Research on the Optimization of Solar Transmittance in Three-Layer Glass Thickness Design Using Ant Colony Algorithm

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Abstract: In light of combating global warming and cutting down on building energy use, the traditional optimization of glass thickness in single-layer structures has become inadequate to meet practical demands. In order to minimize the amount of sunlight that enters the room through the glass window, this study optimizes the thickness of triple-layer glass using the ACA. By modeling the way sunlight travels through three layers of glass and applying the ACA iteratively to find the minimum average transmittance, the optimal thickness combination of the three-layer glass was ultimately obtained: L1 = 0.0097584 m, L2 = 0.0070197 m, L3 = 0.0067324 m. In this configuration, the average transmittance is at least 51.382%, which effectively reduces the incident energy to 496.9769 W/m^2 , only 51.6% of the total energy, which is significantly better than the traditional single-layer glass structure. This study shows that the ACA can effectively process a large amount of data with complex relationships, and the three-layer glass structure has more advantages in suppressing the incident energy of sunlight. This study offers a theoretical foundation and a reference approach for future logical design and optimization of the thickness and structure of glass windows.

INTRODUCTION

In the southern part of China, the climate is generally hot in summer. This kind of hot weather often brings a lot of inconvenience to people's daily lives and work. A large amount of sunlight radiation enters the room through the glass, which becomes one of the key factors in raising the temperature indoors. In order to solve this problem, methods can be taken to improve the structure of the glass. Especially, three-layer glass is widely used due to its good thermal insulation properties. The principle is to change the absorption, reflection, and transmission characteristics of the glass to different wavelengths of sunlight by adjusting the thickness of the three-layer glass reasonably, which achieves the goal of reducing the sunlight radiation into the room ultimately. However, due to the wide wavelength range of sunlight, there is a complex nonlinear relationship between the transmittance of sunlight radiation and the thickness of the glass. As a result, it is very difficult to optimize the thickness of triple glass with conventional methods.

Recent years have seen the optimization of the structure of multi-layer thin film materials due to the ongoing advancements in science and technology. At the same time, people optimize the data with the help of intelligent algorithms and other algorithms, and have achieved many good results. Yang optimized the multi-layer optical thin film system design using the ACA and proposed some new ideas for the optimal design of thin films [1]. Wang used deep reinforcement learning to automate the design of optical multi-layer thin films and discovered the most advanced memetic algorithm [2]. The polymer multi-layer film (PMF) designed by Li has excellent ultraviolet resistance, which finally achieves the equivalent transmittance to between 410 and 1200nm, and a significant increase in reflectivity to more than 90% at 320-400nm, making it suitable for long-term outdoor deployment [3]. Using the ACA, Ying increased the energy transfer efficiency by optimizing the triple-layer glass's thickness. The final thickness combination was L1 = 5.9289 mm, L2 = 7.9309 mm, and L3 = 3.8462 mm [4]. Cui Y optimized the thickness of the three layers of glass using particle swarm optimization in order to reduce the amount of sunlight that was transmitted. The final ideal thickness combinations were L1=0.0099m, L2=0.0099m, and L3=0.0038m, and the transmitted light energy reached a minimum of 374720 J/m2 [5].

Based on the above study progress, it can be seen that although there are a variety of material structure optimization methods and related studies on glass structure, there are still great challenges in exploring a more efficient method to optimize the thickness of triple glass. The ACA was used in this study to optimize the thickness of the glass with a three-layer structure. The goal was to lower the average transmittance of sunlight in order to minimize the energy of sunlight that eventually entered the room.

RESEARCH METHODS

Ant Colony Algorithm

The ACA, which is frequently employed in the fields of mathematics and information analysis by Fidanova S, is the clever algorithm used in this investigation [6]. It has great advantages in processing large amounts of data with nonlinear complex relationships [6]. Ants will release a pheromone, which they can detect, in their path while searching for food. The pheromone concentration represents the length of the route; the higher the concentration, the shorter the length. Ants will therefore almost certainly favor routes with greater pheromone concentrations.

The formula for calculating the probability of an ant transfer is given by:

$$\mathrm{P}_{\mathrm{ij}}^{\mathrm{k}}=\frac{[\mathrm{A}_{\mathrm{ij}}(\mathrm{t})]^{\alpha}[\eta_{\mathrm{ij}}(\mathrm{t})]^{\beta}}{\sum_{\mathrm{s}\in \mathrm{allows}}[\mathrm{A}_{\mathrm{is}}(\mathrm{t})]^{\alpha}[\eta_{\mathrm{is}}(\mathrm{t})]^{\beta}},\mathrm{s}\in \mathrm{allows}\ ,\ \ \mathrm{P}_{\mathrm{ij}}^{k}=0,s\notin allows \tag{1}$$

where represents the pheromone concentrations on the city and connection paths at t, $\eta_{\mathrm{ij}}(t)$ is the heuristic that, with a value of $\frac{1}{\mathrm{d}_{\mathrm{ij}}}$, indicates the intended level of ant transfer from the city, ($\mathrm{d}_{ij}(i,j=1,2,...,n)$ symbolizes the separation between the city i and the city j), $\mathrm{P}_{ij}^{k}(t)$ represents the probability of the ants moving from the city to the city, $\mathrm{allow}_{\mathrm{k}}(k=1,2,...,n)$ represents the set of cities which will be visited by the ants, α represents the pheromone importance factor, β symbolizes the heuristic function's importance factor.

The formula of the pheromone update is given by:

$$\tau_{\mathrm{ij}}(t+1)=(1-\rho)\tau_{\mathrm{ij}}(t)+\Delta\tau_{\mathrm{ij}}, \tag{2}$$

$$\Delta\tau_{\mathrm{ij}}=\sum_{k=1}^{n}\Delta\tau_{ij}^{k}, \tag{3}$$

$\Delta\tau_{\mathrm{ij}}^{\mathrm{k}}$ symbolizes the quantity of pheromones that the NO. k ant releases while traveling between cities i and j, $\Delta\tau_{\mathrm{ij}}$ symbolizes the total amount of pheromone concentrations released by all ants along the route between city i and city j, ρ represents the pheromone volatile factor. The ants can determine the quickest route from the nest to the food source as a result of the positive feedback this produces.

Model Construction

When sunlight hits glass, phenomena such as transmission, reflection, and refraction occur. In this study, due to the sake of calculation convenience, only two cases of transmission and reflection are considered, and the total transmittance of the three layers of glass incident with sunlight is simplified to the product of the transmittance of each layer of glass.

The formula to calculate the solar transmittance of single-layer glass is given by:

$$\mathrm{T} = \frac{I_t}{I_i} = \frac{(1-R^2)}{(1-R^2)+4R\sin^2(kL)}, \tag{4}$$

where $\mathrm{I_i}$ represents the initial light intensity, $\mathrm{I_t}$ represents the transmitted light intensity, R represents the reflectivity, k represents the wave number, and L represents the thickness of the glass.

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

$$\sigma = \frac{FWHM}{2\sqrt{2\ln 2}}, \tag{6}$$

$$\mathrm{R} = (\frac{n-n_0}{n+n_0})^2, \tag{7}$$

$$\mathrm{k} = \frac{2\pi\mathrm{n}}{\lambda}, \tag{8}$$

Where n represents the refractive index of glass, $\mathrm{n_0}$ represents the refractive index of air, and FWHM represents the half-width and height.

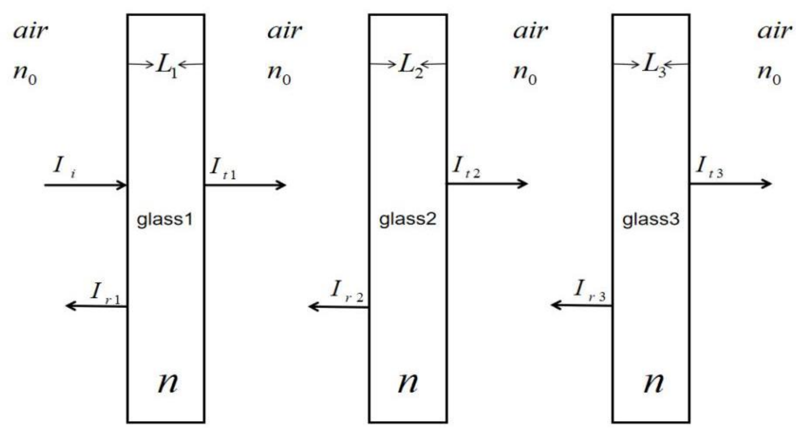

FIGURE 1. Transmission and reflection model of sunlight on a three-layer glass surface (photo/picture credit: original).

Figure 1 shows a model of the transmission and reflection of sunlight on a three-layer glass surface, where the thickness of the three layers of glass is $\mathrm{L_1}$、$\mathrm{L_2}$、$\mathrm{L_3}$, ambient medium, and the medium in the glass interlayer is air. The practical solution of the glass thickness to be optimized in the ACA is represented by the ant's walking path, which is based on the aforementioned models and principles. The ants release more pheromones along the shorter path, which is represented by the thickness and lower sunlight transmittance. The ants keep figuring out the best route as the number of iterations increases, and the pheromone concentration on each path is updated continuously. As the concentration of pheromones accumulated on the shorter path increases and more ants choose this path, the positive feedback effect will eventually cause all of the ants to concentrate on the best path to achieve the ideal thickness combination.

Programming

In the procedure of this study, the parameters were initialized first, such as setting the number of ants to 50, the number of iterations to 50, the pheromone volatilization factor to 0.5, and other key parameters that affect the algorithm. The ant's starting position in the solution space is then established, and because the ant colony algorithm's starting position influences the final result, the starting position is fixed. The range of potential answers for the ant search is then defined by building the solution space. Following an ant search, the pheromones are updated based on the benefits and drawbacks of the solution, making it simpler for succeeding ants to choose the path with the highest concentration. After that, it is judged whether the maximum number of iterations is reached, and if not, return to the construction solution space to continue iteration; When it is reached, the ant colony algorithm's method of determining the best solution is demonstrated by the output of the optimal solution following several iterations.

RESEARCH RESULTS

In this study, the real sunlight spectral data were downloaded from the official website of the National Renewable Energy Laboratory (NREL), and the wavelength range was extended to 300~2000nm to meet the basic situation in reality as much as possible [7].

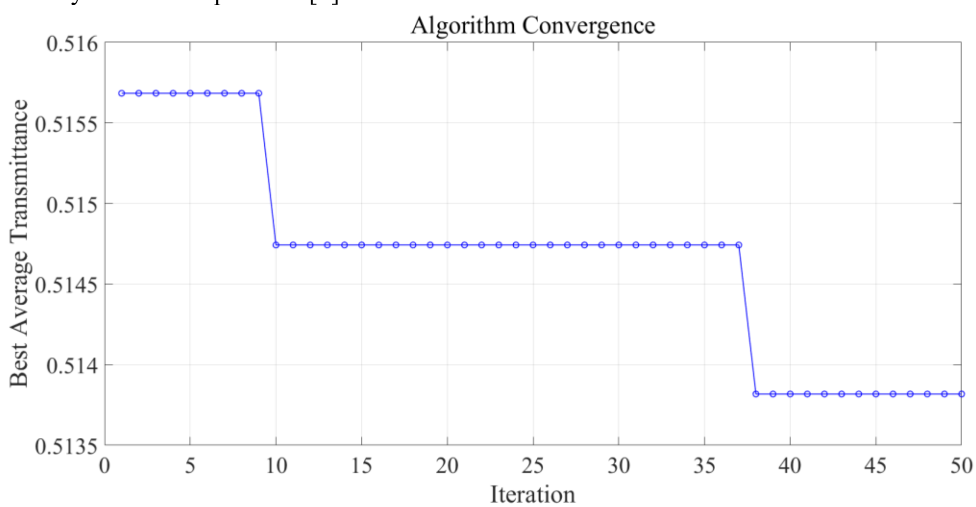

FIGURE 2. Transmittance distribution at different iterations (photo/picture credit: original).

Figure 2 shows the transmittance distribution of sunlight irradiating three layers of glass under different iterations. According to the graph, the ideal solution was discovered at iteration number 38. Following this iteration, the results tended to remain stable, and the ideal solution remained unchanged. It can be seen that the optimal solution is found in the 38th iteration, and the thickness combinations of the three-layer glass are L1 = 0.0097584 m, L2 = 0.0070197 m, L3 = 0.0067324 m, and the average minimum transmittance is 51.382%.

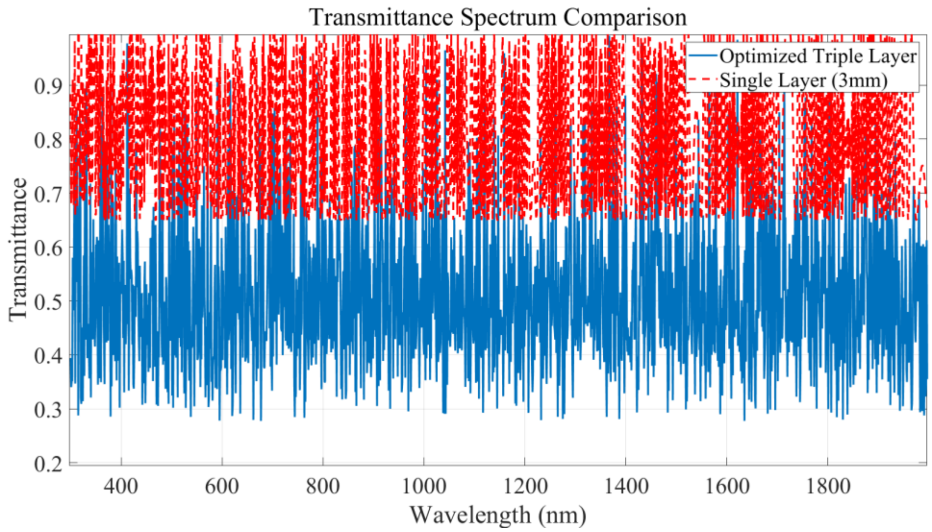

FIGURE 3. Comparison of transmittance at different wavelengths (photo/picture credit: original).

Figure 3 shows the transmittance of the optimized thickness of the triple-layer glass compared to the real-world single-layer 3mm glass with a common 3mm structure under different wavelengths of light. Among them, the red curve represents the transmittance distribution of a single-layer 3mm glass under different wavelengths of light, and the blue curve represents the transmittance distribution of the optimized three-layer glass under different wavelengths of light. It can be found that the sunlight transmittance of three-layer structural glass is generally lower than that of single-layer 3mm structural glass. Another important consideration in the choice of three-layer glass for this study is the clear superior transmission and suppression capabilities of three-layer glass over single-layer glass.

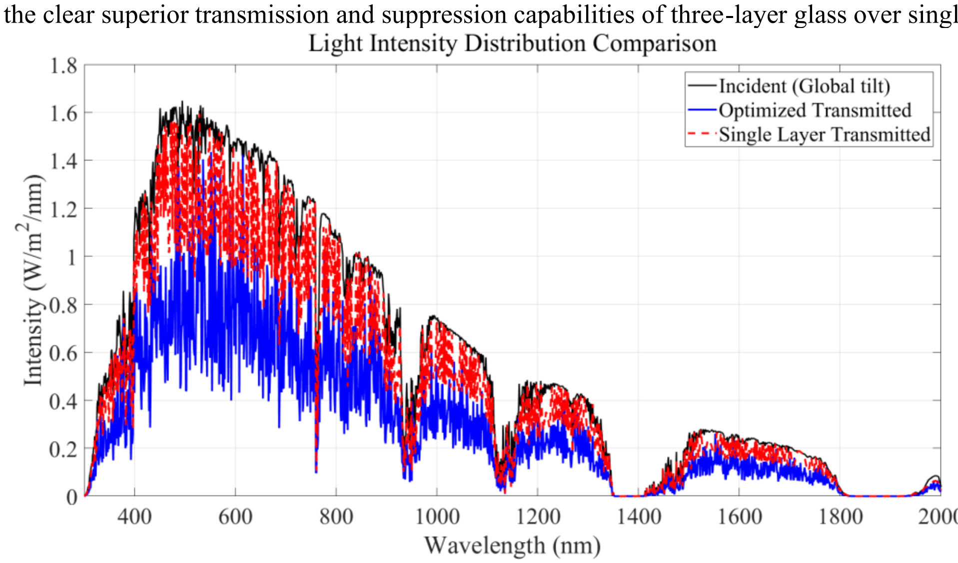

FIGURE 4. Comparison of incident energy distribution (photo/picture credit: original).

Figure 4 shows the analysis of the incident light energy of two structural glasses irradiated by sunlight using the available data. Among them, the black curve represents the original light intensity energy of sunlight, the red curve is the incident light energy distribution after sunlight irradiates the single-layer structured glass, and the blue curve is the incident light energy distribution of sunlight irradiating the three-layer structured glass. The final result is as follows: the total sunlight energy is 963.1248 W/m²; The incident energy through the 3mm single-layer glass is 778.3802 W/m², which is 80.8% of the total energy. The optimized thickness triple-layer glass has an incident energy of 496.9769 W/m2, or 51.6% of the total energy. The findings demonstrate that a single-layer glass structure is not very effective at reducing light transmission, while a three-layer glass structure with optimal thickness is more effective than a traditional structure at lowering solar incident energy.

DISCUSSION AND OUTLOOK

In this study, the thickness combinations of the three layers of glass, which can achieve the lowest average transmittance and the smallest incident energy of sunlight, are L1 = 0.0097584 m, L2 = 0.0070197 m, and L3 = 0.0067324 m. Compared to Ling's particle swarm optimization algorithm, which optimizes the thickness of the triple-layer glass to reduce ultraviolet transmission, it can find the best solution more efficiently and avoid entering the local optimal situation [8].

Initializing the parameters in this study can be better designed based on parameter adaptation, which will increase the optimization efficiency of the algorithm and yield more accurate results [9]. Secondly, many of the data in the study are set under ideal conditions, but there are many influencing factors in reality: the possible defects of the material itself will cause its optical properties to deviate from the theoretical value; Environmental changes, such as temperature, humidity and other factors, can also have an impact on the thermal insulation and light transmission properties of glass. In addition, non-uniform solar illumination is quite different from the ideal uniform illumination assumption. Based on these realistic variables, the model needs to be further improved and optimized in the future. By collecting more data in the actual environment and considering the influence of various complex factors, Miao C et al. used a variety of hybrid algorithms to make them more accurately reflect the real situation, so as to improve the reliability and practicability of the model in practical engineering applications [10]. On the basis of this study, the ACA can be used to achieve multi-objective optimization of three-layer glass insulation and lighting in the future. Current research is focused on reducing the incoming solar energy to achieve thermal insulation, but in practice, the daylighting and acoustic properties of glass are equally important. By learning from Chen J, the ACA can be improved to further increase its effectiveness in maximizing the thickness of triple glazing [11]. The ACA is therefore more accurate than both the spatial shortest distance algorithm and the basic ACA. Based on this, a three-layer glass thickness scheme that strikes a good balance between heat insulation, lighting, and sound insulation can be found in the future using the optimized ACA. This will allow buildings to meet a variety of needs in a variety of use scenarios.

CONCLUSION

This study suggests a technique that uses the ACA to optimize the thickness of triple glazing in order to minimize the incident energy of sunlight. Through continuous iteration and updating, the glass thickness combination of the three layers of the structure with the smallest incident energy of sunlight is determined by combining the ant colony algorithm's principle with the incidence and reflection model of sunlight on the surface of the three layers of glass. In addition, this study also compared the three-layer glass with the conventional 3mm single-layer glass, highlighting the ability of the three-layer glass to suppress the incident energy of sunlight. As a result, the thickness-optimized triple structural glass reduces the incident energy of sunlight to 51.6% of the total energy, which is much lower than the 80.8% of the single-layer structural glass. Nowadays, the global climate is warming, and the rate of resource consumption is on the rise. This study offers a workable solution for the design of glass windows to lower the incidence of sunlight energy in order to address this issue and, at the same time, significantly reduce the use of air conditioning to save energy consumption. In the future, the research conditions should be expanded to consider more influencing factors in reality, such as the change of the incidence angle of sunlight in different periods, the influence of sunlight under different weather conditions, and so on. With the continuous progress of algorithms, the use of algorithms with higher efficiency and more accurate results, or clever use of the advantages of different algorithms, the combination of different algorithms, to ensure the accuracy and applicability of the results in the case of a variety of uncertain conditions in real life.

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