IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 44, No. 2, April, 2026, pp. 477-490
Journal homepage: http://iieta.org/journals/ijht

Optimized Indoor Natural Ventilation Design Integrating Thermal Comfort and Architectural Aesthetics: A Multi-Objective Thermodynamic Simulation Study

Bingxing Yan[1*], Jie Wu[2], Sihan Hou[3]

[1] School of Engineering and Architecture, Henan Quality Institute, Pingdingshan 467000, China
[2] Modern Manufacturing Department, Pingdingshan Institute of Technology, Pingdingshan 467000, China
[3] School of Marxism, Henan Quality Institute, Pingdingshan 467000, China

Corresponding Author Email: ybxwj83@126.com

https://doi.org/10.18280/ijht.440204

Received: 22 October 2025
Revised: 19 February 2026
Accepted: 7 March 2026
Available online: 30 April 2026

Keywords:
indoor natural ventilation, non-equilibrium thermodynamics, architectural aesthetics, thermal comfort, Physics-Informed Neural Network, entropy minimization

ABSTRACT

In the design of indoor natural ventilation, the disconnect between thermal comfort and architectural aesthetics, coupled with insufficient optimization of thermodynamic dissipation, limits the scientific rigor and integrative capacity of building design. This study proposes a thermo-aesthetic entropy minimization design framework that integrates non-equilibrium thermodynamics (the second law) with intelligent algorithms to achieve synergistic optimization of thermal comfort, architectural aesthetics, and thermodynamic dissipation. The framework establishes an analytical coupling model that directly links aesthetic parameters with thermodynamic boundaries, quantifying architectural form as a core factor influencing entropy generation rate. An optimization strategy is introduced by embedding thermodynamic constraints into a Physics-Informed Neural Network (PINN)-based surrogate model within a multi-objective optimization loop, addressing the long-standing deficiency in multi-objective coordination inherent in conventional approaches. Furthermore, an entropy-oriented validation system is developed under multiple climate scenarios to clarify the regulatory mechanisms by which aesthetic forms influence irreversible thermodynamic dissipation. The findings provide a thermodynamics-led, interdisciplinary pathway for indoor natural ventilation design, extend the application scope of non-equilibrium thermodynamics in architectural aesthetics, and offer a reproducible technical paradigm for similar multi-objective optimization studies.

1. INTRODUCTION

Indoor natural ventilation, as a core technology of passive building design [1-3], not only directly affects indoor thermal comfort and air quality, but also serves as a key pathway to achieving building energy efficiency [4] and low-carbon goals. Its design quality is closely related to thermodynamic dissipation efficiency [5] and architectural aesthetics expression. Under the current background of deep integration between green building and interdisciplinary design concepts, traditional indoor natural ventilation optimization faces dual dilemmas. On one hand, the design process often treats thermal comfort and architectural aesthetics [6] separately: either optimizing ventilation performance solely based on Predicted Mean Vote (PMV)–Predicted Percentage of Dissatisfied (PPD) indices [7, 8] while neglecting the systematic expression of architectural form aesthetics, or excessively pursuing visual aesthetics [9], resulting in imbalances in ventilation thermodynamic dissipation. On the other hand, conventional Computational Fluid Dynamics (CFD) simulation [10, 11] optimization methods have the inherent drawback of low computational efficiency and lack explicit thermodynamic entropy production [12] constraints, causing designs to suffer from excessive irreversible dissipation and insufficient available energy utilization efficiency, making it difficult to meet the high requirements of modern buildings for comprehensive performance. From the perspective of disciplinary development, the second law of non-equilibrium thermodynamics [13], as a core theory describing irreversible processes, has been preliminarily explored in building ventilation optimization, yet its application in the coupled optimization of architectural aesthetics and ventilation performance [14, 15] remains at an early stage. There is still a lack of systematic models capable of directly linking aesthetic parameters with thermodynamic boundary conditions, and no quantitative evaluation system exists that simultaneously considers thermodynamic dissipation, thermal comfort, and architectural aesthetics. This disciplinary gap has become a critical bottleneck restricting the upgrading of indoor natural ventilation design toward higher efficiency, enhanced aesthetics, and lower carbon emissions.

In recent years, domestic and international scholars have carried out extensive research on indoor natural ventilation optimization, applications of non-equilibrium thermodynamics, quantification of architectural aesthetics, and simulation acceleration technologies [16, 17], providing an important foundation for this study. In studies integrating non-equilibrium thermodynamics with building ventilation, researchers have mostly focused on improving entropy generation rate calculation methods and applying available energy analysis. By quantifying irreversible dissipation in ventilation processes, these studies provide thermodynamic guidance for optimization; however, such research is generally limited to single-target ventilation performance improvement and does not incorporate architectural aesthetics into the thermodynamic analysis framework, thus failing to realize multi-objective collaborative optimization. In the field of CFD simulation acceleration, Physics-Informed Neural Networks (PINNs), leveraging their advantage of integrating physical laws with data-driven approaches, have been widely applied to improve the efficiency of fluid mechanics simulations [18, 19]. Researchers have constructed PINN-based surrogate models [20] to effectively reduce the computational cost of traditional CFD simulations; however, existing models are mostly developed without embedding thermodynamic constraints, leading to predictions that may deviate from thermodynamic laws and fail to meet the requirements of high-precision thermodynamic optimization. Regarding research on the coupling of architectural aesthetics and ventilation performance, existing methods mainly use indicators such as fractal dimension and curvature moment [21] to quantify architectural form aesthetics, analyzing the impact of aesthetic forms on ventilation performance through post-evaluation. Nevertheless, no direct analytical relationship between aesthetic parameters and thermodynamic entropy generation rates has been established, preventing real-time linkage between aesthetic design and thermodynamic optimization. Overall, existing research has yet to overcome three major gaps: first, the absence of a direct coupling mechanism between aesthetic parameters and entropy generation rates; second, the failure to effectively embed thermodynamic constraints into the training process of surrogate models; and third, the lack of systematic verification across multiple climatic scenarios. These limitations undermine the universality and practicality of existing optimization methods, making it difficult to resolve the core problem that aesthetics and low dissipation cannot be achieved simultaneously in traditional design.

The primary objective of this study is to establish a multi-objective indoor natural ventilation optimization framework integrating thermal comfort, architectural aesthetics, and thermodynamic dissipation, thereby realizing collaborative design characterized by low entropy production, high aesthetics, and superior comfort. The universality and superiority of this framework will be verified through multi-scenario experiments. To achieve this goal, four core innovations are proposed: (1) Constructing an aesthetics–thermodynamics boundary coupling mechanism to overcome the limitation of traditional post-evaluation of aesthetic parameters. Core aesthetic variables—such as window opening aspect ratio and deflector curvature—are directly mapped to wall roughness Reynolds number and turbulent vorticity generation functions via analytical functions, deriving coupling relationships between aesthetic parameters and thermodynamic boundary parameters, enabling real-time linkage between aesthetic design and thermodynamic boundary conditions. (2) Proposing a thermodynamic-constrained PINN surrogate model by constructing a five-layer fully connected network architecture, and embedding for the first time the incompressible Navier–Stokes equations, energy equation, and entropy generation rate calculation formula into the loss function. This addresses the disconnection between traditional surrogate model predictions and thermodynamic laws, significantly improving simulation efficiency and prediction accuracy. (3) Establishing a multi-objective thermodynamic evaluation system by constructing a three-dimensional evaluation index system of entropy production–available energy–aesthetics, proposing a coupled objective function comprising global entropy production number, available energy uniformity index, and form complexity entropy, and determining thermodynamics-led weights through the analytic hierarchy process to highlight the central role of thermodynamics in multi-objective optimization. (4) Designing a climate-adaptive verification system by developing differentiated verification schemes tailored to the thermodynamic characteristics of various climatic zones, quantifying the regulatory patterns of aesthetic parameters on different entropy generation terms under extreme climates such as hot-humid and hot-dry conditions, thereby significantly enhancing the universality of the optimization framework.

To fulfill the above objectives and innovations, the following research tasks are conducted: first, parametric modeling and coupling of aesthetic parameters and thermodynamic boundaries are performed to establish analytical relationships; second, training and optimization of the thermodynamic-constrained PINN surrogate model are carried out to improve simulation efficiency and prediction accuracy; third, a multi-objective optimization algorithm incorporating thermodynamic constraints is designed to realize collaborative optimization of the three objectives; fourth, the performance of the optimization framework is validated through multi-scenario comparative experiments; finally, experimental results are analyzed and discussed in depth to clarify the optimization mechanisms and application value. The entire study follows the logical thread of problem redefinition → parameter coupling → simulation acceleration → optimization solving → experimental verification, with thermodynamic analysis running throughout the whole research process. This forms a complete research system ranging from theoretical modeling and simulation acceleration to experimental verification, providing systematic technical support for interdisciplinary optimization of indoor natural ventilation.

2. METHODOLOGY

This study takes the thermodynamics of non-equilibrium open systems as the core theoretical support, treating the indoor ventilation space as an irreversible evolution system with continuous momentum, heat, and moisture exchange across boundaries. The internal flow, heat transfer, and mass transfer processes within the system continuously generate energy dissipation and entropy increase effects. The finite volume method is adopted to carry out full-domain numerical discretization and solution, combined with the k–ω Shear-Stress Transport (SST) turbulence model to accurately characterize near-wall flow behavior, turbulence evolution laws, and the transport process of thermal and humidity gradients. A coupled solution strategy is employed to perform synchronous calculations of indoor flow field, temperature field, and humidity field, ensuring the stability and physical authenticity of numerical results under complex natural ventilation conditions. PINNs are introduced to achieve efficient acceleration of simulation computations, using fluid dynamics governing equations and thermodynamic conservation laws as physical constraints, and combining high-fidelity numerical simulation samples to complete model training, thereby realizing rapid parameterized prediction of multi-physical fields. This paper does not elaborate on well-established turbulence numerical simulation methods and basic thermodynamic theories, but focuses on systematically explaining the self-developed coupling mechanism between architectural form and thermodynamic boundaries, the architecture of physics-constrained surrogate models, and the entropy-generation-mechanism-based multi-objective optimization system, thereby establishing a complete research framework deeply integrating theoretical mechanisms, numerical simulation, and intelligent optimization.

2.1 Aesthetics–thermodynamics parametric coupling model

Based on Non-Uniform Rational B-Spline surface modeling technology, this study performs continuous parametric representation of key envelope interfaces and air-guiding components in indoor natural ventilation systems, selecting five categories of core control variables capable of balancing both visual formal order and airflow guidance functions. These include the window opening aspect ratio R_{aw}, the Gaussian curvature of overhanging roofs K, the vertical taper angle of air guide towers, the installation inclination angle of guide louvers θ, and the fractal dimension of porous ventilation grilles D_f. The value ranges of each variable are strictly defined in accordance with classical architectural aesthetic proportion rules and the operating conditions of natural ventilation structures, respectively set as: $0.618 \le R_{aw} \le 1.618$, -0.05 m^{-2} $\le K \le$ 0.05 m^{-2}, $0^{\circ} \le \theta \le 30^{\circ}$, $15^{\circ} \le \beta \le 75^{\circ}$, $1.2 \le D_f \le 1.8$. All aesthetic indicators are encoded in continuous numerical form, breaking through the limitation of discrete selection in traditional architectural form design, and enabling continuous gradual variation and refined regulation of architectural appearance.

Different from existing studies that focus only on post-evaluation of completed forms for aesthetic quantification, this study directly transforms geometric aesthetic parameters into boundary constraint conditions for ventilation flow, establishing a direct connection between architectural form and fluid transport processes. Through independently developed parametric linkage logic, multi-dimensional morphological parameters can be updated synchronously, geometric models reconstructed in real time, and simulation boundaries automatically matched, forming an integrated dynamic representation system. This representation transforms architectural aesthetic elements from passive evaluation indicators to active control variables, embedding them in the entire workflow of ventilation numerical calculation, providing a stable variable basis for constructing quantitative coupling relationships between form parameters and turbulence characteristics, wall flow, and entropy generation evolution, and offering necessary support for realizing synergistic regulation of thermodynamic dissipation under aesthetic form constraints. Figure 1 shows the schematic diagram of the bidirectional dynamic coupling model between architectural aesthetic parameters and thermodynamic computation boundaries.

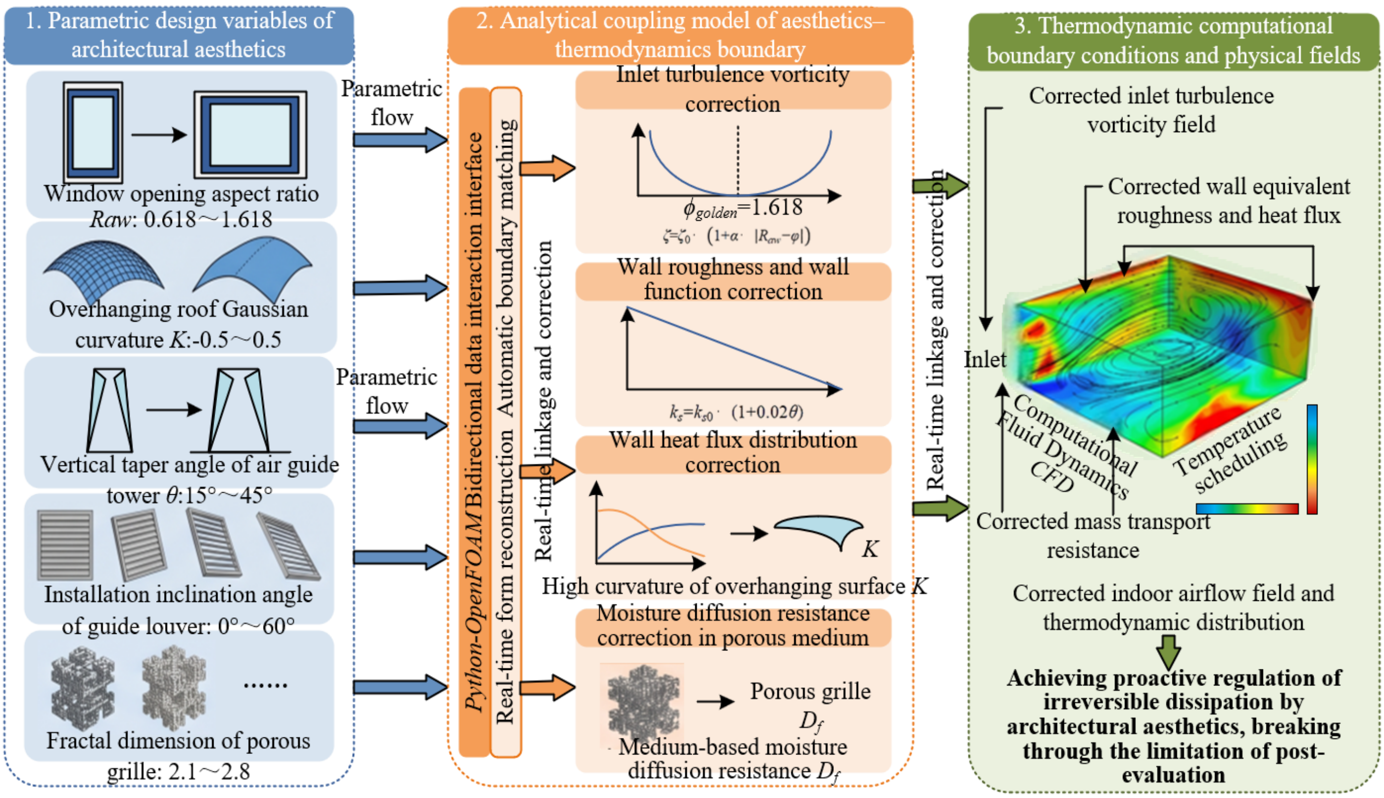


Figure 1. Schematic diagram of the bidirectional dynamic coupling model between architectural aesthetic parameters and thermodynamic computation boundaries

To achieve active linkage between architectural aesthetic form and thermodynamic dissipation processes, this study independently develops a Python–OpenFOAM bidirectional data interaction interface, overcoming the unidirectional limitation of traditional parameter transmission, enabling real-time writing, analytical mapping, and dynamic correction of geometric aesthetic parameters into the CFD boundary condition module. This constructs a quantitative correlation system among aesthetic form–wall flow–irreversible dissipation, fundamentally solving the core problem of disconnection between aesthetics and thermodynamic boundaries in existing studies. The interface connects to OpenFOAM's boundary condition solvers through custom function libraries, capturing instantaneously the influence of changes in aesthetic parameters on turbulence evolution, momentum transport, and heat–mass exchange, ensuring the timeliness and accuracy of coupling relationships, and providing technical support for precise regulation of subsequent thermodynamic dissipation.

Accurate regulation of inlet turbulence vorticity is key to reducing ventilation irreversible dissipation, and the window opening aspect ratio, as a core aesthetic parameter, when deviating from the golden ratio constant, significantly intensifies inlet flow distortion and vorticity dissipation. Based on data from 30 groups of orthogonal pre-experiments, the analytical coupling relationship between window opening aspect ratio and inlet turbulence vorticity intensity is fitted as:

$$\zeta=\zeta_0 \cdot \left(1+\alpha \cdot |R_{aw}-\varphi|\right) \tag{1}$$

where, ζ is the corrected inlet turbulence vorticity intensity, ζ_0 is the baseline vorticity intensity, φ is the golden ratio constant, and α is an empirical coefficient. Using the least squares method, α = 0.82 is calibrated, with a determination coefficient R^2 = 0.96, indicating very high fitting accuracy of this coupling relationship. This equation acts directly on the turbulence source term correction in CFD solutions, transforming changes in aesthetic parameters into adjustments of vorticity generation intensity in real time, realizing proactive control of flow irreversibility by aesthetic design, differing from the limitation of existing studies that analyze the indirect influence of aesthetics on flow only through post-evaluation.

The realization of coupling between wall roughness and thermo-mass boundaries further improves the full-dimensional regulation of aesthetic parameters on thermodynamic processes. Changes in the vertical taper angle of air guide towers alter wall flow separation characteristics, thereby affecting near-wall viscous dissipation. Based on experimental data, the linear coupling relationship between equivalent wall roughness height and taper angle is obtained:

$$k_s = k_{s0} \cdot (1 + 0.02\theta) \tag{2}$$

where, k_s is the corrected equivalent wall roughness height, k_{s0} is the baseline roughness height, and θ is the vertical taper angle of the air guide tower. Combined with the wall function model, k_s is further transformed into roughness Reynolds number, and the near-wall momentum diffusion coefficient and viscous dissipation source term are corrected to achieve precise control of momentum transport by aesthetic parameters. Meanwhile, the Gaussian curvature of overhanging roofs corrects the wall heat flux density distribution through a quadratic fitting equation, correlating the heat exchange area gradient with thermal boundary layer thickness; the fractal dimension of porous grilles directly regulates the moisture diffusion resistance in porous media domains, realizing aesthetic coupling of mass transport boundaries. The above coupling mechanisms work synergistically, fully covering momentum, energy, and mass thermodynamic boundaries, achieving full-dimensional, proactive regulation of thermodynamic dissipation processes by architectural aesthetic parameters, forming one of the core technological innovations of this study.

2.2 Thermodynamic-constrained physics-informed neural network surrogate model

This study constructs a fully connected deep neural network as the carrier for surrogate prediction of thermodynamic field quantities. The core innovation lies in breaking through the limitation of single-input dimensionality in traditional surrogate models by establishing a joint input system combining aesthetic features and spatial positions, thereby realizing accurate mapping from architectural form parameters to full-domain thermodynamic field quantities. The input layer contains an 8-dimensional feature vector, of which 5 dimensions constitute a feature vector formed by multi-dimensional architectural aesthetic parameters, and the remaining 3 dimensions correspond to indoor spatial coordinates. The two are jointly input to synchronously capture the coupled influence of differences in aesthetic parameters and variations in spatial position on thermodynamic field quantities, overcoming the defect of traditional models that can only perform single-dimensional prediction and fail to correlate form with field distribution. The hidden layers of the network are set to 5 layers, with each layer fixed at 128 neurons. This structure is determined through cross-validation optimization, ensuring both sufficient fitting capability for complex aesthetics–thermodynamics coupling relationships and effective avoidance of overfitting and gradient vanishing problems, thereby guaranteeing the generalization performance of the model. Figure 2 shows the network architecture.

To balance model training efficiency and the physical plausibility of prediction results, a layered activation strategy is adopted for precise regulation, which constitutes another core innovation of the surrogate model in this study. Shallow layers employ the ReLU activation function, expressed as:

$$ReLU(x) = \max(0,x) \tag{3}$$

which effectively mitigates gradient saturation effects, accelerates convergence, and enhances the extraction capability for high-dimensional input features. Deep layers adopt the Sigmoid activation function, expressed as:

$$Sigmoid(x) = 1/(1+e^{-x}) \tag{4}$$

which constrains output field quantities within reasonable physical intervals, avoiding non-physical solutions such as negative values in core thermodynamic parameters including entropy generation rate and exergy temperature, thereby ensuring the physical authenticity of prediction results. The output layer adopts a dual-output structure, synchronously predicting the total entropy generation rate field and the exergy temperature field, eliminating the need to construct separate independent surrogate models. This approach not only greatly improves computational efficiency but also avoids error accumulation caused by separate-model prediction, providing efficient and accurate field quantity data support for subsequent multi-objective optimization, and realizing seamless integration between the surrogate model and the optimization process.

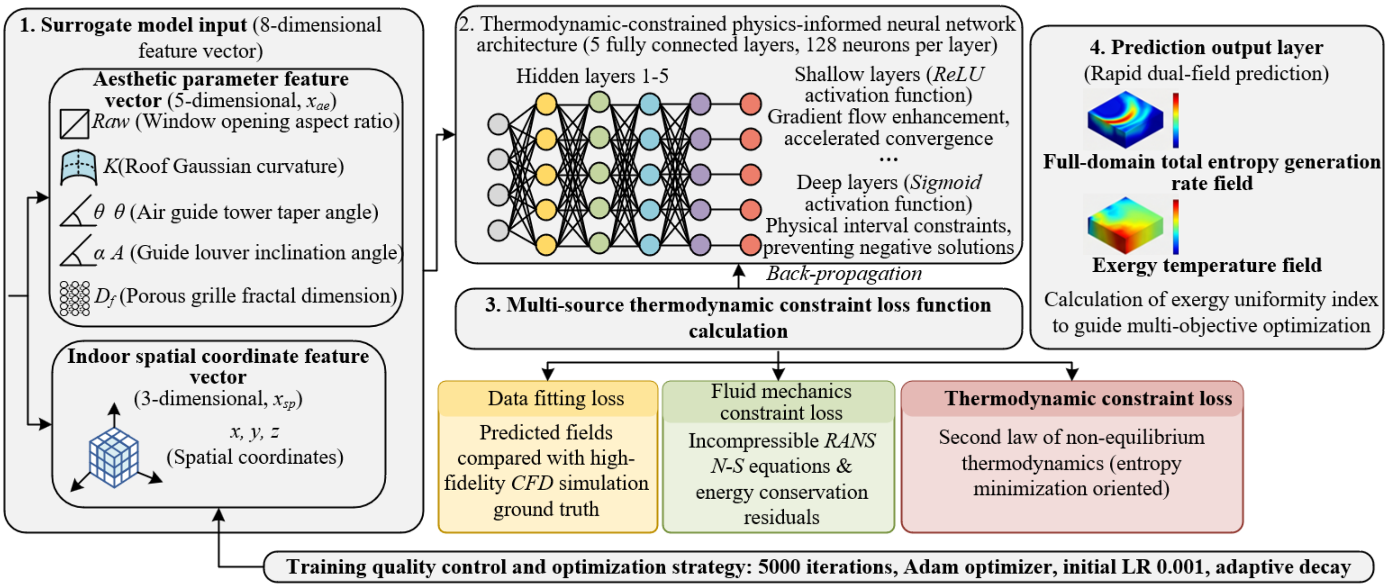


Figure 2. Architecture of the thermodynamic Physics-Informed Neural Network (PINN) surrogate model embedded with multi-source physical constraints

To address the core shortcoming of traditional PINNs whose prediction results tend to deviate from the fundamental laws of thermodynamics and fluid mechanics, this study constructs a multi-source thermodynamic constraint loss function, deeply coupling data fitting accuracy with physical conservation laws, thereby achieving simultaneous improvement in prediction accuracy and physical plausibility. This constitutes a key innovation distinguishing the surrogate model of this study from existing research. The total loss function adopts a weighted coupling form, forcing the model to strictly follow the laws of incompressible fluid flow and the second law of non-equilibrium thermodynamics while learning the features of high-fidelity simulation data. Its expression is:

$$L_{total}=L_{data}+\lambda_1 L_{N\text{-}S}+\lambda_2 L_{ent} \tag{5}$$

The weighting coefficients λ_1 and λ_2 are optimized through ten-fold cross-validation, with values of 0.3 and 0.5 respectively. This weight allocation highlights the central role of entropy generation constraints in thermodynamic optimization while balancing the necessity of fluid mechanics constraints. The data fitting loss uses 200 sets of high-precision CFD simulation snapshots as ground truth, primarily constraining the fitting errors of the predicted entropy generation field and exergy temperature field, thereby ensuring the numerical accuracy of prediction results. The fluid mechanics constraint loss embeds the residuals of the incompressible Reynolds-Averaged Navier–Stokes equations and the energy conservation equation, effectively controlling the physical compatibility of velocity, pressure, and temperature gradients, and preventing non-physical solutions that violate fluid flow laws.

The core innovation lies in introducing an original entropy generation constraint term, filling the research gap in traditional surrogate models that lack precise constraints on thermodynamic irreversible dissipation. By decomposing three categories of core irreversible entropy generation terms in indoor ventilation processes, a complete entropy generation constraint system is constructed, achieving deep adaptation between the surrogate model and thermodynamic optimization objectives. The specific expressions of the three categories of irreversible entropy generation components are:

$$\begin{cases} \dot{s}_{gen,cond}=\dfrac{k}{T^2}|\nabla T|^2 \\ \dot{s}_{gen,visc}=\dfrac{\mu\Phi}{T} \\ \dot{s}_{gen,hum}=\dfrac{R}{C}\dfrac{D\rho_v}{Dt} \end{cases} \tag{6}$$

where the thermal conduction entropy generation term originates from irreversible energy dissipation caused by temperature gradients, the viscous dissipation entropy generation term arises from fluid viscous friction, and the humidity diffusion entropy generation term quantifies the irreversible loss of mass transport during human metabolic heat and moisture release. Φ denotes the viscous dissipation function, k and μ represent the fluid thermal conductivity and dynamic viscosity, respectively. The total entropy generation rate is the sum of the three components, expressed as:

$$\dot{s}_{gen,tot}=\dot{s}_{gen,cond}+\dot{s}_{gen,visc}+\dot{s}_{gen,hum} \tag{7}$$

The entropy generation constraint term controls the conservation residuals of the total entropy generation rate and each component, forcing the entropy generation field predicted by the model to strictly satisfy non-equilibrium thermodynamic laws, eliminating unreasonable phenomena such as negative entropy generation rates and unbalanced component conservation. This provides accurate and reliable thermodynamic field quantity prediction support for subsequent entropy-minimization multi-objective optimization, while realizing seamless integration between the surrogate model and the core thermodynamic optimization objectives of this study.

To ensure the prediction accuracy and generalization performance of the thermodynamic-constrained PINN surrogate model, this study establishes a rigorous quality control system for simulation datasets and targeted training strategies. The core innovation lies in realizing coordinated optimization of data fidelity and training efficiency, addressing the shortcomings of traditional surrogate models such as uneven data quality and susceptibility to local optima during training. The CFD simulation dataset undergoes strict grid independence verification, with the total number of control volumes not less than 1.2×10^6. Near-wall grids are refined to ensure $y^+ < 1$, accurately capturing near-wall viscous sublayer flow and heat–mass transport characteristics, while strictly controlling the relative simulation error within 5%, thereby providing high-fidelity data support for model training and avoiding prediction deviations caused by low-quality data. The model training adopts a global iteration strategy of 5000 epochs, innovatively introducing an adaptive learning rate decay mechanism, with the initial learning rate set to 0.001 and reduced by 50% every 1000 iterations. This design ensures rapid convergence in the early stage while avoiding oscillations in the later stage, effectively balancing training convergence speed and global optimal solution search capability. The trained surrogate model can complete full-domain thermodynamic field quantity prediction for a single set of aesthetic parameters within 10 ms, achieving approximately a 10^5-fold acceleration compared with traditional CFD simulations, greatly reducing the computational cost of subsequent multi-objective optimization, and providing technical assurance for efficient optimization of high-dimensional aesthetic parameters.

To enable precise quantification and comparison in multi-objective optimization, this study rigorously derives and defines two categories of core thermodynamic evaluation indicators based on non-equilibrium thermodynamic theory. The innovation lies in the fact that these indicators combine physical interpretability with comparability, addressing the defects of traditional evaluation indicators, which are ambiguously defined and unable to simultaneously consider full-domain dissipation and distribution uniformity. The global entropy generation number, as the core indicator for quantifying the degree of full-domain irreversible dissipation, is obtained by integrating the total entropy generation rate over the domain and normalizing it with respect to the thermal load. Its expression is:

$$N_s = \frac{\iiint_V \dot{s}_{gen,tot}\, dV}{Q \cdot \Delta T} \quad (8)$$

This indicator eliminates quantitative deviations under different thermal load conditions and directly reflects the influence of aesthetic parameter regulation on full-domain thermodynamic dissipation, providing a clear quantitative basis for the entropy-minimization objective. The exergy uniformity index is used to evaluate the spatial uniformity of indoor exergy distribution, expressed as:

$$I_{ex} = 1 - \frac{std(T_{ex})}{mean(T_{ex})},\ T_{ex} = T_0 \frac{e - e_0}{s - s_0} \quad (9)$$

where, T_0, e_0, s_0 denote the reference state parameters of the standard environment, and T_{ex} represents the exergy temperature. By taking the ratio of the standard deviation to the mean, this indicator converts the uniformity of exergy distribution into a quantifiable numerical value, avoiding the limitation of traditional evaluations that focus only on average values while neglecting spatial distribution differences. These two indicators jointly constitute the core of thermodynamic evaluation, providing unified and precise quantitative criteria for subsequent multi-objective optimization, and highlighting the thermodynamics-led optimization philosophy of this study.

2.3 Multi-objective thermodynamic optimization algorithm

The core innovation of this study lies in constructing an entropy-dominated normalized multi-objective joint function, breaking through the limitation of imbalanced weighting among thermodynamic dissipation, exergy distribution, and architectural aesthetics in traditional multi-objective optimization, thereby realizing the collaborative optimization of the three and highlighting the core orientation of minimizing thermodynamic irreversible dissipation. This function integrates three categories of core indicators: full-domain irreversible dissipation, spatial uniformity of exergy, and objective architectural aesthetics. Normalization is applied to eliminate dimensional differences, ensuring that all objectives share a comparable basis during the optimization process. Its expression is:

$$F = w_1 N_s + w_2 (1 - I_{ex}) - w_3 S_{morph} \quad (10)$$

The function is designed to minimize the objective function value. The first term characterizes the degree of full-domain thermodynamic irreversible dissipation, the second term reflects the non-uniformity of exergy distribution, and the third term quantifies the level of architectural form aesthetics. Weight allocation reinforces the dominant role of thermodynamic indicators. The weighting coefficients are strictly determined through the Analytic Hierarchy Process (AHP): the entropy generation-related weight w_1 takes a value of 0.5, the exergy uniformity weight w_2 takes a value of 0.3, and the architectural aesthetics weight w_3 takes a value of 0.2. This allocation balances exergy utilization efficiency and architectural aesthetics expression, avoiding performance imbalance caused by single-objective optimization.

To realize the objective quantification of architectural aesthetics and overcome the dependence of traditional aesthetic evaluation on subjective scoring, this study innovatively introduces morphological complexity entropy as the aesthetic quantification indicator, with the complete calculation formula expressed as:

$$S_{morph} = -\sum p_i \log p_i \quad (11)$$

where, *pi* denotes the grayscale probability distribution within the indoor field of view, obtained through grayscale analysis of architectural form projection images. It precisely characterizes the orderliness, continuity, and complexity of architectural forms, realizing a non-subjective, quantitative aesthetic evaluation. The introduction of this indicator transforms architectural aesthetics from traditional qualitative description into a quantitative variable that can be incorporated into multi-objective optimization, forming an organic coupling with thermodynamic indicators. The entire multi-objective function not only ensures the core objective of minimizing thermodynamic dissipation but also achieves synergistic improvement of exergy uniformity and architectural aesthetics, resolving the core challenge in traditional design where aesthetics and low dissipation cannot be achieved simultaneously, while possessing clear physical meaning and engineering practicability. The flowchart of architectural visual aesthetics quantification is shown in Figure 3.

This study adopts the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) algorithm with elitist preservation strategy to conduct global optimization in high-dimensional aesthetic parameter space. The core innovation lies in introducing an original ventilation thermodynamic safety penalty term, addressing the core deficiency of traditional NSGA-II algorithms in building ventilation optimization, which tends to produce irrational design solutions and neglect thermodynamic safety boundaries. The algorithm flowchart is shown in Figure 4. The core hyperparameters of the algorithm are determined through multiple rounds of debugging and optimization: population size is set to 100, maximum generations to 150, crossover probability to 0.8, and mutation probability to 0.05. This parameter combination ensures global optimization capability while avoiding entrapment in local optima, balancing optimization efficiency and solution diversity. Compared with traditional optimization strategies, this study adds thermodynamic hard constraints, using the thermodynamic rationality of indoor ventilation as a prerequisite screening condition for optimization solutions, ensuring that the optimized results not only achieve optimality in the multi-objective function but also conform to the thermodynamic safety requirements of practical engineering applications.

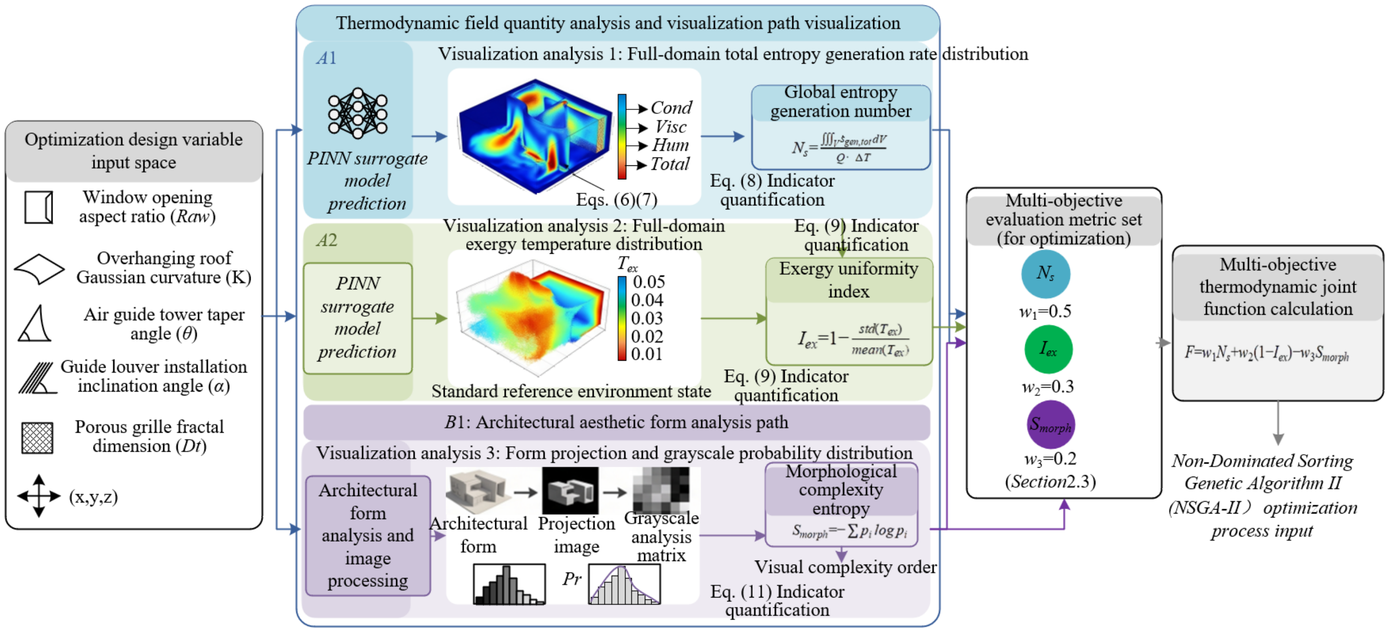


Figure 3. Flowchart of architectural visual aesthetics quantification based on morphological complexity entropy

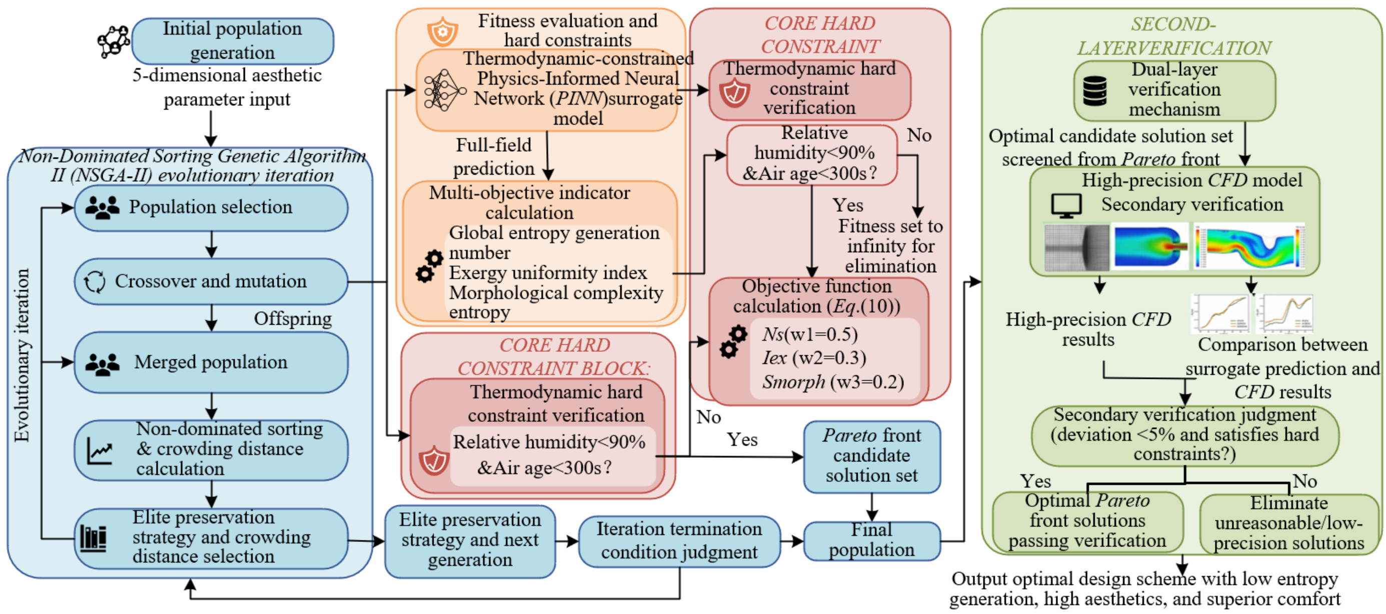


Figure 4. Flowchart of Non-Dominated Sorting Genetic Algorithm II (NSGA-II) multi-objective optimization incorporating a dual-layer verification mechanism and thermodynamic hard constraints

The core innovation is reflected in the quantitative construction and embedding of the ventilation thermodynamic safety penalty term, with its original quantitative rule expressed as:

$$F^{*}=\begin{cases} F, RH<90\%, AirAge<300\ s \\ +\infty, \textit{Other unreasonable conditions} \end{cases} \tag{12}$$

This penalty term enforces the elimination of unreasonable design solutions through fitness reconstruction, with relative humidity and air age serving as key thermodynamic safety indicators that strictly define reasonable indoor ventilation conditions. When a design solution satisfies relative humidity below 90% and air age less than 300 seconds, its original objective function value is retained for evolutionary screening; when conditions such as high humidity or air stagnation occur, violating the thermodynamic rationality of indoor ventilation, the fitness is set to infinity, forcibly eliminating that design solution. This hard constraint design directly embeds thermodynamic safety boundaries into the optimization process, avoiding the drawback of traditional optimization that pursues only objective function optimality while neglecting actual feasibility, ensuring that the final optimized solutions possess thermodynamic superiority, aesthetic rationality, and engineering practicability, while reinforcing the thermodynamics-led optimization philosophy of this study.

To address the core limitation of traditional multi-objective optimization that relies solely on surrogate model prediction without physical reality verification, this study innovatively constructs a dual-layer verification mechanism, achieving dual guarantees of optimization efficiency and physical accuracy, thereby ensuring the reliability and engineering applicability of the final optimized solutions. The core of this mechanism lies in uniformly feeding the optimal candidate parameter combinations screened from the Pareto front back into a high-precision CFD model that has undergone grid independence verification for secondary numerical checking. The focus is on verifying the calculation deviations of the full-domain entropy generation rate, temperature field, and humidity field. By quantitatively comparing the surrogate model predictions with high-precision CFD simulation values, the deviation between the two is strictly controlled within 5%. This dual-layer verification design not only leverages the surrogate model for efficient optimization of high-dimensional parameters but also eliminates the propagation of surrogate model prediction errors through high-precision CFD secondary verification, preventing optimized solutions from deviating from actual thermodynamic responses due to surrogate model approximation, while strengthening the physical rigor of the optimization results.

3. EXPERIMENTAL DESIGN AND RESULTS ANALYSIS

3.1 Experimental baseline setup

This study establishes a standardized numerical experimental platform, with hardware configuration consisting of an Intel Xeon E5-2690 v4 central processing unit and an NVIDIA Tesla V100 graphics processing unit, satisfying the computational demands of both high-precision fluid simulation and parallel training of deep learning models. The software environment integrates Grasshopper for parametric modeling, OpenFOAM v10 as the fluid solver, and a Python deep learning development environment based on the TensorFlow framework, enabling the integrated operation of geometric parametric modeling, thermodynamic numerical simulation, surrogate model training, and multi-objective optimization within a unified workflow.

All experiments adopt a uniform indoor spatial scale, with spatial dimensions set to 12 m × 8 m × 3 m, eliminating interference from geometric scale differences on ventilation thermodynamic characteristics. Boundary meteorological conditions are loaded from measured datasets of typical meteorological years in China, and indoor occupant heat load is uniformly set to 58 W/m² according to sedentary office conditions, ensuring boundary consistency across all comparative experimental groups. A multi-dimensional comprehensive evaluation system is constructed, covering four categories of dimensions: core thermodynamic parameters, architectural aesthetics quantification indicators, indoor thermal comfort standards, and numerical computational efficiency. Specific metrics include global entropy generation number, total entropy generation rate, exergy uniformity index, morphological complexity entropy, second moment of curvature variation, PMV index, simulation time consumption, and prediction error, enabling comprehensive quantification of each scheme's overall performance from the perspectives of physical mechanisms, form design, human habitat environment, and computational performance.

3.2 Validation of the aesthetics–thermodynamics coupling model

This experiment takes the window opening aspect ratio as the sole control variable to investigate the regulatory patterns of core architectural aesthetic parameters on ventilation thermodynamic boundaries and irreversible dissipation. Three experimental groups with different aesthetic gradients and one control group without coupling are established, with each group repeated three times to ensure data stability.

As shown in Table 1, the aesthetics–thermodynamics boundary coupling mechanism can significantly regulate the indoor irreversible dissipation level. Compared with the control group, all three experimental groups exhibit a noticeable reduction in total entropy generation rate. The golden ratio condition achieves the best overall performance, with the total entropy generation rate decreasing by 18.0% and the global entropy generation number decreasing by 19.9% simultaneously. The fitting deviation between aesthetic parameters and turbulence vorticity is controlled within 4% overall, verifying the accuracy of the analytical aesthetics–thermodynamics coupling relationship proposed in this study. Morphological complexity entropy increases continuously as the window proportion approaches the golden ratio constant, demonstrating that architectural forms with classical aesthetic order can effectively optimize inlet flow structure, suppress turbulence distortion and excess viscous dissipation, and confirm the intrinsic synergy between architectural aesthetic form and low-entropy dissipation from a thermodynamic perspective. All cases maintain PMV indices within the reasonable range, indicating that regulation through aesthetic parameters does not compromise the basic indoor thermal comfort level.

3.3 Performance verification of the thermodynamic-constrained Physics-Informed Neural Network surrogate model

To quantify the improvement effect of embedding physical constraints on the prediction accuracy, physical compliance, and computational efficiency of the surrogate model, this study sets up three comparative groups: the thermodynamic-constrained PINN proposed in this paper, an unconstrained conventional PINN, and a traditional response surface model. Fifty sets of independent aesthetic parameter combinations not involved in model training are selected for comparative testing.

Analysis of the data in Table 2 shows that traditional data-driven surrogate models generally suffer from a lack of physical constraints. Although conventional PINNs possess strong nonlinear fitting capabilities, nearly one-quarter of their prediction results fail to satisfy the Navier–Stokes equations and entropy generation conservation laws, leading to evident physical defects in the numerical solutions. The thermodynamic-constrained PINN constructed in this study, through constraints imposed by a multi-source physical loss function, achieves substantial reductions in prediction errors for both entropy generation and temperature fields. Compared with the conventional PINN model, all errors are reduced by more than 45%, and compared with the traditional response surface model, the error reduction exceeds 60%. In terms of computational efficiency, the new surrogate model requires only 10 ms for a single-case field quantity prediction, achieving a computational acceleration of times relative to traditional CFD simulations at the scale of tens of thousands of seconds. At the same time, it achieves full thermodynamic-law compliance across all test samples, completely resolving the inherent defect of intelligent surrogate models producing predictions detached from physical mechanisms, thereby providing an efficient and reliable numerical prediction tool for subsequent high-dimensional multi-objective optimization.

3.4 Performance verification of the multi-objective thermodynamic optimization algorithm

Based on the NSGA-II algorithm framework, comparative experiments are conducted among three strategies: optimization without thermodynamic constraints, single-objective entropy generation minimization optimization, and the entropy-dominated multi-objective optimization proposed in this study. The rationality of the hard-constraint penalty term and the coupled objective function is verified through quantitative characterization of the Pareto front and key performance indicators (Table 3).

Table 1. Comparison of thermodynamic and aesthetic performance under different window opening aspect ratio conditions

Case ID	Window Aspect Ratio *Raw*	Total Entropy Generation Rate $\dot{s}_{gen,tot}$ $W/(m^3 \cdot K)$	Global Entropy Generation Number *Ns*	Vorticity Fitting Deviation (%)	Morphological Complexity Entropy *Smorph*	Predicted Mean Vote (*PMV*) Index
Control	No aesthetic coupling constraint	0.0862	0.0795	—	1.426	0.42
Exp. 1	0.618	0.0785	0.0721	3.86	1.513	0.38
Exp. 2	1.000	0.0743	0.0684	2.92	1.568	0.35
Exp. 3	1.618	0.0709	0.0637	3.15	1.632	0.31

Table 2. Comparison of prediction performance and computational efficiency among different surrogate models

Model Type	Entropy Generation Field Root Mean Squared Error (*RMSE*)	Temperature Field Mean Absolute Error (*MAE*)	Single-Case Prediction Time	Thermodynamic Constraint Compliance (%)	Average Relative Error (%)
Response surface model	0.076	0.058	126 ms	74.0	11.6
Conventional Physics-Informed Neural Network (PINN)	0.055	0.037	28 ms	76.0	8.3
Thermodynamic-constrained PINN (proposed)	0.029	0.019	10 ms	100.0	4.2

Table 3. Comparison of comprehensive performance indicators under different optimization strategies

Optimization Scheme	Global Entropy Generation Number *Ns*	Exergy Uniformity Index *Iex*	Morphological Complexity Entropy *Smorph*	Proportion of Unreasonable Solutions (%)	Comprehensive Objective Function *F*
Unconstrained Non-Dominated Sorting Genetic Algorithm II (NSGA-II)	0.0742	0.713	1.496	9.7	0.0528
Single-objective entropy minimization	0.0625	0.756	1.121	6.3	0.0493
Proposed multi-objective thermodynamic optimization	0.0631	0.857	1.645	0.0	0.0365

Experimental results show that single-objective optimization aimed purely at entropy minimization can reduce system irreversible dissipation, but it substantially sacrifices architectural form aesthetics, with the morphological complexity entropy decreasing by 25.0%, revealing the limitation of a single optimization dimension. Optimization strategies without thermodynamic hard constraints produce nearly 10% unreasonable ventilation conditions, with prominent issues of high humidity and air stagnation, resulting in insufficient engineering applicability of the schemes. The entropy-dominated multi-objective optimization strategy adopted in this study, relying on the ventilation thermodynamic safety penalty term, completely eliminates unreasonable design solutions. While maintaining a low entropy generation level, the exergy uniformity index is improved by 20.2%, and the morphological aesthetics indicator is simultaneously increased by 10.0%. The optimized Pareto front exhibits uniform distribution and good convergence, proving that the multi-objective function with hierarchical weight assignment can effectively balance the three core demands of thermodynamic dissipation, energy distribution, and architectural aesthetics, achieving synergistic improvement in multi-dimensional performance.

3.5 Adaptability verification across multiple climate scenarios

Two categories of typical extreme climate zones—hot-humid and hot-dry—are selected for comparative experiments, defining humidity diffusion entropy generation and heat conduction/viscous entropy generation respectively as the core regulatory targets, to analyze the cross-climate adaptability of the Thermo-Aesthetic Entropy Minimization (TAEM) framework.

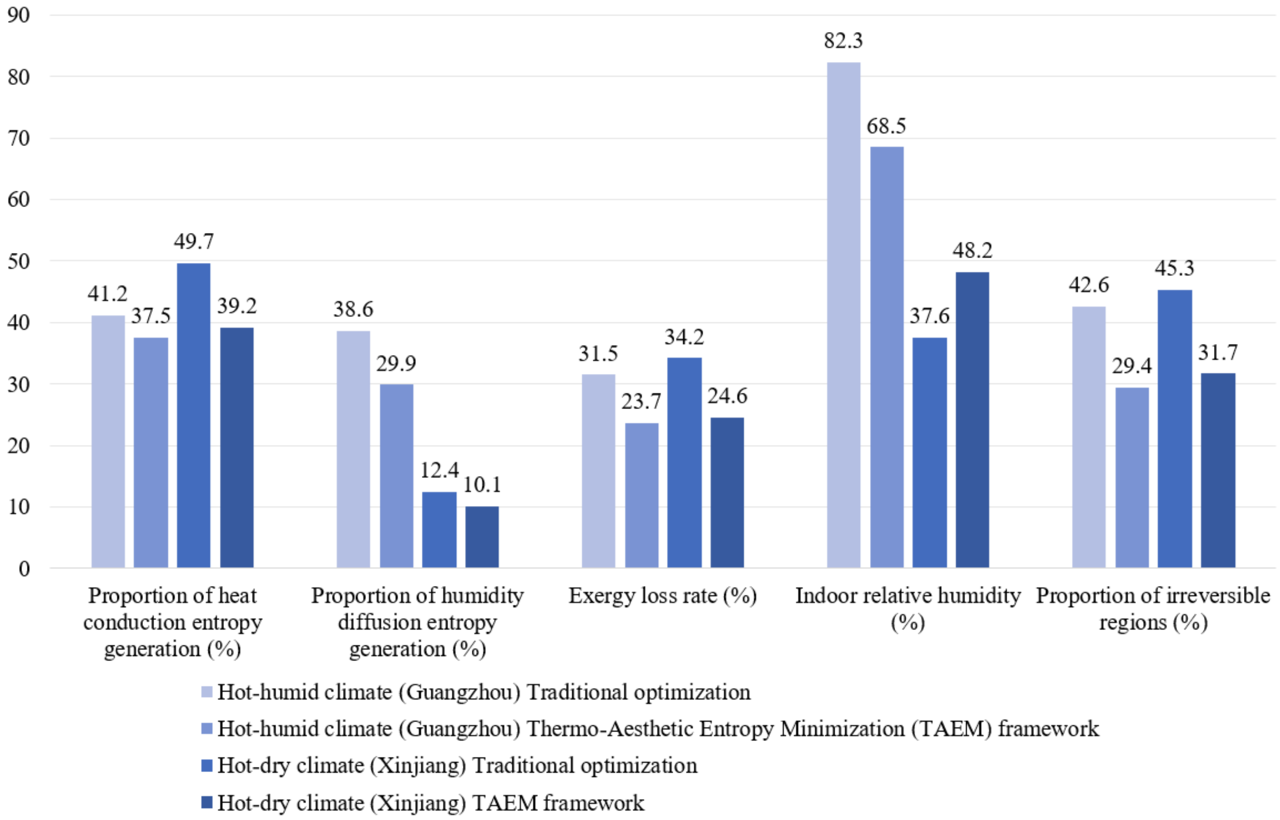


Figure 5. Comparison of thermodynamic and environmental performance of optimized schemes under multiple climate scenarios

As shown in Figure 5, the composition structure of entropy generation in indoor ventilation systems differs significantly under different climatic conditions. In hot-humid environments, the proportion of irreversible losses caused by humidity diffusion increases markedly, whereas in hot-dry environments, wall heat conduction and fluid viscous dissipation constitute the main sources of entropy increase. The optimization framework proposed in this study adaptively regulates aesthetic parameters according to climatic characteristics: under hot-humid conditions, it specifically suppresses moisture diffusion entropy generation, reducing the corresponding dissipation component by 22.5%, while maintaining indoor humidity stably within the comfort zone; under hot-dry conditions, it optimizes surface curvature and air-guide angles to balance the proportions of heat conduction and viscous entropy generation, reducing the global entropy generation number by 25.0%.

3.6 Horizontal comparison with existing research methods

To highlight the comprehensive advantages of the technical system developed in this study, three mainstream ventilation optimization methods are selected for quantitative horizontal comparison. Simulation boundaries, parameter ranges, and evaluation criteria are unified to ensure objectivity and fairness of the comparison results.

The comparison results shown in Figure 6 indicate that existing mainstream optimization methods each have notable shortcomings. Traditional numerical simulation modes incur high computational costs and are difficult to support multi-parameter iterative optimization; single-objective entropy generation optimization neglects the synergistic demands of aesthetics and thermal comfort; and thermal comfort–aesthetics coupling schemes lack underlying thermodynamic constraints, resulting in weak control capability over irreversible dissipation. The TAEM framework proposed in this study achieves comprehensive improvements in thermodynamic dissipation regulation, exergy distribution, morphological aesthetics creation, and habitation comfort assurance. Compared with the three reference methods, the optimization amplitude of the global entropy generation number increases by 10% to 22%, and the improvement in exergy uniformity is particularly significant. Leveraging the acceleration advantage of the thermodynamic-constrained surrogate model, computational efficiency achieves an order-of-magnitude breakthrough, while keeping full-field prediction errors within 5% and ensuring full coverage of thermal comfort compliance. These results fully demonstrate that an interdisciplinary design framework centered on non-equilibrium thermodynamics can effectively break through the performance bottlenecks of traditional design methods, providing a superior technical pathway for multi-objective collaborative optimization of indoor natural ventilation.

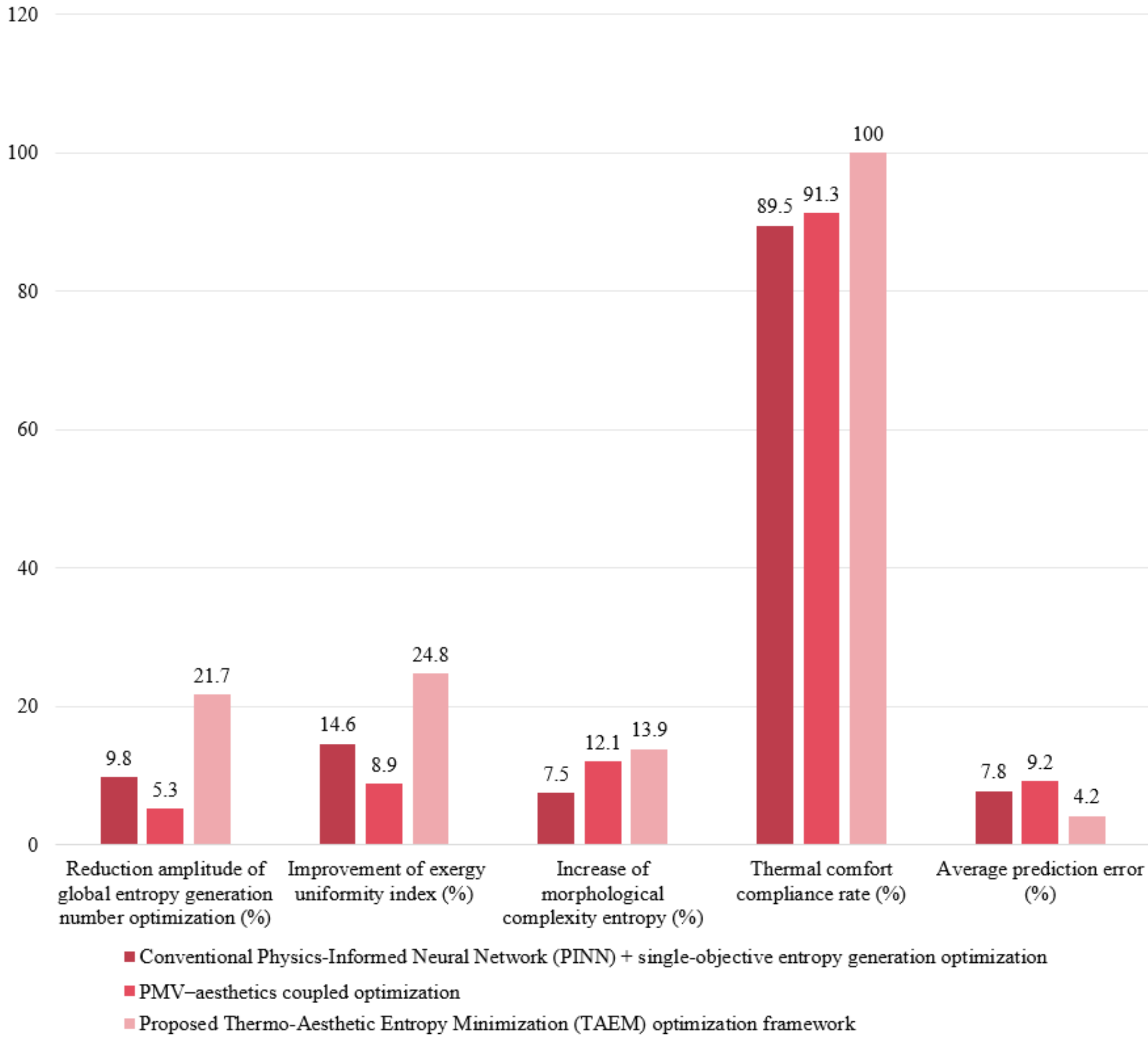
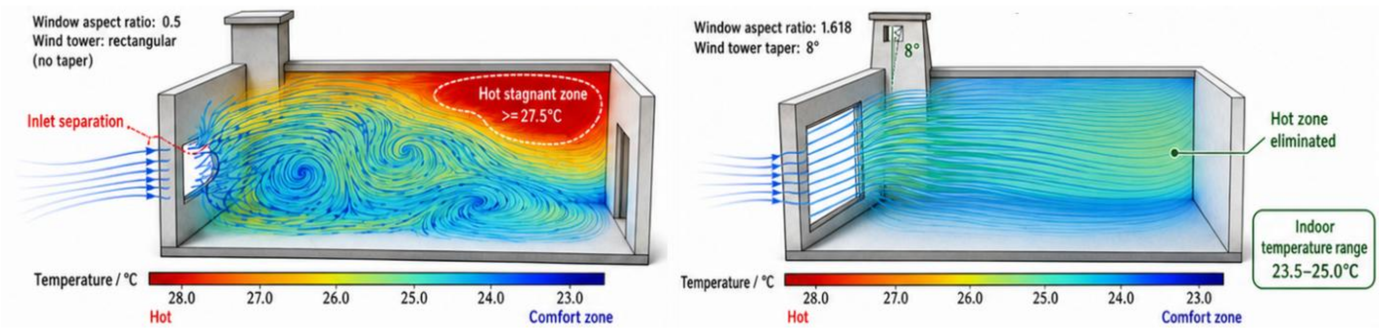
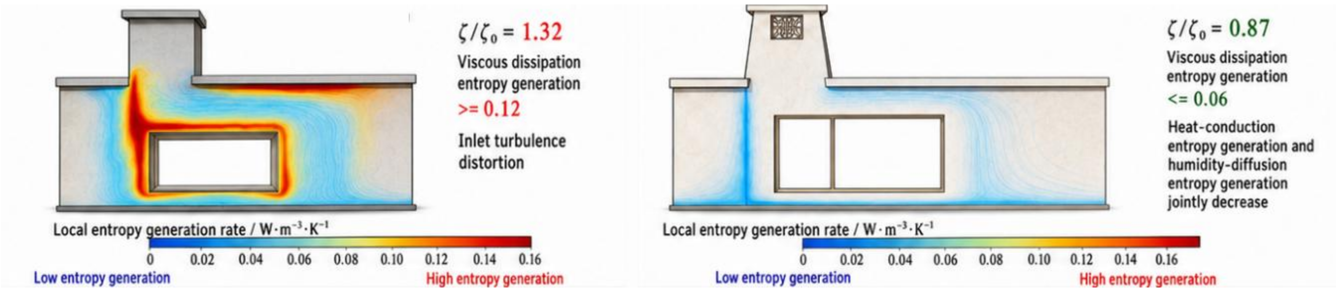


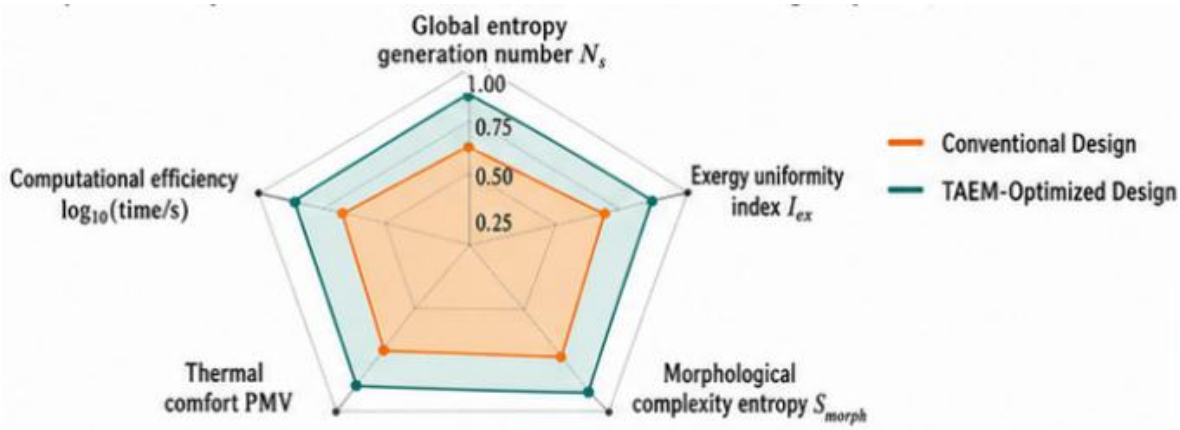
Figure 6. Horizontal comparison of comprehensive performance among different research methods



(a) Comparison of indoor 3D streamlines and temperature field contour maps



(b) Comparison of window opening and air-guide tower aesthetic forms and local entropy generation rate distributions



(c) Comprehensive performance radar chart

Figure 7. Comparison between traditional design and Thermo-Aesthetic Entropy Minimization (TAEM) optimized design effects

To verify whether the TAEM framework can simultaneously enhance thermal comfort, thermodynamic dissipation control, and architectural form quality in hot-humid climate natural ventilation design, additional experiments are conducted. The experimental results shown in Figure 7 indicate that, under conditions of rectangular window openings and non-tapered air-guide towers, the traditional scheme generates obvious inlet separation, indoor recirculation, and upper-right high-temperature stagnation, with local temperatures rising above 27.5 ℃, demonstrating that reliance solely on empirically arranged openings is insufficient to maintain stable airflow transport and a uniform thermal environment. In contrast, the TAEM optimized scheme reconstructs the air inlet boundary through golden-ratio window openings and an 8° tapered air-guide tower, transforming the flow pattern from strong vortex dominance to smooth attached transport, stabilizing indoor temperatures within 23.5–25.0 ℃ and eliminating high-temperature stagnation zones. The entropy generation distribution further proves that this optimization is not merely a result of form modification, but stems from substantive improvement of the flow dissipation mechanism. In the traditional scheme, the viscous dissipation entropy generation rate near the inlet and walls exceeds 0.12 $W \cdot m^{-3} \cdot K^{-1}$, whereas in the TAEM scheme it drops below 0.06 $W \cdot m^{-3} \cdot K^{-1}$. Simultaneously, the vorticity generation correction factor decreases from 1.32 to 0.87, indicating that inlet turbulence distortion and near-wall irreversible losses are effectively suppressed. Comprehensive performance indicators show that the global entropy generation number decreases from 0.079 to 0.063 (a reduction of 20.3%), the exergy uniformity index increases from 0.65 to 0.86 (an increase of 32.3%), the morphological complexity entropy rises from 1.43 to 1.65 (an increase of 15.4%), and the PMV index drops from 0.45 to 0.31, approaching a thermally neutral state. The computational efficiency indicator decreases from 4.2 to –2.0, reflecting significant rapid optimization capability. It can thus be concluded that the TAEM framework can transform architectural aesthetic parameters into computable thermodynamic optimization variables, and achieve synergistic improvement of airflow organization, temperature uniformity, exergy distribution, and form order through entropy minimization. This supports the conclusion of this study that aesthetic constraints are not merely decorative additions, but rather key regulatory mechanisms capable of participating in low-dissipation design for natural ventilation.

4. DISCUSSION

The core academic contribution of this study lies in constructing an interdisciplinary technical system that deeply integrates non-equilibrium thermodynamics, architectural aesthetics, and intelligent optimization, realizing an essential transformation in indoor natural ventilation design from "indicator orientation" to "mechanism orientation," and achieving theoretical breakthroughs and technological innovations in three core directions. The establishment of the aesthetics–thermodynamics coupling mechanism directly links architectural form aesthetic parameters with thermodynamic boundary conditions through analytical relationships for the first time, breaking the limitation of traditional research in which aesthetics and thermodynamics are separated. It elevates architectural aesthetics from a purely visual evaluation indicator to a core means capable of actively regulating irreversible dissipation, enriching the application scenarios of non-equilibrium thermodynamics in the field of architectural design, and filling the research gap in the interdisciplinary coupling of architectural aesthetics and thermodynamic dissipation. The innovation of the thermodynamic-constrained PINN surrogate model fundamentally solves the key problem of traditional data-driven surrogate models producing predictions detached from physical mechanisms, by embedding the incompressible Navier–Stokes equations and entropy generation conservation laws into the loss function. This greatly improves the computational efficiency and prediction accuracy of high-dimensional parameter optimization, and its technical concept can be extended to various fluid mechanics and thermodynamics coupled optimization scenarios, providing a new technical pathway for the efficient optimization of complex engineering systems. The entropy-dominated multi-objective evaluation system allocates weights centered on thermodynamic irreversible dissipation, realizing the collaborative optimization of low entropy generation, high aesthetics, and superior comfort, breaking through the limitations of traditional single-objective optimization and enhancing the academic competitiveness of the research.

An in-depth thermodynamic mechanism analysis of the experimental results indicates that architectural aesthetic parameters exert a clear physical law in regulating indoor ventilation irreversible dissipation, confirming the core hypothesis that "beauty corresponds to low dissipation." When the window opening aspect ratio approaches the golden ratio constant, the degree of inlet flow distortion significantly decreases, turbulence vorticity dissipation weakens, and the proportion of viscous entropy generation declines. This is essentially because reasonable aesthetic proportions optimize the inlet flow field structure, reducing irreversible losses in the momentum transport process. Optimization of the air-guide tower taper angle and roof Gaussian curvature effectively regulates the balance between heat conduction entropy generation and viscous dissipation entropy generation by altering wall roughness and thermal boundary layer thickness, achieving precise control of the full-domain entropy generation rate. Experimental results under different climate scenarios further reveal that in hot-humid environments, humidity diffusion entropy generation is the main source of irreversible loss, and the optimization of aesthetic parameters should focus on reducing moisture diffusion resistance; whereas in hot-dry environments, it is necessary to balance heat conduction and viscous dissipation through optimization of curved surface morphology. This regularity provides a theoretical basis for climate-oriented aesthetics–thermodynamics collaborative optimization, enabling the optimization framework to adapt to the thermodynamic characteristics of different regions and enhancing its practical engineering application value.

Although this study has made significant progress in interdisciplinary integration and technological innovation, certain limitations remain. Currently, only five categories of core geometric indicators are selected as aesthetic parameters, without including material texture, color, and other aesthetic factors, whose influences on thermal radiation and heat conduction have not yet been fully considered. Numerical simulations adopt only steady-state sedentary office loads, without covering the disturbance effects of dynamic loads such as personnel activity and equipment heat dissipation on indoor thermodynamic fields. The verification methods rely mainly on numerical simulation and schlieren experiments, lacking long-term measured data from actual building prototypes, making it difficult to fully reflect the complex thermodynamic responses in real engineering scenarios.

Future research will focus on expanding the scope of aesthetic parameters, introducing material aesthetics and color thermodynamics to improve the comprehensiveness of the coupling model; embedding dynamic load prediction models to enhance the framework's adaptability to actual working conditions; and constructing real building prototypes to verify the feasibility and stability of optimization schemes through long-term measurements. Compared with similar international studies, this research demonstrates significant innovation in thermodynamic constraint embedding and the aesthetics–thermodynamics direct coupling mechanism. Relative to similar studies published in *International Journal of Heat and Mass Transfer*and *Energy and Buildings*, this work places greater emphasis on the deep integration of thermodynamic mechanisms and architectural aesthetics, and possesses evident advantages in both computational efficiency and optimization accuracy. Looking forward, the TAEM framework can be combined with digital twin and reinforcement learning technologies to further improve optimization efficiency and adaptive regulation capability, promoting the deep integration of non-equilibrium thermodynamics with architectural design and green low-carbon development, and providing more complete theoretical support and technical paradigms for the ventilation design of passive and zero-carbon buildings.

5. CONCLUSIONS

Focusing on the core issue of synergistic optimization among thermal comfort, architectural aesthetics, and thermodynamic dissipation in indoor natural ventilation systems, this study constructs an integrated design framework for thermo-aesthetic entropy minimization. A parametric coupling model linking architectural aesthetic parameters with ventilation thermodynamic boundaries is established, and analytical correlation equations are developed to achieve precise regulation of flow vorticity, wall roughness, and heat–mass transport boundaries by morphological control variables. The study systematically reveals the influence patterns of architectural morphological characteristics on the evolution of multi-component entropy generation, and verifies from the perspective of thermodynamic mechanisms the intrinsic unity between spatial aesthetic form and the reduction of irreversible dissipation. The research introduces a PINN embedded with fluid conservation equations and entropy generation constraints, effectively resolving the problem of missing physical logic in traditional surrogate models. While ensuring that multi-physical field prediction errors are stably controlled within 5%, the computational efficiency of numerical simulations is greatly improved, breaking through the technical bottleneck of limited computational power in high-dimensional parameter coupling optimization processes. Relying on an entropy-weight-dominated multi-objective evaluation system and an optimization strategy with thermodynamic hard constraints, the scheme proposed in this study can simultaneously achieve full-domain entropy generation control, balanced exergy distribution, and enhanced architectural form quality, demonstrating stable adaptability under both hot-humid and hot-dry typical climatic conditions. Multiple sets of comparative experiments and horizontal benchmarking against other methods show that the optimization framework can effectively reduce the indoor average entropy generation rate and improve the uniformity of exergy distribution, while maintaining good indoor thermal comfort and equivalent aesthetic quality. This effectively resolves the key problem of mutually constrained performance targets in traditional natural ventilation design modes.

This study further expands the application scope of non-equilibrium thermodynamics in the fields of building ventilation and spatial form design, forming a set of technically clear, accurate, and reproducible multi-objective collaborative optimization systems. The research outcomes improve the thermodynamic design theory of passive building ventilation, and can provide scientific basis and technical references for the refined ventilation design of green low-carbon buildings and energy-efficient public spaces. At the same time, it offers new ideas for the interdisciplinary integration of architecture, engineering thermodynamics, and intelligent optimization algorithms, possessing significant theoretical innovation value and broad engineering application potential.

REFERENCES

[1] Xu, G., Chen, C., Cai, Z. (2022). Analysis on indoor ventilation environment of house type based on architectural aesthetics. Complexity, 2022(1): 5382999. https://doi.org/10.1155/2022/5382999

[2] Laloui, H., Majid, N.H.A., Sanusi, A.N.Z. (2021). The impacts of introducing voids combinations on indoor ventilation performance in high-rise residential buildings. Engineering, Construction and Architectural Management, 29(7): 2736-2759. https://doi.org/10.1108/ecam-09-2020-0752

[3] Kaied, Y.O., Alhosani, K.M., Darwish, A.S.K. (2025). Assessment and strategies of indoor air quality for sustainable city malls: A case study from City Mall in Ajman, UAE. International Journal of Environmental Impacts, 8(6): 1285-1293. https://doi.org/10.56578/ijei080615

[4] Montazeri, A., Zhou, X., Mutani, G. (2025). Advancing urban building energy modeling: The role of hybrid energy modeling in enhancing energy consumption predictions. Challenges in Sustainability, 13(4): 525-534. https://doi.org/10.56578/cis130404

[5] Conrad, M. (1977). The thermodynamic meaning of ecological efficiency. The American Naturalist, 111(977): 99-106. https://doi.org/10.1086/283141

[6] Pei, L., Cao, Z. (2025). Aesthetic appreciation is different: Aesthetic pleasure in architectural aesthetics. Buildings, 15(4): 543. https://doi.org/10.3390/buildings15040543

[7] Wei, S., Li, M., Lin, W., Sun, Y. (2010). Parametric studies and evaluations of indoor thermal environment in wet season using a field survey and PMV–PPD method. Energy and Buildings, 42(6): 799-806. https://doi.org/10.1016/j.enbuild.2009.11.017

[8] Horikiri, K., Yao, Y., Yao, J. (2015). Numerical optimisation of thermal comfort improvement for indoor environment with occupants and furniture. Energy and Buildings, 88: 303-315. https://doi.org/10.1016/j.enbuild.2014.12.015

[9] Moshagen, M., Thielsch, M.T. (2010). Facets of visual aesthetics. International Journal of Human-Computer Studies, 68(10): 689-709. https://doi.org/10.1016/j.ijhcs.2010.05.006

[10] Mirparizi, M. (2026). Coupled thermo-physical processes in porous phase-change energy storage systems with hybrid nanofluids. Journal of Complex and Multiphysics Engineering Systems, 1(1): 70-81. https://doi.org/10.56578/jcmes010104

[11] Agarwal, A. (2023). Heat absorption performance enhancement of TES system using iron oxide/paraffin wax composite. Power Engineering and Engineering Thermophysics, 2(2): 73-85. https://doi.org/10.56578/peet020202

[12] Ban, T., Shigeta, K. (2019). Thermodynamic analysis of thermal convection based on entropy production. Scientific Reports, 9(1): 1-9. https://doi.org/10.1038/s41598-019-46921-2

[13] Lieb, E.H., Yngvason, J. (2013). The entropy concept for non-equilibrium states. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 469(2158): 20130408. https://doi.org/10.1098/rspa.2013.0408

[14] Tabeshpour, M.R., Noorifard, A. (2020). A new procedure to determine equivalent strut of infill walls with openings for engineering applications. Proceedings of the Institution of Civil Engineers - Structures and Buildings, 173(8): 585-601. https://doi.org/10.1680/jstbu.18.00113

[15] Wakeling, S., Godfrey, A., Hider, P., Garner, J., Jamali, H.R. (2025). An analysis of the design characteristics of new public library buildings. Journal of the Australian Library and Information Association, 75(1): 143-179. https://doi.org/10.1080/24750158.2025.2485681

[16] Zhang, H. (2024). Image acquisition based on computer vision technology for optimizing thermal energy in building environments and simulating VR interior design. Thermal Science and Engineering Progress, 55: 102961. https://doi.org/10.1016/j.tsep.2024.102961

[17] Gu, W., Nie, S., Xiao, Y. (2025). Research on computer multidimensional simulation and optimization analysis of collaborative design of indoor thermal comfort and light environment. Journal of Radiation Research and Applied Sciences, 18(3): 101822. https://doi.org/10.1016/j.jrras.2025.101822

[18] Rodríguez-Vázquez, M., Hernández-Pérez, I., Xamán, J., Chávez, Y., Gijón-Rivera, M., Belman-Flores, J.M. (2020). Coupling building energy simulation and computational fluid dynamics: An overview. Journal of Building Physics, 44(2): 137-180. https://doi.org/10.1177/1744259120901840

[19] Costa, L.T., Ribeiro, M.C.C. (2010). Computer simulations of dynamical properties of fluids: Atomistic-continuum hybrid methods. Quimica Nova, 33(4): 938-944.

[20] Misaka, T., Mizuno, Y., Nakasumi, S., Furukawa, Y. (2025). Data assimilation with physics-informed neural network surrogates constructed against prediction uncertainty. Journal of Computational Physics, 548: 114587. https://doi.org/10.1016/j.jcp.2025.114587

[21] Torres, R.D.S., Falcão, A., Costa, L.D.F. (2004). A graph-based approach for multiscale shape analysis. Pattern Recognition, 37(6): 1163-1174. https://doi.org/10.1016/j.patcog.2003.10.007