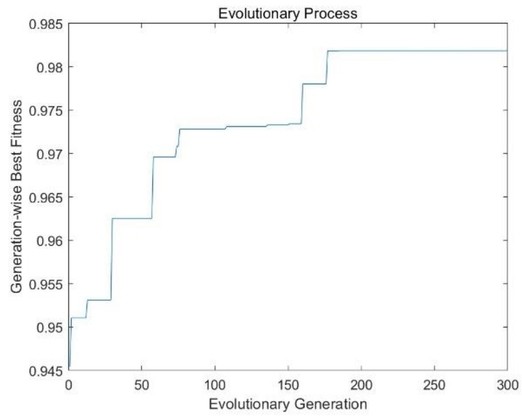

FIGURE 4. Schematic diagram of the evolution process (Photo/Picture credit: Original).

TABLE 3. Three-layer glass with different thickness combinations and their transmittance

L1 (mm)	L2 (mm)	L3 (mm)	Fitness
3.0240	6.9552	8.3297	0.9678
3.1280	5.3040	5.8001	0.9647
5.5692	7.2072	3.5401	0.9819
6.3840	6.5520	6.7682	0.9714
5.5328	9.0288	9.1839	0.9692
6.6528	3.8808	4.4509	0.9712
8.5120	7.2072	3.5930	0.9809
9.3912	5.0490	4.4644	0.9714
9.6096	3.4020	5.4952	0.9761
8.5272	4.8672	3.4860	0.9647
5.8968	6.5520	3.8150	0.9711
6.5142	8.8704	4.2683	0.9693
8.7360	5.8212	5.1183	0.9815
8.2368	3.9312	6.0764	0.9692
5.3928	6.6528	7.1025	0.9721
7.3416	3.5280	8.9822	0.9663
9.7944	4.4352	4.0006	0.9640
7.9800	8.3538	3.2982	0.9655
6.5142	9.2708	3.6195	0.9641
9.6096	9.4595	4.0920	0.9743

Figure 5 is the transmission spectrum of the best individual, where the abscissa is the wavelength range of the solar spectrum and the ordinate is the transmittance. The spectrum indicates that the optimized triple-layer glass structure exhibits an overall higher transmittance in the range of 200–2000 nm, with the primary value exceeding 0.85. The spectrum shows periodic oscillations, significant interference effects, and obvious transmittance decrease at some wavelengths.

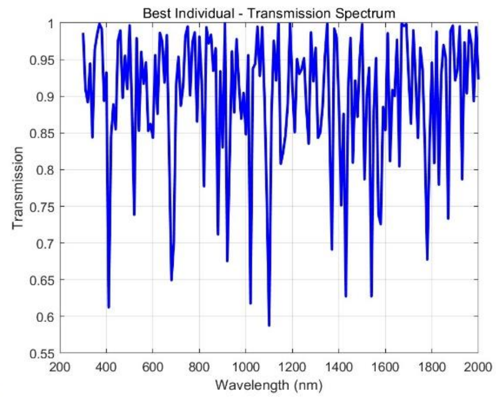

FIGURE 5. Schematic diagram of the best individual transmission spectrum (Photo/Picture credit: Original).

Finally, to verify the effectiveness of the performance optimization of triple-layer glass, it compared the triple-layer glass model with 3mm-5mm single-layer glass in three dimensions: total transmitted energy, total transmittance, and thickness. It found that the triple-layer glass, after the thickness combination was optimized by the quantum genetic algorithm, increased the energy gain by 12% compared with the single-layer glass. The energy of the single-layer glass in the range of 3mm-5mm decreased slightly with the increase of thickness.

DISCUSSION

In the future, this research can be further expanded to introduce new glass materials and structures to meet various architectural needs. For example, in recent years, new phase-change glass windows containing silica aerogel have been developed. The three-layer phase-change glass windows with silica aerogel insulation on the outside can ensure that the phase-change material on the inside undergoes phase change in winter in cold regions, thereby improving the thermal inertia of the glass enclosure structure and reducing the energy consumption of building operation [9]. Or adjust the optimization target according to different regions. For example, in Shanghai, where it is hot in summer and cold in winter, a glass curtain wall with good thermal insulation performance is needed. The use of glass panels with LowE film added to the single-layer glass panels can reduce the total solar transmittance by 14% and the heat transfer coefficient by 53% [10]. In recent years, double-layer hollow high-transmittance Low-E glass can achieve the optimal value of light and heat performance in the selection of architectural glass in severe cold regions, with high cost performance and suitable for wide application [11]. Or use other methods, such as the fish swarm algorithm, the ant colony algorithm, particle swarm algorithm to optimize the glass structure.

CONCLUSION

This study applied a quantum genetic algorithm to the optimization design of a triple-layer glass structure and obtained the optimal thickness combination, achieving a maximum transmittance of 98.186%. If this structure can be applied in the northern winter, it will provide better lighting conditions, maximize the use of solar energy without increasing costs, provide a new solution for energy conservation and emission reduction in the construction industry, and improve the indoor comfort of northern residents in winter.

Compared with traditional single-layer glass, the three-layer optimized structure proposed in this study improves the lighting performance while taking into account the stability and economy of the structure. By rationally adjusting the thickness of each layer of glass, this design effectively reduces the reflection loss of light at the multi-layer interface, while avoiding the cost increase problem caused by excessive thickening. In addition, high transmittance means that more solar radiation can enter the room, which helps to improve indoor thermal comfort in winter, reduce the building heating load, and meet the requirements of green buildings and sustainable development.

In the future, this technology can be further combined with intelligent dimming materials to achieve dynamic transmittance adjustment to adapt to lighting needs in different seasons or weather conditions. This study provides a new solution for energy conservation and emission reduction in the construction industry, and also provides a theoretical reference for the structural optimization design of optical materials.

AUTHORS CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

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