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Optimization of Ultraviolet Transmittance of Three-Layer Glass Based on Quantum Genetic Algorithm

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Abstract:

In response to the current issue of high ultraviolet incident intensity in residential buildings and considering the objective factor that ultraviolet rays can cause damage to the human body, this paper studies which glass thickness combination can minimize the indoor ultraviolet transmittance. In the design process, this paper introduces the quantum genetic algorithm to optimize the ultraviolet transmittance. By deriving the objective function of the ultraviolet transmittance and combining the simulation of the random population with the equal probability superposition state of qubits, multiple runs are conducted to obtain the optimal one. The optimal glass thickness combinations of L_1 = 2.7 mm, L_2 = 2.3 mm, L_3 = 2.2 mm were obtained. The experimental results show that the algorithm logic optimized through multiple iterations has improved the stability and accuracy of the algorithm's optimization. The three-layer glass thickness design optimized by the quantum genetic algorithm significantly weakens the ultraviolet transmittance, thereby reducing the harm of ultraviolet rays to the human body to a certain extent, ensuring the physical health of residents and improving their quality of life. This research also provides new ideas for the optimization of intelligent construction design.

Keywords: Quantum genetic algorithm, optical optimization, transmittance

1. Introduction

With the increase in the urbanization rate and people's pursuit of living comfort, the humanization of architectural design has gradually gained attention. For instance, the Kim team designed smart window materials with spectral adaptability by constructing a collaborative simulation modeling framework and introducing bionic concepts [1]. Sheng et al. designed a smart window with a co-assembly strategy of nanowires, which can block 90% of infrared light in the case of coloring, so as to achieve the effect of cooling by 5°C [2]. In natural light, ultraviolet light is a potential threat to human health. Therefore, how to effectively weaken the incident ultraviolet light in the building design has become a key issue in the glass design.

In recent years, multilayer structures have shown great potential for optical modulation in fields such as solar reflection and selective transmission. Inspired by the snail shell, Khot et al. used a genetic algorithm to optimize the design and obtained a multilayer structure with higher solar reflectance, showing the powerful ability of the intelligent optimization algorithm in multilayer optical design [3]. From the study of membrane structure to glass, Elyes Garoudja's team used the bee colony algorithm to optimize the thickness of glass in 2021, and obtained an efficient algorithm based on the ABC algorithm and the Cauchy dispersion model to determine the optical constants and thickness of the deposited film [4].

In the existing research on multilayer film, the traditional genetic algorithm has completed many complex optimization problems. However, the genetic algorithm still has the problems of premature iteration and low search efficiency. Quantum genetic algorithm can effectively improve the global search ability and individual diversity of the algorithm by introducing the concepts of quantum bit and superposition state. Wang et al. proposed an improved quantum genetic algorithm (IQGA), which significantly improved the convergence accuracy of the algorithm by introducing the speed update idea of PSO and Hadamard gate mutation [5]. With the research and promotion of the quantum genetic algorithm, quantum genetic algorithm is being applied to various fields. Wei et al. applied the quantum genetic algorithm to the field of architecture and obtained the quantum genetic algorithm for the optimization design of architectural shells [6]. Hua Congcong team optimized the quantum genetic algorithm by increasing the dynamic adjustment ability of the quantum rotation Angle, so as to realize the efficient management of both sides of the supply and demand of office buildings, showing the wide applicability of the quantum genetic algorithm in various fields [7].

In this paper, a quantum genetic algorithm is used to optimize the selection of the thickness of the three-layer window glass for the ultraviolet transmittance in the wavelength range of 300-400nm in the solar spectrum. By establishing an objective function of ultraviolet transmittance, considering the optical properties of glass materials and interlayer interference, the optimal combination of glass thickness is iteratively optimized to achieve the research goal of minimizing the indoor incident ultraviolet rays.

2. Methods

The following is the transmittance formula for a single layer glass

$$T = \frac{(1-R)^2}{(1-R)^2 + 4Rsin^2(kL)} \tag{1}$$

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

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

In the formula, T is the transmittance, R is the reflectivity of the air-glass interface, k is the wave number, L is the glass thickness, n is the glass refractive index, which is taken as 1.5 in this study, and n_0 is the air refractive index, which is taken as 1.0 in this study.

In the interference formula of transmittance, for each layer of medium, the phase shift is

$$\delta_j = \frac{2\pi n_j L_j}{\lambda} \tag{4}$$

δ_j is the phase difference of the j layer of glass, L_j is the thickness of the layer, $L_j \in [2,4]mm$, n_j is the refractive index of the layer.

Assuming that the thickness of the air layer between adjacent glasses is negligible, the total transmittance can be approximated by the formula

$$T_{total} \approx T_1 \cdot T_2 \cdot T_3 \tag{5}$$

T_{total} is the total transmittance, and T_1, T_2, T_3 are the UV transmittance of each layer of glass, respectively.

In this paper, we study the case of minimizing UV transmittion. Therefore, we define $\lambda \in [300,400]$ nm in the function expression. Considering the spectral energy distribution, the energy of ultraviolet band entering the room is as follows:

$$E_{UV} = \int_{300}^{400} I_i(\lambda) \cdot T_{total}(\lambda) d\lambda \tag{6}$$

$$I_i = \frac{1000}{(\lambda - 580)^2 + 1} \tag{7}$$

$$T_{total}(\lambda) \approx T_1(\lambda) \cdot T_2(\lambda) \cdot T_3(\lambda) \tag{8}$$

$$T_j(\lambda) = \frac{(1-R)^2}{(1-R)^2 + 4Rsin^2\left(\frac{2\pi n}{\lambda} L_j\right)} \tag{9}$$

$$R = \left(\frac{1.5-1.0}{1.5+1.0}\right)^2 = \left(\frac{0.5}{2.5}\right)^2 = 0.04 \tag{10}$$

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E_{UV} is the total UV energy entering the room, I_i is the incident spectrum, $T_j(\lambda)$ is the j layer transmittance.

In summary, the formula of ultraviolet transmittance required in this paper is as follows:

$$T_{UV-total}(\lambda)=\prod_{j=1}^{3}\frac{(1-R)^2}{(1-R)^2+4Rsin^2\left(\frac{2\pi n}{\lambda}L_j\right)} \quad (11)$$

$R=0.04$, $n=1.5$, $\lambda\in[300,400]$ nm. $T_{UV-total}(\lambda)$ is the total spectral transmittance of the three-layer glass combination system at wavelength λ.

The optimization objective is to minimize

$$\int_{300}^{400} I_i(\lambda)\cdot T_{UV-total}(\lambda)d\lambda \quad (12)$$

Quantum genetic algorithm makes each qubit in the initial population in equal probability superposition state by quantum bit coding.

$$|\psi ? = \alpha|0?+\beta|1? \quad (13)$$

$$|\alpha|^2=|\beta|^2=0.5 \quad (14)$$

$|\psi ?$: qubit, $|0?$: Ground state in quantum computation, $|1?$: Excited state in quantum computation, α : Probability amplitude of the quantum state being in the $|0?$ state, β : The probability that the quantum state is in the $|1?$ state, the probability that the $|\alpha|^2$ qubit collapses into the $|0?$ state when measured, Probability that $|\beta|^2$ qubits collapse to $|1?$ states when measured.

The initial probability amplitude of each qubit is set as

$$\alpha=\beta=1/\sqrt{2} \quad (15)$$

This represents that each quantum is in the state $|0?$ and $|1?$ with the same probability. Secondly, the algorithm collapses the quantum state into a binary string by measurement. Where the measurement probability is determined by $|\alpha|^2$ and $|\beta|^2$. Each stage, from qubit encoding to quantum state initialization to quantum state collapse, increases the quantum randomness, so that the population has great diversity, to cover the whole search space as much as possible.

Focus to this topic, due to the objective function

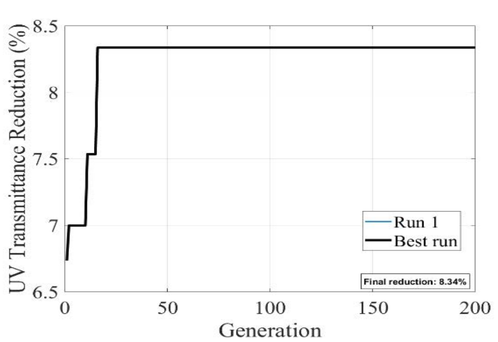
$$T\propto\frac{1}{1+4Rsin^2(2\pi nL/\lambda)} \quad (16)$$

This gives the objective function itself a multi-peak property. When L changes, T will change significantly and produces many extreme points. This allows many different thickness combinations to produce similar minimum transmittances. In addition, the population used in each iteration is randomly generated, which is likely to make the iteration process fall into a local optimal solution among many extreme values.

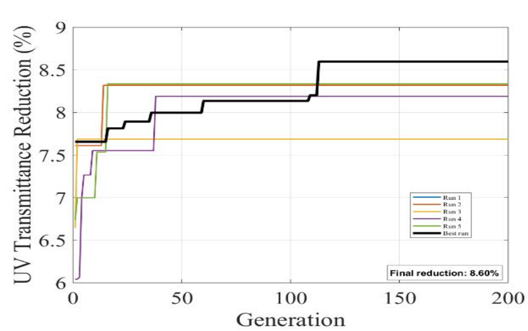
Therefore, in order to reduce the local optimization problem caused by the above objective function as much as possible, this study chooses to increase the number of runs from 1 to 5 and then to 10 to test the influence of multiple optimizations on obtaining the global optimal solution.

3. Result

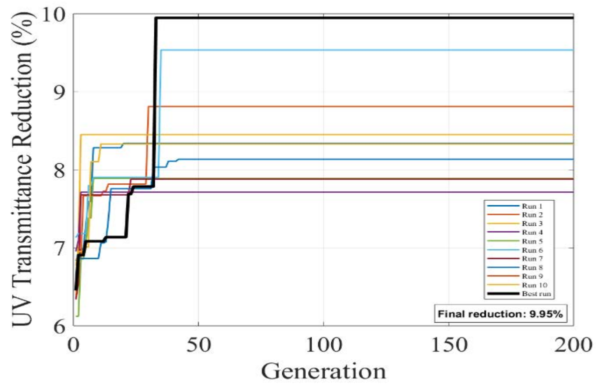
In order to reduce the local optimization problem caused by the above objective function as much as possible, this study chooses to increase the number of runs from 1 to 5 and then to 10 to test the influence of multiple optimizations on obtaining the global optimal solution.



(a)



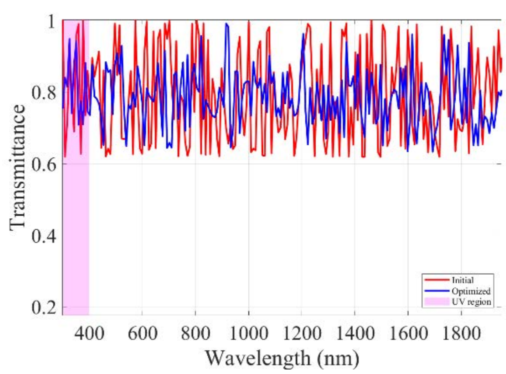
(b)



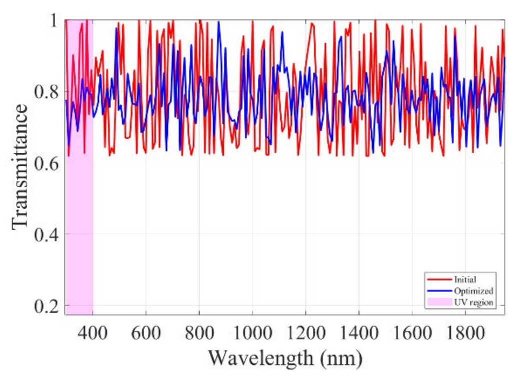
(c)

Fig. 1 Variation of UV transmittance reduction with the number of iterations (Photo/Picture credit: Original).

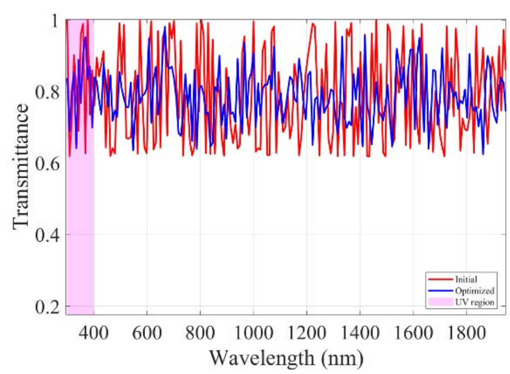
Fig. 1 shows the change process of the reduction of UV transmittance obtained when the number of optimization times is 1,5, and 10 times in turn with the number of iterations. Where the abscissa is the number of iterations, and the ordinate is the UV reduction rate. The black line is the image of ultraviolet reduction with the number of iterations under the optimal combination obtained by running. The other colored lines are the change images of UV reduction under other thickness combinations in this optimization process. By comparing Figs. 1(a)-(c), it can be seen that with the increase of the number of iterations, the reduction of ultraviolet transmittance under the optimal solution obtained by the algorithm is decreasing. After 10 optimizations, the reduction of ultraviolet transmittance in the optimal solution can reach 9.23%, which is significantly higher than 8.98% of 5 optimizations and 8.11% of 1 optimization.



(a)



(b)



(c)

Fig. 2 Full-band transmittance curves before and after optimization (Photo/Picture credit: Original).

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Fig. 2 shows the comparison plot of the transmittance of light in the wavelength range of 200 to 2000 nm before and after optimization under the conditions of optimization for 1, 5, and 10 times. Where the abscissa is the wavelength range of sunlight, and the ordinate is the transmittance. The blue curve is the transmittance curve of each band before optimization, and the red curve is the optimized one. The optimized standard depth is in the 300 to 400 nm ultraviolet band, which is the focus of this paper. In Fig. 2 (a), the fluctuation of the transmittance of the full band under the first optimization is reduced. Although the fluctuation of transmittance of the ultraviolet band is also smaller than that before optimization, the overall curve is roughly distributed in the range of transmittance higher than 0.8.

Fig. 2 (b) shows that when the number of optimizations increases to 5, the transmittance fluctuation of the full band does not change significantly compared with Fig. 2 (a). However, focusing on the UV band, the UV transmittance curve of Fig. 2 (b) is roughly distributed below the transmittance of 0.8. However, there are still a few bands with a peak transmittance higher than 0.9.

Finally, compared with Fig. 2 (c), the transmittance fluctuation of the optimal solution obtained by optimizing 10 times in the whole band range is reduced compared with that of optimizing for 1 time. In the ultraviolet band, compared with Fig. 2 (b), the optimized transmittance curve of Fig. 2 (c) distributes more parts below the transmittance of 0.8, and the peak transmittance in this wavelength range is significantly reduced by optimizing 10 times.

After the above comparative analysis, the optimal solution of the three-layer glass thickness optimized for 10 times is obtained as follows: $L_1 = 2.7$ mm, $L_2 = 2.3$ mm, $L_3 = 2.2$ mm.

4. Discussion

Due to the periodicity of the objective function, the multi-peak of the optimization results makes the gap between the optimization results large, which brings more difficulties to obtain more accurate optimization results.

When the number of runs n increases, the probability of finding the global optimal solution increases exponentially. In the quantum genetic algorithm, the initial quantum superposition states are generated independently and randomly in each run, which is equivalent to starting the search from different „starting points“, which greatly increases the chance of exploring different regions of the solution space.

In previous studies, Sharma and Kumar‘s research team systematically reviewed the development of multi-objective optimization technology, representative algorithms, and their applications in various engineering fields, analyzed the advantages, disadvantages, and application scope of various algorithms, and pointed out that multi-objective optimization has significant advantages in dealing with engineering problems with conflicting objectives. This provides a theoretical basis for algorithm selection and problem modeling for introducing the conflict optimization objectives of „the lowest ultraviolet transmittance“ and „the highest indoor transmittance“ [8]. In addition, Pereira‘s team focused on multi-objective optimization problems in mechanical engineering and reviewed the application of multi-objective methods in areas including design optimization, manufacturing processes, and structural health monitoring, with particular emphasis on the effectiveness of algorithms such as NSGA-II and MOPSO in solving practical engineering problems. It provides a practical reference for this study in the multi-objective optimization design of glass structures [9]. Guo and Zhang systematically reviewed the application status of multi-objective optimization in construction engineering management, and pointed out that the current multi-objective optimization research has challenges in dynamic adaptability and decision maker participation. This result provides an important reference for this study on how to construct multi-objective functions, select optimization algorithms, and decision rules in future multi-objective optimization improvement [10].

In this project, a three-layer glass thickness optimization method based on a quantum genetic algorithm is developed to achieve the goal of minimizing the UV transmittance. However, in the process of algorithm design, this study only focused on optimizing the ultraviolet transmittance to the minimum, and failed to consider the influence of the glass thickness on the light intensity before and after optimization. This one-sidedness of single-objective optimization is a problem to be solved in subsequent research.

5. Conclusion

This paper focuses on the optimization problem of civil glass window thickness, aiming to find the glass thickness combination with the minimum ultraviolet transmittance through scientific methods, so as to improve the indoor living comfort and improve the quality of life of residents. In this paper, a quantum genetic algorithm is used to optimize the thickness of residential glass Windows to obtain the combination of glass thickness with the minimum ultraviolet transmittance. According to the transmissibility formula of single-layer glass, the objective optimization function of ultraviolet transmittance of three-layer glass is derived under the assumption that the thickness of the air layer is negligible. Considering the multi-peak of the objective function, this paper chooses the improved genetic algorithm to optimize many times and output the optimal solution.

The research results show that the improved quantum genetic algorithm improves the accuracy of the optimization results of the quantum genetic algorithm to a certain extent, provides a more reliable optimization scheme for the optimization of glass thickness, provides a new reference for urban construction, and improves people's quality of life.

In the future, how to simultaneously meet the multiple requirements of ultraviolet transmittance control and indoor natural light intensity optimization, and realize the collaborative design and multi-objective global optimization of architectural glass performance, is a topic that needs to be continuously explored. This requires further research on algorithms to promote the deep integration of intelligent design methods with material science and architectural practice, so as to achieve the long-term goal of a more comfortable, healthy and energy-saving building environment.

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