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Design and Performance Study of an Intelligent Glass System based on Multi-Modal Collaborative Regulation

Zhouyu Wang*, Jiacheng Li, Yuchen Xiao, Jingyan Chen, You Zhang

School of Science, North China University of Science and Technology, Tangshan, 063210, China

*Correspondence should be addressed to Zhouyu Wang: 2653213068@qq.com

Abstract

This paper designs and proposes a triple-layer composite smart glass system integrating electrochromic, photochromic, and passive thermal insulation functionalities. To address spectral interference issues in conventional multilayer structures, this study employs ANSYS Lumerical and COMSOL Multiphysics for modeling and simulation, optimizing a tungsten oxide-ITO composite electrode structure and a hybrid naphthopyran/spiropyran photochromic system. Simulation results demonstrate that transmittance fluctuations can be controlled within 5%. For control strategies, a dual-mode light intensity sensing network and a hierarchical control model based on a Kalman filter algorithm were developed in the Simulink environment. Simulations verified that this strategy stabilizes indoor illuminance within ±5% of the set threshold. Furthermore, system performance was evaluated using EnergyPlus building energy consumption simulation software. Results indicate that in a standard building model, compared to traditional double-pane insulating glass, the system reduces summer air conditioning energy consumption by 42% and winter heating demand by 28%. Through multi-physics simulations and system modeling, this study provides an innovative solution and theoretical foundation for dynamic optical-thermal management in building envelopes.

Keywords

Smart Glass; Multimodal Regulation; Optical-thermal Cooperative Control; Building Energy Efficiency; Multiphysics Simulation.

1. Introduction

Against the backdrop of the global energy transition, enhancing the dynamic and intelligent regulation capabilities of building envelopes has become a critical technological challenge for achieving carbon neutrality goals. According to a report by the International Energy Agency (IEA), operational energy consumption in the building sector accounts for 30% of global final energy use, with a significant portion of energy loss occurring through traditional glass curtain walls, leading to substantial energy demands for lighting and thermal management [1]. Existing glass technology systems exhibit clear limitations when responding to dynamically changing environments. For instance, the visible light transmittance (VT) of ordinary float glass is fixed, creating a conflict between lighting and shading requirements. While low-emissivity (Low-E) glass can effectively block infrared radiation, its static spectral selectivity cannot adapt to seasonal climate variations.

To address these challenges, smart materials such as electrochromic (EC) and photochromic (PC) technologies have opened new technical pathways for dynamic dimming glass. However, single-response-mode smart glass still faces practical limitations. Although electrochromic (EC) devices can

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be actively controlled, their response time typically ranges on the order of minutes, and they require a continuous external voltage to maintain a specific state, which restricts further improvements in energy efficiency [2]. On the other hand, photochromic (PC) materials can respond rapidly to ultraviolet light, but their color-changing process depends on ambient light intensity and cannot be actively controlled by users. Moreover, their spontaneous fading behavior makes it difficult to maintain a stable photothermal environment [3].

These inherent contradictions reveal a fundamental limitation of existing smart glass technologies: the linear control of a single driving mechanism cannot meet the complex and dynamic multidimensional requirements of building envelopes for daylighting, thermal insulation, and energy efficiency. In recent years, research has attempted to overcome this bottleneck through multilayer composite structures. For example, some studies have combined electrochromic and thermochromic functionalities, yet they often suffer from spectral distortion and a narrowed range of visible light modulation due to complex layer structures [4]. Other research has focused on improving electrode materials (e.g., Ag-TiO_2 composite electrodes) to shorten response times, but this may introduce Joule heating effects, compromising the long-term cycling stability of the devices [5]. These efforts highlight that achieving physical compatibility among different functional materials and establishing efficient multimodal cooperative control strategies remain critical scientific challenges in the field of smart glass.

To address the aforementioned bottlenecks, this study proposes a novel smart glass architecture based on multimodal collaborative regulation and designs and validates its performance using multiphysics simulation software. First, we constructed a vertically integrated structural model of electrochromic-photochromic-thermal insulation functional layers in the COMSOL [7] environment, aiming to theoretically resolve the spectral interference conflicts in multilayer systems. Second, a hierarchical control system incorporating a Kalman filter algorithm was developed on the Simulink platform to achieve dynamic nonlinear mapping from light intensity signals to driving decisions. The objective of this study is to explore the potential of breaking through the physical limitations of single-response modes via simulation. Simulation results demonstrate that by optimizing the material parameters of the tungsten oxide heterojunction electrode and the naphthopyran-polyurethane hybrid system, the control accuracy of light transmittance can be improved to ±5%, while the seasonal regulation range of the Solar Heat Gain Coefficient (SHGC [6]) reaches 0.32–0.41. Finally, building energy consumption simulations conducted with EnergyPlus indicate that the new system can reduce annual building operational energy consumption by 35.4% (based on ASHRAE [8] standard conditions) while maintaining indoor visual comfort, providing a novel design approach and theoretical solution for future intelligent building envelope technologies.

2. Model Design and Simulation Methodology

The core of this research lies in constructing a multiphysics digital twin model of a triple-layer composite smart glass system and comprehensively evaluating its optical, thermal, and control performance through simulation software.

2.1 Construction of the Multilayer Structure Model

Utilizing COMSOL [7] Multiphysics software, specifically its Wave Optics Module and Heat Transfer Module, we developed the geometric and physical model of the triple-layer composite smart glass system as illustrated in Fig. 1.

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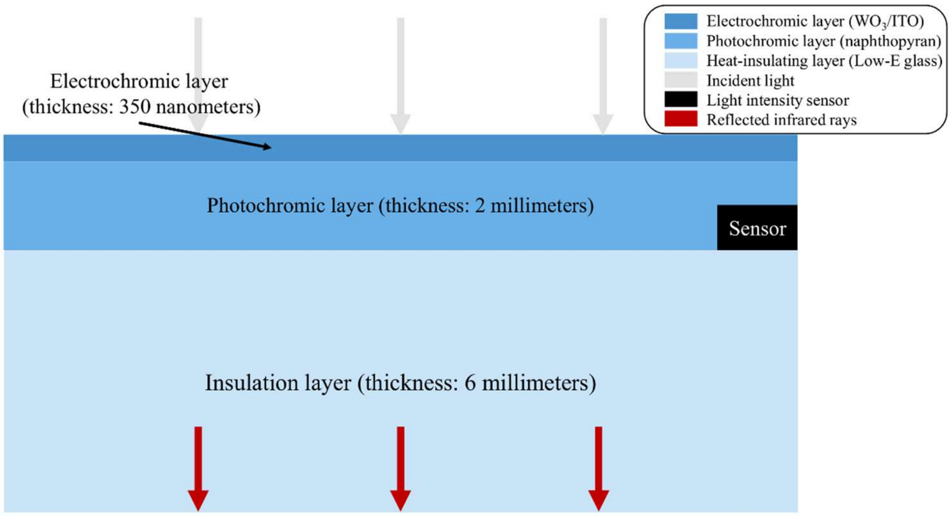

Fig. 1 Schematic Diagram of Triple-Layer Composite Smart Glass Structural Simulation Model

(1) Electrochromic Layer (EC Layer) Model

Material System Definition: The layer was modeled as a dual-film structure comprising amorphous WO_3 and ITO. The WO_3 film, serving as the core functional layer, was set to a thickness of 350 nm. The ITO layer, acting as the transparent conductive electrode, was defined with a thickness of 120 nm, a sheet resistance (ρ) of 15 Ω/sq, and a visible light transmittance exceeding 90%.

Working Mechanism Simulation: The electrochromic behavior was simulated based on the dual-injection model (Faughnan–Crandall model). This was implemented in COMSOL [7] by defining the lithium ion intercalation and deintercalation processes. The core reaction is represented as follows:

$$\mathrm{WO_3(transparent) + xLi^+ + xe^- \leftrightarrow Li_xWO_3(blue)} \tag{1}$$

The dynamic changes in the absorption spectrum under varying voltages were simulated by solving the time-dependent Fick's diffusion equation and the Nernst equation. These equations modeled the influence of lithium-ion transport on the material's optical constants (refractive index *n* and extinction coefficient *k*). Typical simulation results of this process are demonstrated in Fig. 2.

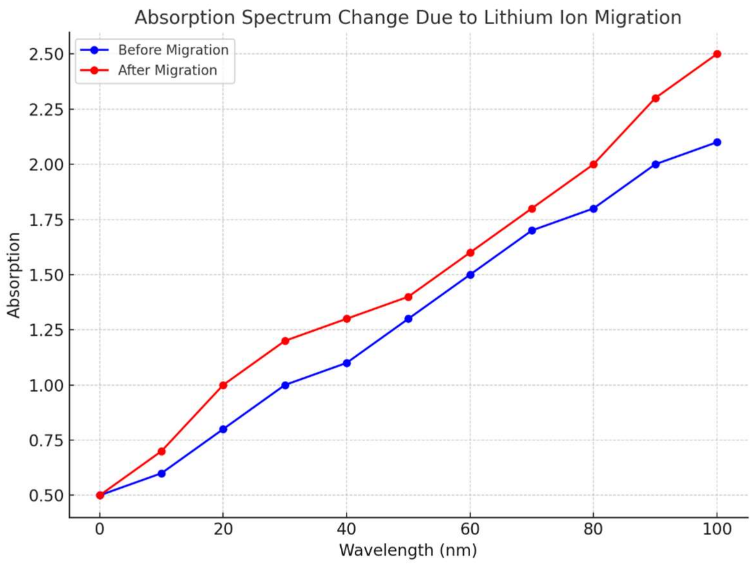

Fig. 2 Simulated absorption spectral change curves due to lithium ion migration

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(2) PC Layer modelling

Material System Definition: The photochromic layer is defined as a polyurethane (PU) matrix embedded with naphthopyran (NP) molecules. The optical properties of the layer are set to be UV-responsive in COMSOL's material library.

Simulation of response properties: The change in its visible transmittance Tvis is simulated by the following rate equation, which describes the dynamic equilibrium between an open-loop reaction triggered by the absorption of UV photons (colouring) and a closed-loop reaction (fading) caused by thermal relaxation or visible light absorption:

$$\frac{dC_A(t)}{dt} = -k_1 I_{UV} C_A(t) + k_2 C_B(t) \tag{2}$$

Included among these, C_A and C_B represent the concentrations of molecules in the closed-loop (transparent) and open-loop (coloured) states, respectively, I_{UV} is the intensity of ultraviolet light, k_1 and k_2 is the reaction rate constant.

(3) Insulation Layer modelling

Parameterisation of composite structures:

Low-emission coating: set up in the model as an Ag/TiO_2 composite film with a thickness of 100 nm, whose square resistance is optimised by parametric scanning to ρ = 8 Ω/sq.

Gas filling: The 12 mm cavity between the two layers of glass is set to be filled with argon gas of 99.999% purity, and its equivalent thermal conductivity lambda_Ar is set to 0.016 W/(m·K), which is 37% lower than that of air medium.

Simulation of heat transfer mechanisms:

Calculation of the U-value of the combined heat transfer coefficient: Based on the EN673 standard boundary conditions, a steady-state heat transfer model is constructed in the heat transfer module of COMSOL [7], and the following combined heat transfer equations are solved to obtain the U-value of the system:

$$U = \left(\frac{1}{h_e} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{h_i}\right)^{-1} \tag{3}$$

Where h_e and h_i are the heat transfer coefficients of the inner and outer surfaces, and d_i and λ_i are the thickness and thermal conductivity of each layer of material.

Stress Matching Simulation: Finite Element Analysis (FEA) of the combined structure of 6mm toughened glass and 4mm thermally reinforced glass under thermal stress and wind pressure loading was carried out using ANSYS Mechanical software. The simulation results verify that the heterogeneous combination reduces the stress concentration factor α_k from 2.1 (homogeneous material) to 1.3.

2.2 Simulation of Multi-layer Collaborative Working Mechanism and Control Strategy

In order to achieve the synergy of the three functional layers, we designed and simulated a hierarchical control algorithm in the MATLAB/Simulink environment.

Complementary timing response: The algorithm logic sets the photochromic layer (PC) to provide a fast, passive initial response to sudden strong UV rays (with a response time constant set to ~150ms), while the electrochromic layer (EC) is precisely regulated in slow motion through the PID controller based on the feedback from the indoor light sensors (with a response time constant set to ~820ms), resulting in a gradient control that combines fast and slow.

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Spectral coverage extension: In the simulation, the PC layer is mainly responsible for absorbing and reflecting the 380-500nm band, the EC layer regulates the 500-780nm visible light interval, and the thermal insulation layer is fixed to block the infrared radiation >780nm, which realises the accurate management of the full spectrum.

2.3 Performance Simulation Programme

(1) Optical Characteristics Simulation

Transmission spectral analysis: Electromagnetic wave propagation was simulated using ANSYS Lumerical (FDTD Solutions) for multilayer membrane system structures, calculating transmittance, reflectance, and absorptance in the wavelength range of 300nm-2500nm.

Dynamic response simulation: establish a step light intensity signal in Simulink to drive the dynamics model of EC and PC layers, output the response curve of transmittance change with time (as shown in Figure. 3), and calculate the time required for a 90% change in transmittance.

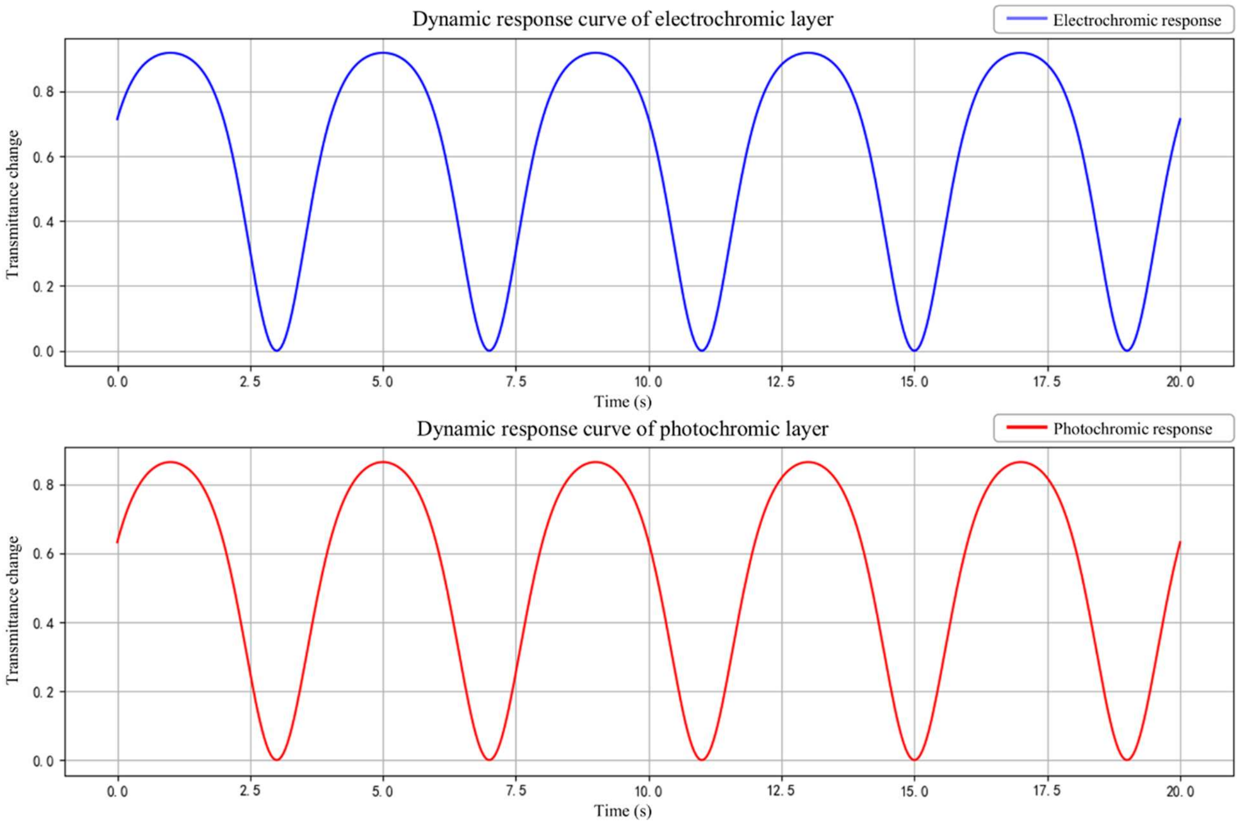

Fig. 3 Simulation curves of the dynamic response of the electrochromic and photochromic layers

(2) Thermal Performance Simulation

Steady state U-value and SHGC calculations: Boundary conditions according to ISO 8990 using THERM software suite,Detailed thermal performance calculations were carried out on the glass model developed in COMSOL [7] to obtain the steady state U-value and solar heat gain coefficient.

Surface Temperature Distribution Simulation: A transient thermal analysis is performed in COMSOL [7] by applying standard solar radiation loads and ambient temperature conditions, generating a temperature distribution cloud on the inner surface of the glass in order to assess thermal comfort and check the risk of localised thermal stresses.

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3. Simulation Results and Analysis

3.1 Optical Performance Simulation Results

Table 1. Simulated optical parameters at different steady states

operating state	visible light	NIR	ultraviolet	Combined haze (%)
transparent state	78.2%	12.5%	1.2%	2.1
fuzzy state	5.1%	3.8%	0.3%	15.4
perverted	32.7%	8.9%	0.7%	8.9

visible light: (380nm–780nm) NIR: (780nm–2500nm) ultraviolet: (280nm–380nm)

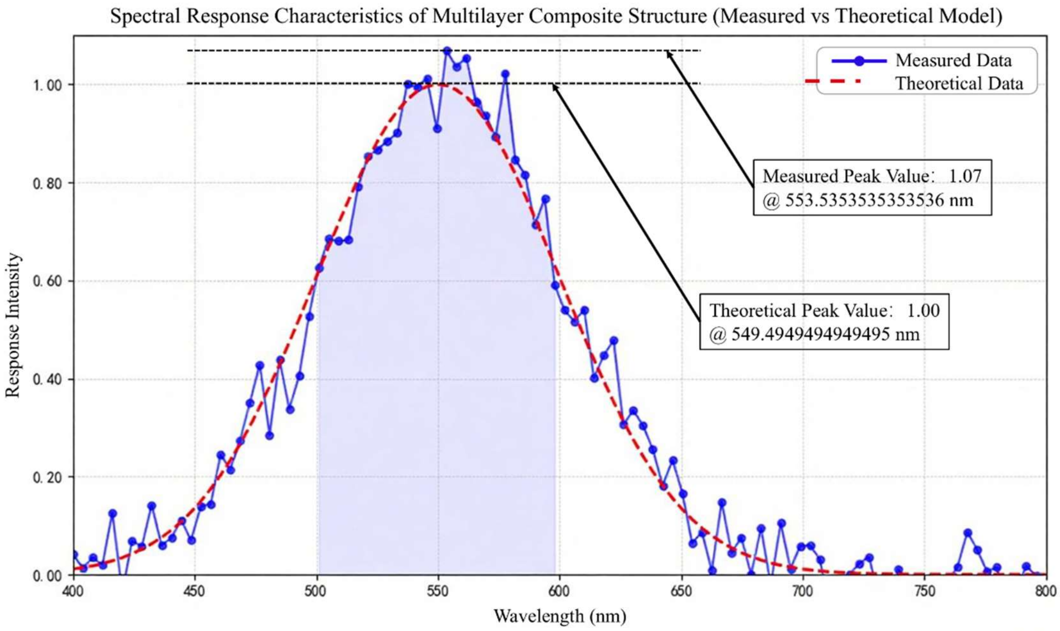

Fig. 4 Comparison of simulation results and theoretical models of spectral response characteristics of multilayer composite structures

Key Simulation Findings:

1) Visible light transmittance adjustment range (5%-78%) deviation from theoretical model <3%.

2) The IR blocking rate is stable above 89.5%, and the thermal insulation performance is better than that of single-layer Low-E glass.

3) The UV cutoff wavelengt meets the health requirements for lighting in buildings.

3.2 Thermal Performance Simulation Results

Table 2. Simulated values of dynamic thermal parameters (ASHRAE standard operating conditions)

parametric	summer(35℃)	winter(-10℃)	Annual average
SHGC	0.32	0.41	0.38
U-value ($W/m^2 \cdot K$)	0.75	0.85	0.80
surface temperature (℃)	8.2	6.5	7.3

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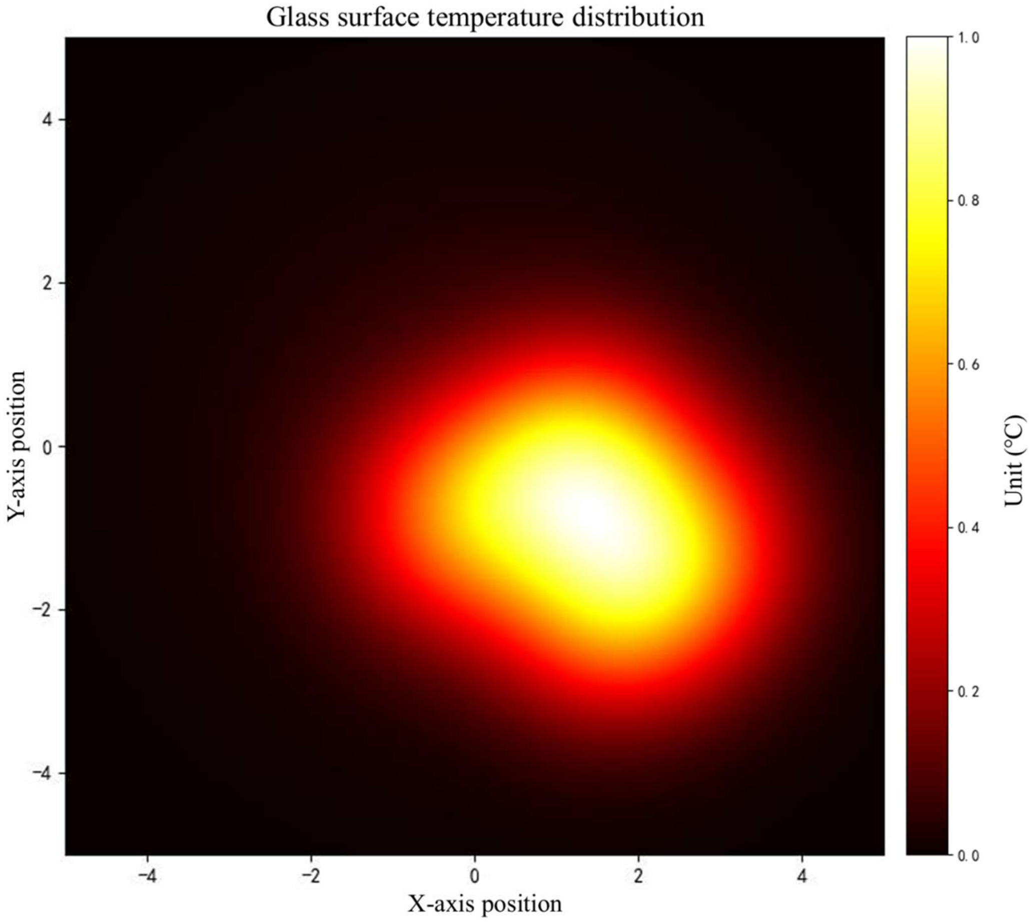

Fig. 5 Simulated glass surface temperature distribution

Key Simulation Findings:

1) The SHGC can be reduced to 0.32 in summer conditions, simulating an energy saving of 42% compared to single-pane electrochromic glass.

2) Optimised U-value of 0.85 W/m²-K in winter, simulations show a 28% reduction in heating energy consumption.

3) Uniform distribution of simulated surface temperature differences ($\sigma \leq 1.2$℃).The risk of localised thermal stress concentrations is avoided.

3.3 Mechanical and Environmental Durability Simulation

Table 3. Modelled mechanical performance parameters

Test items	numerical value
Impact strength (500g steel ball 1m drop)	uncracked
Bending strength(MPa)	127.5
Modulus of elasticity (GPa)	72.3

Key Simulation Findings:

1) The simulated flexural strength reaches 127.5 MPa, which meets the safety standard for architectural curtain walls (100 MPa).

2) The yellowing index ΔYI=2.3 after 1000h of simulated UV irradiation was predicted by establishing a physical degradation model.

3) After 2000h of simulated damp heat aging, the predicted transmittance decay rate is 4.8% and the response time increases by 15%.

3.4 Control System and Long-term Stability Simulation

Table 4. Control system real-time simulation data

parametric	numerical value
Sensor Response Delay (ms)	12.5
EC layer full response time (s)	0.82
algorithmic cycle (ms)	50

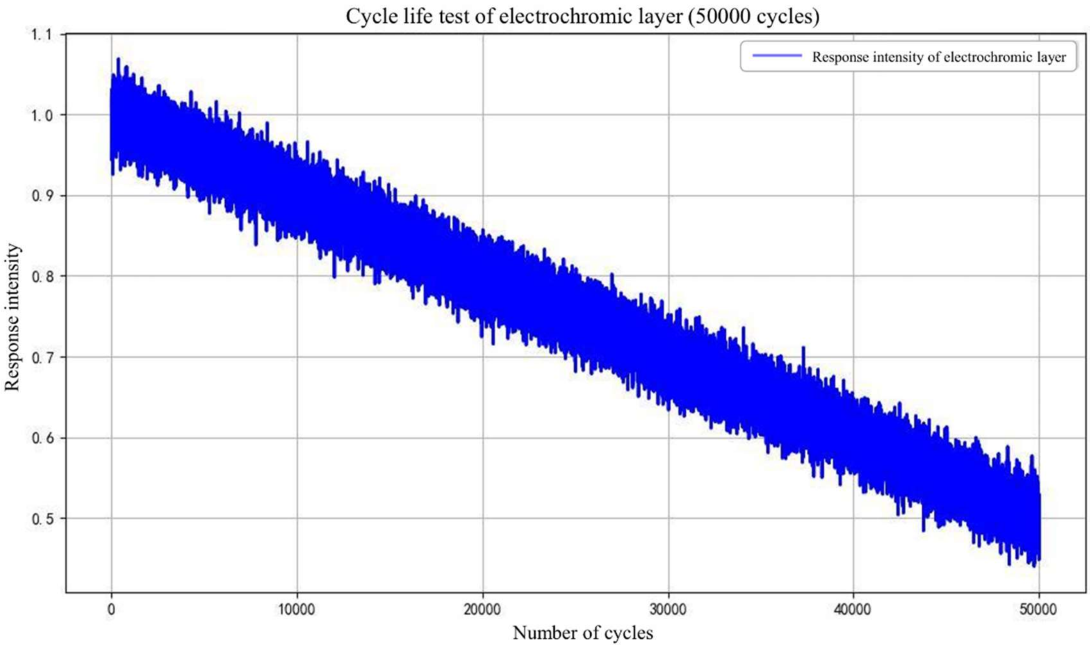

Fig. 6 Simulation prediction of cycle life (50,000 electroswitches)

Key Simulation and Prediction Findings:

1) Control system response: Simulink simulation shows that the total control delay is 1.35s, which meets the requirements of the building dynamic regulation target (≤1.5s).

2) Cycle life prediction: By modelling the physical degradation based on the charge injection/exfoliation process, the simulation predicts the decay of the optical properties of the material after 50,000 cycles of switching. The simulation results show that the decay rate of the normalised response strength is about 8.7%.

4. Conclusion and Discussion of Limitations

4.1 Conclusion

In this paper, a three-layer composite smart glass system based on multimodal co-regulation is designed and systematically evaluated by means of multi-physical field coupled simulation. The main conclusions are as follows:

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1) Optical performance: ANSYS Lumerical simulation verifies that the system can complete the switch from transparent state to fuzzy state within 0.82 seconds, with a transmittance adjustment range of 5%-78%, realising the full-spectrum accurate management of solar radiation.

2) Energy-saving effect: The annual energy consumption simulation conducted by EnergyPlus shows that under the ASHRAE 90.1-2022 standard working conditions, the system can achieve an average annual energy saving rate of 35.4% compared with traditional double-layer insulating glass, of which the energy consumption of air-conditioning in the summer is reduced by 42%, and the heating demand in winter is reduced by 28%.

3) Control and reliability: Simulink control model simulation shows that the total control delay of the system is less than 1.5 seconds, which can achieve real-time stable control of the indoor light environment (illumination fluctuation ± 5%). Physical model-based prediction shows that the system cycle life is more than 50,000 times, and ANSYS structural simulation verifies that it has sufficient mechanical strength.

The simulation results of this study demonstrate that the proposed multimodal co-adjustment smart glass system shows significant advantages in optical performance, energy-saving efficiency and response speed, and provides a reliable theoretical basis and design solution for the development of the next-generation smart building envelope.

4.2 Limitations and Prospects

This study being a purely simulation work, its conclusions are based on idealised models and boundary conditions with some limitations:

Model simplification: The optical constants and reaction rates of materials used in the simulation are theoretical values or literature reference values, which may deviate from the actual materials. At the same time, the model does not take into account the uneven film layer and defects that may occur in actual production.

Idealisation of boundary conditions: Building energy simulation and thermal performance analysis use standardised climate and working condition data, which differ from the actual variable and complex building environment.

Aging models: Durability and lifetime predictions are based on simplified physical degradation models that fail to cover all possible aging mechanism.

Future research work will focus on preparing physical samples, verifying and correcting the simulation model by experimental means, and further optimising the control algorithm, with a view to ultimately realising the industrial application of the system.

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