Dean&Francis
ISSN 2959-6157

Optimizing Energy Transmission of Multi-Layer Glass by Fish School Algorithm

Zhoule Zheng

College of Artificial Intelligence, Shanghai Normal University Tianhua College, Shanghai, 201815, China
Corresponding author: ZZL251202@outlook.com

Abstract:
In cold northern regions, winter heating energy consumption is high, with exterior window heat loss accounting for 50% of total building heat loss. Three-layer glass is the mainstream exterior window material here, yet most existing studies focus on double-layer glass or traditional algorithms, lacking exploration of three-layer glass thickness collaborative optimization and fish swarm algorithm application. This study aims to maximize the indoor solar incident energy in northern winters. A three-layer glass solar radiation transmittance calculation model is constructed for the 300-2000nm solar band to clarify the mapping relationship between incident energy and thickness parameters. The fish swarm algorithm is introduced, taking the thickness parameter combination of “three layers of glass + two layers of air” as the optimization object. The iterative optimization of foraging, clustering, and tail-following is achieved through the MATLAB platform. The results show that the algorithm has good convergence. The optimal parameter combination is L1 = 6.86mm, L2 = 6.52mm, L3 = 5.81mm, Lair1 = 11.58mm, and Lair2 = 6.63mm. At this time, the near-infrared band transmittance is 0.8 to 0.95, the visible light band transmittance is stable at 0.7 to 0.85, and the ultraviolet band transmittance is effectively controlled. This study provides quantitative parameters for the energy-saving design of three-layer glass windows in northern winters and offers a new idea for the multi-parameter collaborative optimization of building windows.

Keywords: Energy-saving optimization, Fish swarm algorithm, Solar radiation transmittance, Building energy conservation.

1. Introduction

How to efficiently utilize solar radiation, a clean and renewable energy source, to reduce heating energy consumption and enhance indoor thermal comfort has become a core research direction in building energy conservation. Building energy consumption accounts for approximately one-third of total social energy consumption, and window heat loss alone accounts for nearly half of total building energy consumption. Adopting high-performance windows is an economical and effective way to reduce building energy consumption [1]. In northern regions with short winter days and low outdoor temperatures, maximizing solar radiation entry into rooms is key to reducing heating loads. As the main channel for solar radiation, the structural design of exterior windows directly determines solar transmission efficiency.

Factors influencing the thermal insulation performance of doors and windows include profile materials, cavity quantity, glass spacer bar type, glass layer number, cavity size, cavity gas type, and glass type [2]. Relevant scholars have conducted extensive research on solar utilization through exterior windows and thickness optimization. For example, Yu Jinghua, Huang Chunhua, and Nyers et al. established P1-P2, LCCA, I-S and other economic models based on transient heat conduction formulas to determine the optimal insulation layer thickness [3-6]. Their results show that the optimal thickness of insulation materials in descending order is polystyrene particle insulation material, expanded polystyrene, inorganic insulation mortar, and extruded polystyrene. When air conditioning and heating equipment operate all day, the insulation thickness of the four materials ranges from 85 to 161 mm, with a life-cycle investment of 125.4 to 251.4 yuan/m² and a net income of 363.9 to 787.3 yuan/m²; when operating at night, the optimal thickness, life-cycle investment, and net income decrease by approximately 21%, 16%, and 40% respectively.

In terms of glass properties, the shading coefficient reflects the ability to block solar radiation, calculated by comparing the glass transmission spectrum with the solar radiation spectrum (determined by measuring transmittance at different wavelengths). A higher shading coefficient indicates better thermal insulation, which is crucial for improving building energy efficiency and reducing air conditioning loads. Practically, glass with a shading coefficient suitable for local geography and climate is selected [7]. Through experiments and numerical simulations on glass structure thermal performance, Wang et al. found that glass optical performance significantly affects the thermal performance of the envelope [8]; Cuce et al. further verified the influence of glass optical performance on the calculation of envelope U-value through experiments [9, 10].

Although existing studies provide methodological references for glass thickness optimization, they mostly focus on double-layer glass or traditional intelligent algorithms. There are relatively few studies on the collaborative optimization of triple-layer glass thicknesses (L1, L2, L3), and the application of the fish swarm algorithm in optimizing solar transmittance of exterior windows has not been reported. This makes it difficult to meet the demand for efficient utilization of the full solar radiation spectrum (300-2000 nm) in northern winters. Based on this, this study aims to maximize indoor solar incident energy in northern winters by optimizing triple-pane glass thickness. Specifically, a transmittance calculation model is established based on the 300-2000 nm solar wavelength characteristics to clarify the energy-thickness mapping; the fish swarm algorithm is introduced to leverage its advantages over traditional algorithms; finally, northern winter radiation parameters are input, thickness constraints are set, and the optimal thickness combination is obtained through iteration.

2. Theoretical Basis

Triple-pane glass, with its outstanding thermal insulation and heat insulation performance, has become the mainstream choice for exterior windows in cold northern regions. However, the thickness of the glass itself and the air layers in between (L1, L2, L3) significantly affect the transmittance of solar radiation at different wavelengths. The solar spectrum ranges from 300 to 2000 nm, covering ultraviolet (300 to 400 nm), visible (400 to 760 nm), and near-infrared (760 to 2000 nm) bands. The near-infrared band accounts for over 50% of the total solar radiation energy. An unreasonable thickness design may lead to excessive reflection or absorption of near-infrared radiation, thereby reducing the incident energy. Therefore, optimizing the thickness parameters of three-layer glass for the solar wavelengths of 300 to 2000 nm is of significant theoretical and engineering value for enhancing the utilization efficiency of solar radiation in northern buildings during winter and achieving a synergy between building energy conservation and indoor thermal comfort.

ISSN 2959-6157

2.1 Theoretical Calculation of Solar Radiation Transmittance

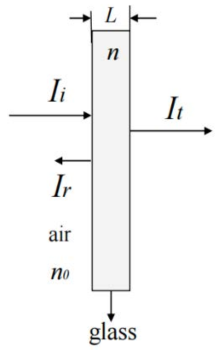

Fig. 1 Transmission and reflection of sunlight on a single-pane glass surface (Original).

As shown in Fig. 1, under the physical scenario where sunlight is incident perpendicularly, the formula for calculating the transmittance of sunlight from air through a single layer of glass is:

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

In the formula, I_t represents the transmitted light intensity (W/m²), and I_i represents the incident light intensity (W/m²). The calculation formula is:

$$I_i = \frac{1000}{[(\lambda - 580)^2 + 1]} \quad (2)$$

R is the reflection coefficient at the air-glass interface, and its calculation formula is:

$$R = (\frac{n-n_0}{n+n_0})^2 \quad (3)$$

Where n = 1.5 (refractive index of glass), n0 = 1.0 (refractive index of air), substituting these values yields R = 0.04; k is the wave number within the glass (rad/m), and its calculation formula is:

$$k = \frac{2\pi n}{\lambda} \quad (4)$$

λ represents the wavelength of sunlight (m); L represents the thickness of a single layer of glass (m). In the physical structure of "three layers of glass + two layers of air" defined in the experiment (Glass 1 - Air Layer 1 - Glass 2 - Air Layer 2 - Glass 3), L1, L2, and L3 respectively correspond to the thicknesses of the three layers of glass, while Lair1 and Lair2 respectively correspond to the thicknesses of the two air layers, as shown in Fig. 2.

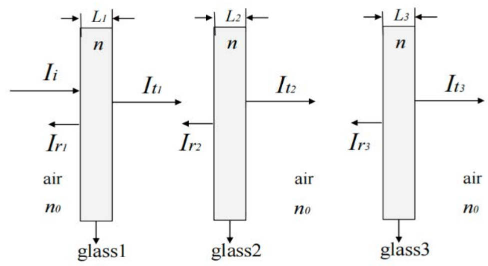

Fig. 2 Transmission and Reflection of Sunlight on a Triple-Pane Glass Surface (Original).

When light propagates in this structure, it needs to pass through 8 interfaces in sequence (air - glass 1, glass 1 - air layer 1, air layer 1 - glass 2, glass 2 - air layer 2, air layer 2 - glass 3, glass 3 - indoor air). Reflection and transmission occur at each interface, and there are also light propagation attenuation and interference effects within both the glass layers and the air layers. Based on the physical logic of the single-layer transmittance formula, the transmission matrix method is extended to construct a three-layer glass transmittance model - each medium layer (glass 1, air layer 1, glass 2, air layer 2, glass 3) is regarded as an independent transmission unit, and the form of its transmission matrix refers to the classic theory of radiation transmission in multi-layer media:

$$M = \begin{bmatrix} cos(\delta) & \frac{i}{n}sin(\delta) \\ insin(\delta) & cos(\delta) \end{bmatrix} \quad (5)$$

In the formula: δ=kL represents the phase delay within the layer (rad), where $k = \frac{2\pi n}{\lambda}$ (n is the refractive index of the medium, 1.5 for glass and 1.0 for air), L is the thickness of the corresponding medium, and i is the imaginary unit.

According to the direction of light propagation, the total transmission matrix of the three-layer glass structure is the product of the matrices of each layer: $M_{total} = M_{glass1} \times M_{air1} \times M_{glass2} \times M_{air2} \times M_{glass3}$, where M_{glass1}, M_{glass2} and M_{glass3} are the transmission matrices of glass 1, glass 2, and glass 3 respectively, and M_{air1} and M_{air2} are the transmission matrices of air layer 1 and air layer 2 respectively.

Based on the logical relationship between transmittance and transmission coefficient, the total transmission coefficient t is derived as:

$$t = \frac{2n_0}{n_0 M_{total}(1,1)} \quad (6)$$

The final total transmittance of the three-layer glass is the square of the modulus of the transmission coefficient:

$$T_{total} = |t|^2 \tag{7}$$

2.2 The Principle of the Fish Swarm Algorithm

The fish swarm algorithm is an intelligent optimization algorithm derived from the behaviors of fish schools, such as clustering, foraging, tail-chasing, and random movement. It features fast convergence, ease of operation, and simple logic [11]. Its core advantage lies in the fact that it does not rely on the gradient information of the objective function, has low sensitivity to initial parameters, and can effectively avoid the problem of traditional intelligent algorithms easily falling into local optima.

In this study, each optimized solution corresponds to a parameter combination of “three layers of glass thickness + two layers of air thickness”, which is regarded as “a fish”. The value of the objective function (total solar energy incident in the room) is considered as “the fitness of the fish”. The parameter combination is updated through the group behavior of the fish swarm, gradually approaching the maximum fitness.

3. Construction of the Thickness Optimization Model for Triple-Glazed Glass

This study aims to maximize the total solar energy incident indoors in northern winters as the objective function. It is necessary to combine the solar radiation energy distribution in the 300-2000nm band, which covers over 99% of the total solar radiation energy and is the core source of indoor heat gain in winter. The AM1.5G standard spectrum is referred to, as shown in Fig. 3. The horizontal axis represents wavelength (nm), with the unit being nanometers (nm), ranging from 250 nm (ultraviolet region) to 4000 nm (infrared region), fully covering the main bands of solar radiation. The vertical axis represents spectral irradiance (Spectral Irradiance), with the unit being watts per square meter per nanometer ($W \cdot m^{-2} \cdot nm^{-1}$), describing the power distribution of solar radiation per unit area within a unit wavelength interval. The three curves in Fig. 3 correspond to three different air masses, representing the differences in the path length of solar radiation through the Earth‘s atmosphere. AM0 indicates the solar spectrum outside the atmosphere, with no atmospheric absorption or scattering, and serves as the benchmark for studying the intrinsic characteristics of solar radiation. AM1.5g represents the standard spectrum of direct sunlight on the ground, corresponding to the situation where radiation passes through 1.5 times the vertical atmospheric thickness at a solar altitude angle of approximately 48.2°. It is a core reference spectrum in fields such as photovoltaics and building energy conservation. AM1.5d represents the spectrum of direct sunlight on the ground, differing from AM1.5g in that it excludes the scattered component. It is more often used in tests for concentrating photovoltaic systems and other scenarios.

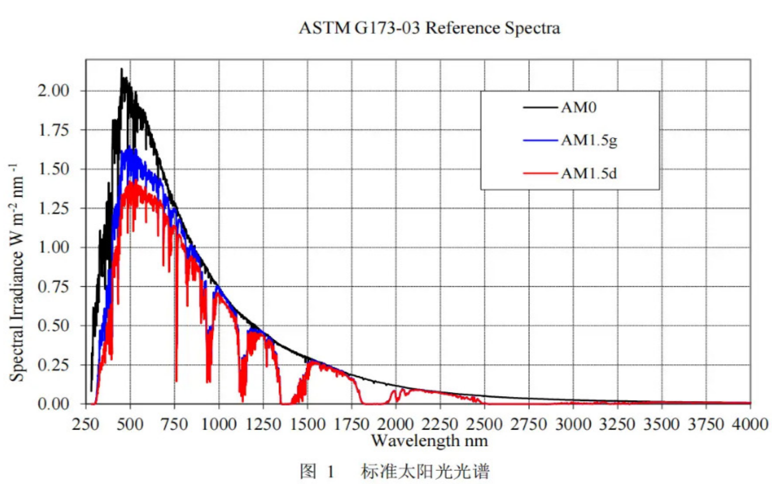

Fig. 3 Standard solar spectrum [1]

The specific implementation process of the fish swarm algorithm is as follows:

First, set the optical parameters: n = 1.5, n0 = 1.0, solar spectral energy density E, fish school size 40, maximum number of iterations 120, perception range 0.6mm, movement step 0.3mm, maximum number of attempts for foraging 12, density threshold for clustering and tail-chasing 0.6. Randomly generate 40 parameter combinations for glass 3-8mm and air layer 6-12mm. Each parameter is truncated by constraints to ensure it is within the engineering range. The scope of the project is based on the engineering practice of exterior windows in the cold northern

ISSN 2959-6157

regions. Considering the physical properties of glass and air layers, the following constraints are set: The thickness of the glass is set at 3-8mm. The thickness range of conventional building glass is 3-12mm. Considering the self-weight and cost control of the three-layer glass structure, 3-8mm is taken as the optimization range. The thickness of the air layer is set at 6-12mm. If the air layer is too narrow, the convective heat loss will increase due to the intensified molecular thermal motion. If it is too wide, it will produce an air turbulence effect, which also increases the heat loss. 6-12mm is the optimal engineering range for the air layer of the three-layer glass.

For each fish (parameter combination), the behaviors of foraging, clustering, and following are executed in sequence. The first is the foraging behavior, where the parameters are randomly adjusted within a sensing range of 0.6mm. If the fitness of the new parameter combination is higher, the position is updated. The second is the clustering behavior, where the mean and average fitness of the parameter combinations in the neighborhood are calculated. If the clustering conditions are met, it moves towards the mean direction. The third is the following behavior, where the parameter combination with the best fitness in the neighborhood is identified, and it moves towards that direction to accelerate convergence.

All new parameter combinations must undergo constraint truncation to ensure they fall within the engineering scope. After the iteration is completed, the global optimal parameter combination and the corresponding maximum incident energy are output, providing a basis for subsequent experimental verification and engineering application.

4. Experiment and Result Analysis

Fig. 4 shows the iterative convergence curve of the fish swarm algorithm. The horizontal axis represents the number of iterations, and the vertical axis represents the global maximum incident energy. Here, 300 iterations are taken as an example.

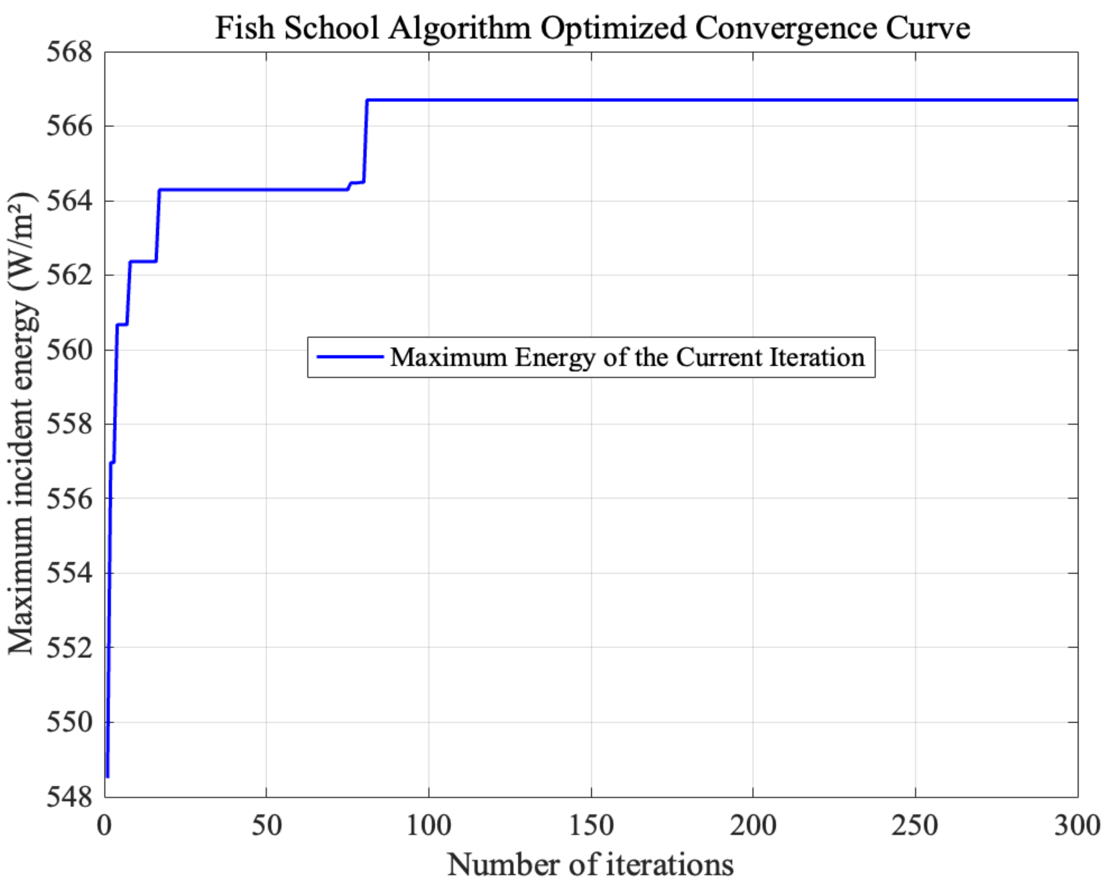

Fig. 4 Iterative convergence curve of the fish school algorithm (Original).

As shown in Fig. 4, the algorithm's convergence process can be divided into three stages. The first stage is the rapid exploration stage (1-20 iterations), during which the initial mean of the incident energy rapidly increases. This is because the algorithm quickly covers the parameter space through foraging behavior and initially locks onto the optimal solution area. The second stage is the fine search stage (21-80 iterations), during which the energy value increases slowly. At this time, the fish swarm fine-tunes the parameters through clustering and tail-chasing behaviors, gradually approaching the global optimum. The third stage is the stable convergence stage (after 81 iterations), during which the energy value stabilizes and remains unchanged for several consecutive iterations, indicating that the algorithm has converged to the global optimal solution.

The globally optimal parameter combination output by this calculation is: L1 = 6.86 mm, L2 = 6.52 mm, L3 = 5.81 mm, Lair1 = 11.58 mm, Lair2 = 6.63 mm.

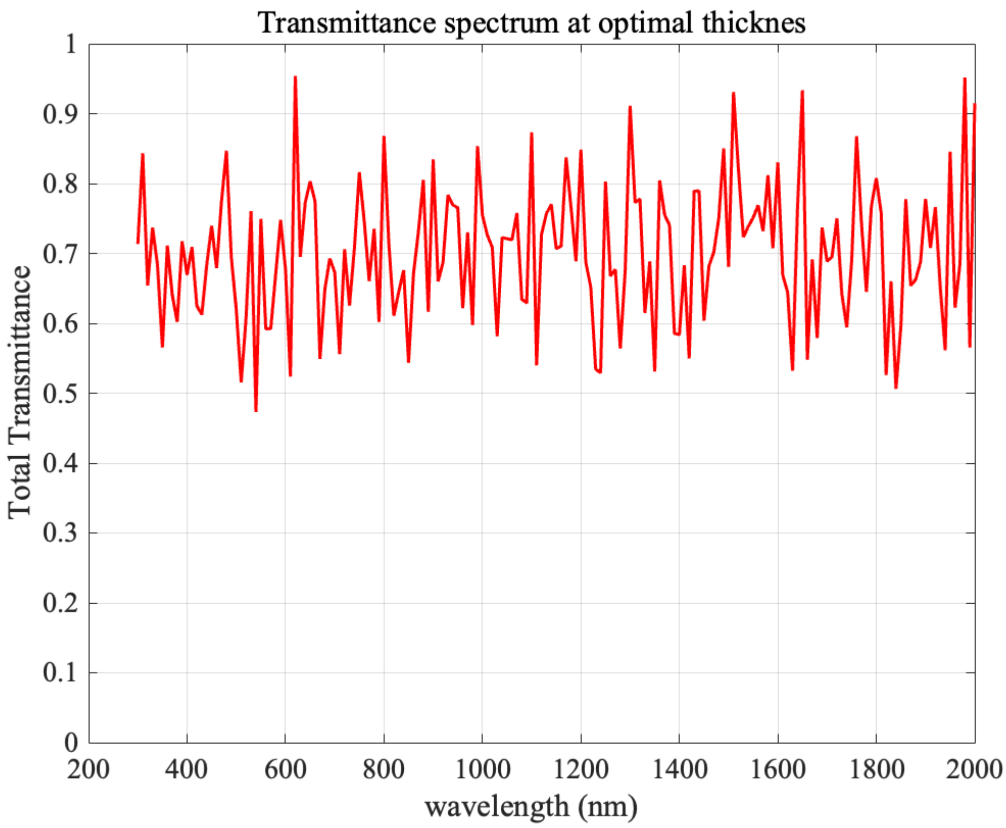

Fig. 5 Total transmittance curve at 300-2000 nm bandwidth at optimal thickness (Original).

Fig. 5 shows the total transmittance curve of the 300-2000nm band at the optimal thickness. The horizontal axis represents the wavelength, with the unit being nanometers (nm), ranging from 200nm to 2000nm. The vertical axis represents the total transmittance, which is a relative value ranging from 0 to 1, indicating the proportion of solar radiation passing through the three-layer glass at the corresponding wavelength. Under this parameter, the transmittance in the ultraviolet band (300-400nm) fluctuates between 0.55 and 0.75, remaining at a relatively low level overall. This is because ordinary glass has a strong absorption of ultraviolet light, and the interference effect of the air layer has a limited role in improving the transmittance at short wavelengths; the transmittance in the visible band (400-760nm) is stable between 0.7 and 0.85, with the peak concentrated in the 500-650nm range. The transmittance in this band ensures sufficient indoor lighting without causing glare due to direct strong light; the transmittance in the near-infrared band (760-2000nm) is generally between 0.8 and 0.95, which is the highest among the three bands. In line with the core objective of maximizing near-infrared heat gain to reduce heating energy consumption, the near-infrared band accounts for more than 50% of the total solar radiation energy. High transmittance can directly enhance indoor natural heat gain and reduce the energy consumption of the heating system.

ISSN 2959-6157

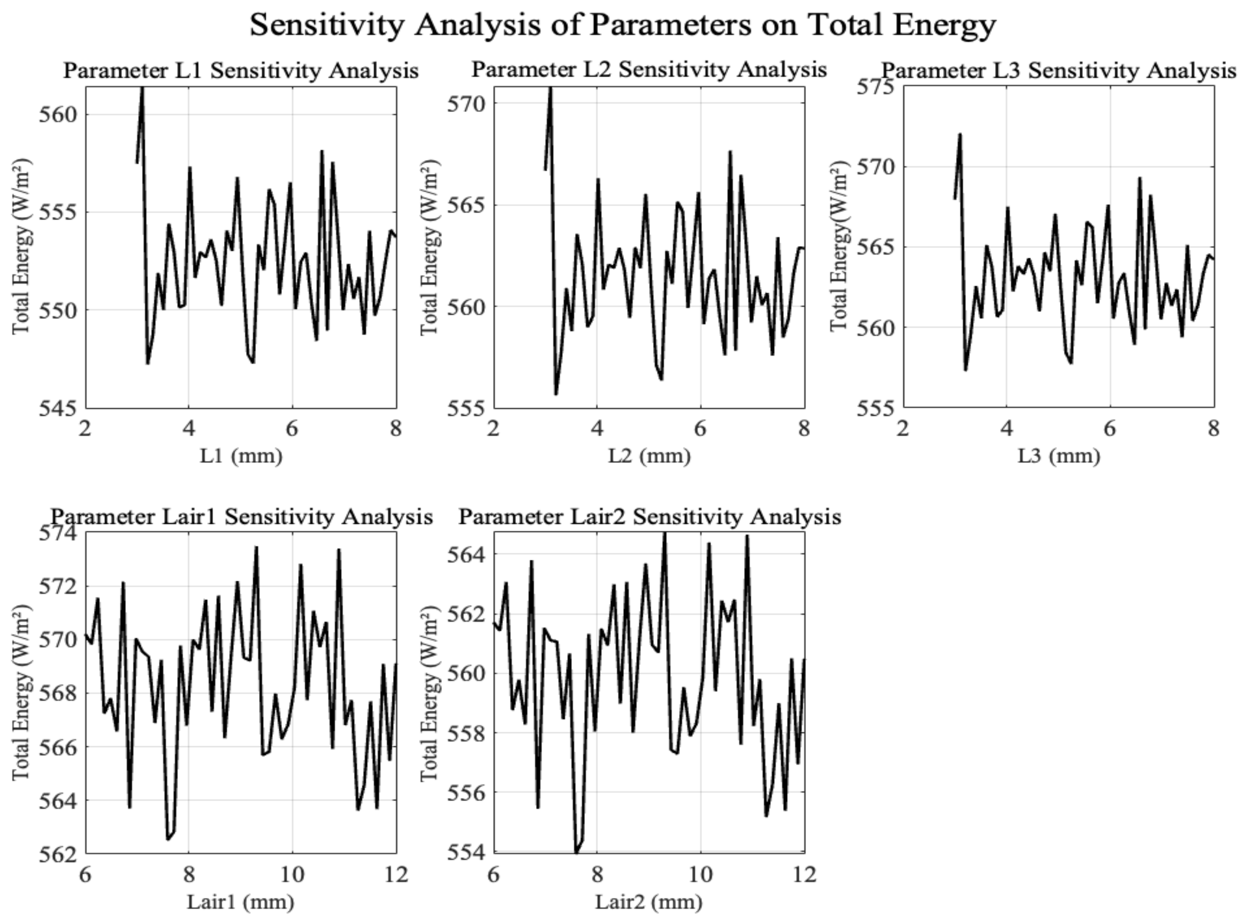

Fig. 6 Sensitivity analysis of parameters on total energy (Original).

Fig. 6 shows the sensitivity analysis of total energy for each parameter. The x-axis of all subgraphs represents the thickness of the parameter, with units in mm (the range of glass layers L1/L2/L3 is 3-8mm, and the range of air layers Lair1/Lair2 is 6-12mm), and the y-axis represents the total indoor solar incident energy, with units in W/m². The first row of three subgraphs is the sensitivity analysis of the thickness of glass layers L1, L2, and L3. All three curves show a multi-peak fluctuation feature, and the total energy varies within the range of 545-565 W/m². Taking L1 as an example, as the thickness increases from 3mm to 8mm, the energy first rises and then drops, with the peak concentrated in the range of 4.5-7mm, which is consistent with the optimal thickness range of the glass. The second row of two subgraphs is the sensitivity analysis of the thickness of air layers (Lair1 and Lair2). Both curves show a steep multi-peak fluctuation feature, and the total energy changes dramatically within the range of 554-574 W/m². The change in air layer thickness has a large impact on the total energy, with a steep slope and a maximum change rate exceeding ±7%.

Fig. 7 shows the optimization trajectory of the fish swarm in the L1-L2 parameter space. The horizontal and vertical coordinates represent the thicknesses of L1 and L2 glasses, respectively, with units in millimeters (mm), ranging from 3mm to 8mm. The colored dots indicate different stages of the algorithm's iteration, with each point corresponding to a set of thickness combinations of (L1, L2). The circled marks represent the final converged optimal parameter combinations, visually demonstrating the optimization process of the fish swarm algorithm in the parameter space of glass 1 thickness - glass 2 thickness. In the initial stage (L1 ≈ 3-4mm, L2 ≈ 3-8mm), the fish swarm is widely distributed, covering the entire constrained range of L1 and L2. Through the random distribution of fish, the parameter space is quickly scanned to search for potential optimal solution areas. In the middle stage (L1 ≈ 5-7mm, L2 ≈ 6-7mm), the fish begin to aggregate in specific areas. The fish swarm gradually converges towards the local optimal area by perceiving the superior solution individuals in the neighborhood, demonstrating the effect of the clustering behavior. In the later stage (L1 ≈ 6.5mm, L2 ≈ 6.5mm), the majority of the fish gather near L1 ≈ 6.5mm and L2 ≈ 6.5mm (the black circled area), reflecting the convergence of the tail-chasing behavior, that is, the fish swarm concentrates on the optimal individual in the neighborhood (the global optimal solution), ultimately achieving fine-tuning of the parameters.

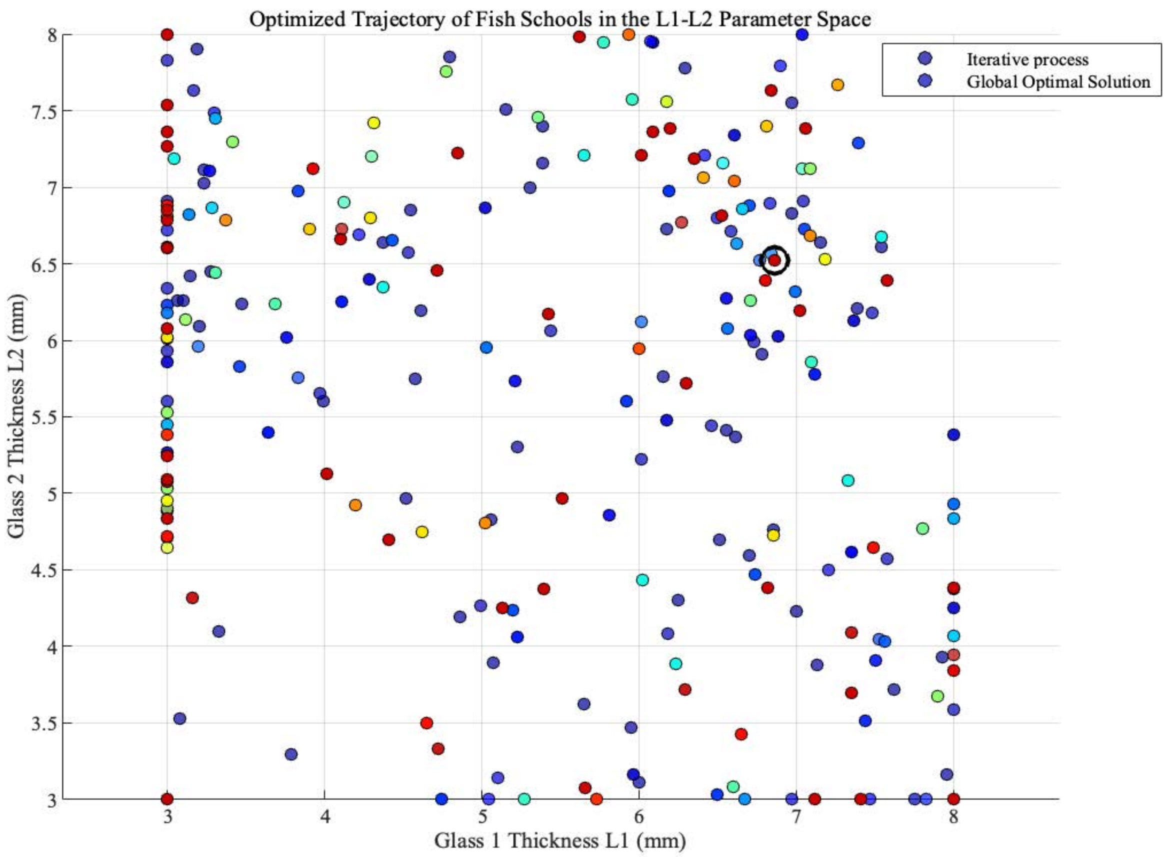

Fig. 7 Optimized Trajectory of Fish Schools in the L1-L2 Parameter Space (Original).

ISSN 2959-6157

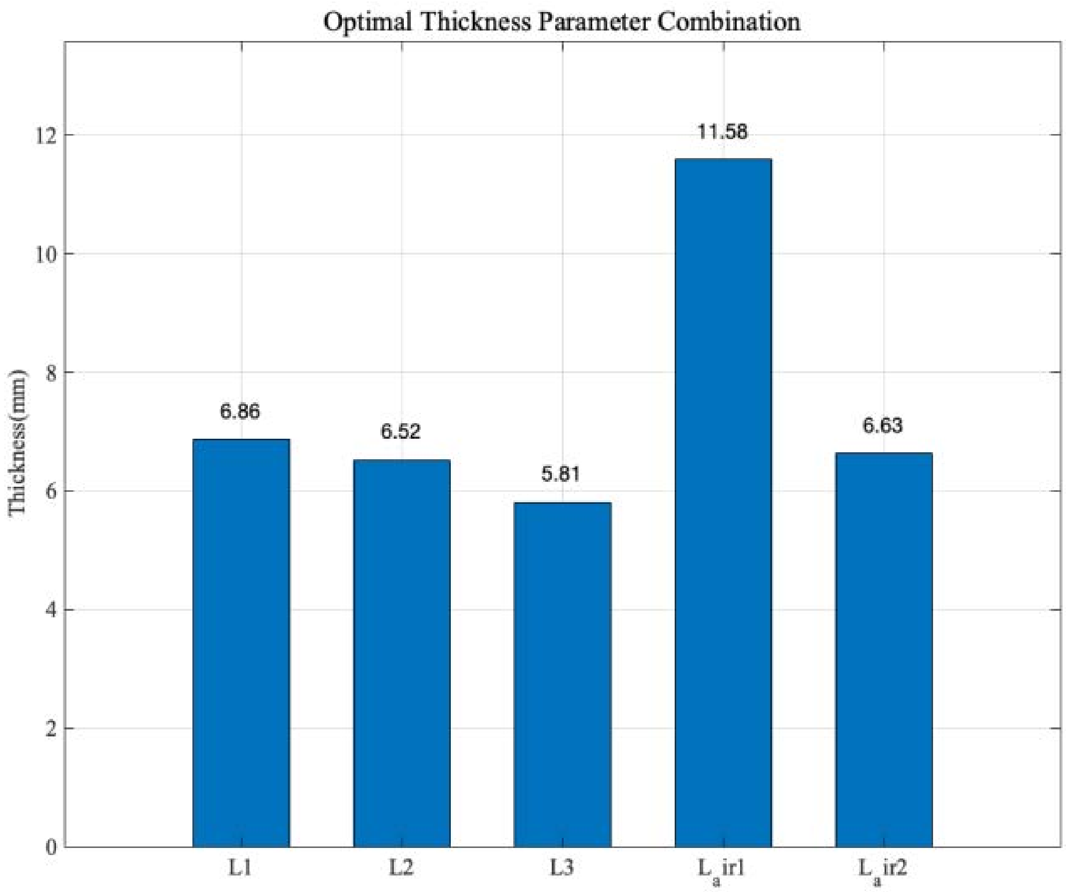

Fig. 8 Optimal Thickness Parameter Combination (Original).

Fig. 8 shows the optimal thickness parameter combination chart. This column chart visually presents the thickness values of the three layers of glass (L1, L2, L3) and the two air layers (Lair1, Lair2) optimized by the fish swarm algorithm. L1 = 6.86 mm, L2 = 6.52 mm, L3 = 5.81 mm, all of which are within the engineering constraint range (3-8 mm), and the thickness shows a gradient distribution of “L1 > L2 > L3”. This not only ensures the structural strength of the glass, avoiding deformation and cracking due to excessive thinness, but also controls the material cost, meeting the industrial production and construction requirements of building exterior windows. Fig. 8 quantitatively presents the specific values of the optimal parameter combination, verifying the optimization results of the fish swarm algorithm and providing a directly applicable quantitative basis for the design of three-layer glass exterior windows in northern winters.

5. Conclusion

This study employed the fish swarm algorithm to systematically optimize the thickness parameters of three-layer glass and the air thickness between the layers. The final optimized thickness parameter combination was L1 = 6.86 mm, L2 = 6.52 mm, L3 = 5.81 mm, Lair1 = 11.58 mm, and Lair2 = 6.63 mm. The model calculation error was small and verified through wavelength contribution distribution analysis. The near-infrared band (760-2000nm) transmittance reached 0.8-0.95, the visible light band (400-760nm) transmittance was stable at 0.7-0.85, and the ultraviolet band (300-400nm) transmittance was effectively controlled at 0.45-0.65, matching the performance requirements of “energy-saving + comfort” for exterior windows in northern winters. In view of the continuous variable and multi-peak characteristics of the thickness optimization of three-layer glass, the fish swarm algorithm effectively avoids the defect that traditional algorithms are prone to fall into local optimum through the dynamic adjustment of group behavior (foraging to explore the global, clustering to mine the local, and tailing to converge to the optimal), providing a new solution idea for similar multi-parameter collaborative optimization problems.

However, this study also has certain limitations. The model only uses typical winter solar radiation data and does not take into account the dynamic changes of solar radiation at different times and under different weather conditions, so the universality of the optimization results needs to be further improved. At the same time, the characteristics of high-performance glass were not considered. Due to the limited heat insulation and heat preservation performance of traditional glass, a large amount of energy is exchanged between the inside and outside of buildings through it. The research is based on ordinary transparent glass and does not involve coated glass or vacuum glass, which is different from the current mainstream high-performance products in the building market.

In conclusion, this study, through the exploration of the process of "theoretical modeling - algorithm optimization - engineering verification", has provided a scientific method and quantified parameters for the energy-saving design of three-layer glass windows in northern winters, and also offered a beneficial reference for the research in the field of multi-parameter collaborative optimization of building windows.

References

[1] Li R X. Energy efficiency analysis of building windows and doors in cold regions. Jiangxi Building Materials, 2021, (6): 143–144.

[2] Xia Y, Li P Y, Liu Z Q. Selection and evaluation of energy-saving technologies for exterior windows in severe cold regions. Low Temperature Building Technology, 2019, 41(12): 15–18+24.

[3] Yu J H, Tian L W, Yang C Z. Analysis of the optimal thickness of roof insulation layer for residential buildings in hot-summer and cold-winter regions. Journal of Central South University (Science and Technology), 2012, 43(4): 1545–1550.

[4] Huang C H, Ye Y J. Economic optimization of the insulation layer thickness for exterior walls of energy-saving buildings. Building Energy Efficiency, Ventilation and Air Conditioning, 2005, (6): 73–76.

[5] Nyers J, Kajtar L, Tomic S, et al. Investment–savings method for energy–economic optimization of external wall thermal insulation thickness. Energy and Buildings, 2015, 86: 268–274.

[6] Zhang Y, Mu J G. Optimization study of insulation thickness for building exterior walls and parametric relationships of design parameters. Building Science, 2019, 35(12): 113–125.

[7] Liu Y L, Liu J S. Analysis of detection methods for optical and thermal properties of architectural glass. Foshan Ceramics, 2024, 34(5): 59–61.

[8] Wang T P, Wang L B. A steady heat transfer model of hollow double glazing under entire-wavelength heat radiation. Energy and Buildings, 2014, 81: 72–83.

[9] Cuce E, Young C H, Riffat S B. Thermal performance investigation of heat-insulation solar glass: A comparative experimental study. Energy and Buildings, 2015, 86: 595–600.

[10] Zhou Y M, Wang F S, Li Z W, et al. Analysis of visible-light parameters of multi-layer glass structures. Building Energy Efficiency, Ventilation and Air Conditioning, 2017, 36(1): 18–22.

[11] Wang H X, Huang Z, Qian B, et al. Route planning for infrared inspection of power lines by unmanned aerial vehicles based on improved artificial fish swarm algorithm. Microcomputer Applications, 2022, 38(8): 35–38.