

Wind environment optimization of traditional villages using Sware numerical simulations: a case study of Shuicheping old street, Chongqing

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Abstract: Traditional mountainous villages embody regional ecological wisdom through their wind environments, yet face challenges including blocked natural wind corridors, increased building density, and inadequate ventilation during modernization. This study investigates Shuicheping Old Street using Sware numerical simulations integrated with field measurements and CFD modeling to establish a 3D wind environment model. Quantitative analysis revealed disorderly construction caused 42% wind speed attenuation between clusters, 35% vortex-dominated street areas, and substandard ventilation (0.5 ACH) in dwellings. On this basis we propose a tripartite strategy—hierarchical wind corridor restoration, building interface optimization, and microclimate regulation—improved cluster ventilation efficiency by 28.6%, reduced street vortices to 22%, and enhanced indoor ventilation to 1.2 ACH. An economic feasibility analysis was conducted on the adopted three in one strategy, estimating the construction and maintenance costs of different optimization measures as well as the subsequent economic benefits, providing a more comprehensive decision-making basis for practical engineering applications. The final proposed framework balances heritage preservation with climate adaptation, offering a replicable design paradigm for sustainable renewal of Southwestern China's mountainous settlements.

1. Introduction

Traditional villages, as treasures of Chinese historical culture, preserve rich socio-cultural heritage and collective memory^[1]. However, escalating ecological and climatic challenges—exacerbated by outdated architectural configurations, inefficient spatial layouts, and inadequate greening—have intensified conservation-development conflicts^[2]. In Chongqing's complex terrain and variable climate, wind environments critically influence residents' living quality. Effective natural ventilation enhances air circulation, removes pollutants and humidity, regulates indoor thermal conditions, reduces disease transmission risks, and lowers energy consumption. Current conservation practices predominantly focus on preserving architectural structures and historical aesthetics, often neglecting improvements to indoor/outdoor environmental performance, particularly in ventilation and thermal comfort. Furthermore, traditional designs, once adapted to historical living needs, now fail to meet modern comfort standards due to insufficient airflow regulation and temperature control.

Responding to China's Carbon Peak Action Plan before 2030, which advocates "green renewal of traditional villages," this study explores low-carbon-oriented wind environment optimization. Focusing on a

representative Chongqing village, field surveys and Sware Green Technology simulations were conducted to diagnose existing ventilation issues. Innovatively, a tripartite strategy is proposed:

- Hierarchical wind corridor restoration. (regional-village-alleyway scales),
- Building interface airflow optimization. (diagonal window placement, ventilated grilles),
- Microclimate node regulation. (greening retrofits, wind-guiding vegetation).

This systematic framework addresses multi-scale conflicts between heritage preservation and climate adaptation, validated through simulations to enhance ventilation efficiency. The methodology provides actionable insights for improving wind environments while advancing sustainable revitalization of Chongqing's mountainous traditional settlements.

2. Natural ventilation challenges in Chongqing's traditional villages

Chongqing's mountainous terrain, characterized by slopes and valleys, creates complex wind environments around traditional buildings. These topographically sensitive settlements frequently experience unstable wind speeds and directional variability, leading to low-velocity zones

and turbulent vortices that hinder effective airflow. Calm wind conditions prevail for approximately 50% of the year, exacerbating ventilation deficiencies. While national building codes prioritize natural ventilation for thermal regulation in civil structures^[3], traditional villages exhibit critical mismatches with modern comfort requirements: outdated spatial configurations, inadequate environmental controls, and poor ventilation efficiency fail to address contemporary living standards amidst rapid socio-economic development.

2.1. Outdoor wind environment

The historical architectural layouts of traditional villages, shaped by terrain and cultural practices, exhibit constrained adaptability due to dense building clusters, narrow alleys, and fixed orientations. These configurations result in restricted airflow, low wind speeds (annual average: 0.9–2.1 m/s), and persistent air stagnation. Rapid urbanization has further aggravated these issues: increased building density—particularly in central areas—causes significant wind speed reduction, while ill-planned new constructions obstruct natural wind corridors. Notably, structures exceeding local height norms disrupt original ventilation patterns, diminishing inherent aerodynamic advantages. Additionally, although greenery is integral to traditional settlements, excessive or improperly arranged vegetation exacerbates airflow blockage, creating stagnant zones in narrow alleys and densely built areas, thereby impairing microclimate regulation^[4].

2.2. Indoor wind environment

Traditional dwellings face dual challenges: inherent design limitations and incompatible modern interventions. Restricted window/door dimensions and compartmentalized spatial layouts inhibit cross ventilation, despite historical adaptations like maoer zuan (ventilation slots) and dormer windows that leverage stack effects. Contemporary renovations often neglect passive ventilation principles, while modern materials enhance airtightness—improving thermal retention at the expense of natural airflow. This paradox elevates indoor pollutant concentrations, particularly from wood-burning stoves, and escalates reliance on mechanical ventilation systems, contradicting global energy conservation imperatives^[5].

3. Simulation study on indoor/outdoor wind environments in Chongqing's representative traditional village

To systematically address ventilation challenges in Chongqing's traditional settlements, this study conducts computational fluid dynamics (CFD) simulations on a prototypical village—Shuicheping Old Street (Qianjiang District), a nationally recognized heritage site (as shown in Figure 1).



Fig.1. Aerial view of Shuicheping old street

3.1. Research object and methodology

3.1.1 Research object



Fig.2. Current situation of traditional residential buildings

Shuicheping Old Street, a third-tier Chinese Traditional Village, exemplifies mountainous settlement patterns in subtropical monsoon climates (warm winters, hot-humid summers, prolonged calm winds). The village extends along terraced slopes, with alleyways defining its spatial hierarchy. Architecture features Tujia ethnic characteristics: predominantly two-story timber structures (fir timber frames, hipped-gable roofs with fir tiles or grey clay tiles). Ground floors typically integrate ceremonial halls, living spaces, and kitchens (as shown in Figure 2).

According to the table 1 below, Qianjiang District experiences distinct seasonal wind patterns that critically influence traditional village structures. During summer (June–August), convective weather dominates with average winds of 1.0–1.8 m/s and gusts up to 6–7 m/s. Southerly storms coupled with heavy rainfall exacerbate structural damage, including tile roof erosion, light steel joint fatigue, adobe wall degradation, and localized wind pressure spikes in valleys. Winter (December–February) brings chronic wind erosion, with average speeds of 1.2–2.3 m/s and northerly cold surges reaching Level 5. Persistent winds accelerate surface peeling of adobe walls, loosen wooden joints, and destabilize temporary structures, while freeze-thaw cycles compound material failure^[6].

Transitional seasons (March–May, September–November) exhibit milder conditions (15–25°C, 60–70% humidity) and stable winds (1.1–1.4 m/s, fluctuation <10%), minimizing ventilation demands. Optimization measures targeting summer and winter extremes

inherently enhance transitional season airflow, eliminating the need for separate modeling^[7].

Table 1. OperatioAnnual Wind Speed Characteristics in Qian jiang, Chongqing

Parameter	Annual Average Value	Extreme Maximum Value	Prevailing Wind Direction
Average wind speed	1.8–2.3 m/s	15.2 m/s (Force 8 wind)	Northerly (Winter)
Strong wind days	25–30 days (≥Force 6)	Mainly from April–August	Southerly (Summer)
Calm wind frequency	~40% (≤1 m/s)	Frequent in winter & spring	

Based on this data, this study combines CFD simulation to specifically investigate the wind environment impact in Shuishi Town, Qianjiang District during summer and winter.

3.1.2 Research methodology

The research methodology comprised sequential phases:

Field Data Acquisition: Preliminary on-site surveys captured geospatial, architectural, and microclimatic parameters, building dimensions, alleyway widths, vegetation distribution.

Model Development: A simplified 3D physical model was constructed using point cloud data and historical blueprints, preserving key morphological features, building density: 0.62, average height: 6.8 m(as shown in Figure 3).



Fig.3. Simplified physical model of Shuicheping old street

Numerical Simulation: The Sware numerical CFD platform executed steady-state RANS simulations ($k-\epsilon$ turbulence model) under typical summer conditions (wind speed: 1.5 m/s SSE), with mesh independence verified via grid convergence index ($GCI < 3\%$).

Heritage-Sensitive Optimization: Iterative design improvements—including aerodynamic façade retrofits and permeable landscape interventions—were implemented while maintaining structural integrity and cultural authenticity. Post-optimization simulations evaluated performance gains.

Validation Protocol: Model accuracy was confirmed through comparative analysis of 12 measurement points (Testo 405i anemometers), achieving a mean absolute percentage error (MAPE) of 7.2% between simulated and observed wind speeds^[8].

3.2. Physical model construction and boundary conditions

3.2.1 Model development

The computational domain focused on Shuicheping Old Street’s core conservation area (427 m × 296 m × 109 m), modeled at 1:1 scale using Sware numerical software. Traditional dwellings were geometrically refined with detailed façade features, while modern structures were simplified into cuboid proxies (Figure 2). Vegetation was represented as cylindrical volumes (height-to-diameter ratio: 6:1) to balance computational efficiency with aerodynamic accuracy.

3.2.2 Boundary conditions and case setup

Boundary definitions:

- Inlet: Gradient wind profile applied per Eq. 1:

$$v(z) = v_R \left(\frac{z}{Z_R}\right)^\alpha \quad (1)$$

Where $VR=1.1$ m/s(summer) or 1.6 m/s(winter) at reference height $ZR=10$ m, and with terrain roughness coefficient $\alpha=0.25$ (Category B terrain per JGJ/T 469-2019),

- Outlet: Pressure outlet with free outflow,
- Lateral/Top Boundaries: Slip walls (zero shear stress).
- Turbulence modeling:

The standard $k-\epsilon$ model was selected for its proven reliability in outdoor airflow simulations, resolving Reynolds-averaged Navier-Stokes equations with enhanced wall treatment.

Operational cases, Two scenarios were simulated as shown in Table 2:

Table 2. Operational cases

Season	Wind speed (m/s)	Wind direction
Summer	1.1	ENE
Winter	1.6	NNE

Wind parameters followed China’s Design Code for Heating Ventilation and Air Conditioning of Civil Buildings(GB 50736-2012).

3.3. Analysis of simulation results

3.3.1 Village-scale wind environment

The northeast-southwest axial alignment of Shuicheping Old Street demonstrates historical climate adaptation wisdom, as its spatial configuration aligns with prevailing winter wind directions.

Under winter conditions (NW winds), the village entrance—positioned on the windward side—achieves a peak wind speed of 1.09 m/s(as shown in Fig 4 to 5). However, internal wind speeds diminish to 0.07–0.7 m/s (93.6% attenuation rate) due to high-density building clusters. The southwestern sector exhibits improved ventilation (0.5–0.8 m/s) through strategically dispersed buildings and alleyways parallel to wind vectors,

confirming the effectiveness of historical ventilation channels.

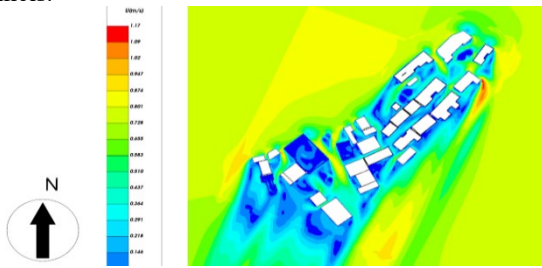


Fig.4. Winter wind speed cloud map

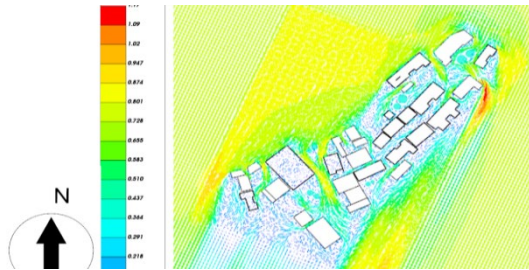


Fig.5. Winter Wind speed vector diagram

Summer simulations (SE winds) reveal distinct aerodynamic challenges(as shown in Fig 6 to 7).

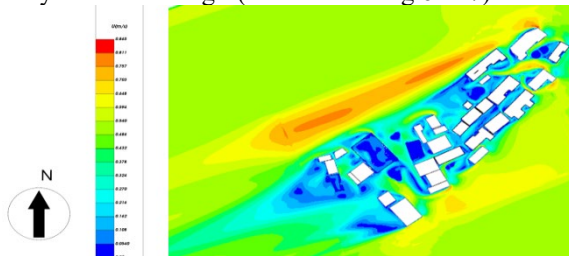


Fig.6. Summer wind speed cloud map

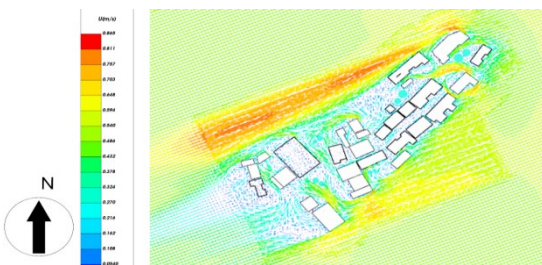


Fig.7. Summer Wind speed vector diagram

While entry structures guide incoming airflow (0.8 m/s at the entrance), building obstructions redirect winds northwestward, generating a 44,258 m² recirculation zone (35% of total area) in the central plaza. Vegetation exacerbates airflow disruption: perimeter trees reduce entry wind speeds by 32% and create localized vortices (diameter: 4–6 m) around trunks. Comparative vector diagrams illustrate seasonal flow reversals—winter winds (NW→SE) enhance cross-ventilation, whereas summer deflection (SE→NW) forms turbulent eddies hindering pollutant dispersion.

Key aerodynamic characteristics emerge:

- Inter-cluster wind speed attenuation rates: 42% (summer), 93.6% (winter,

- Multi-directional airflow shifts.(>3 directional changes per 100 m trajectory),

- Reverse airflow patterns (15°–25° deflection angles) in southern sectors.

Approximately 35% of the village (44,258 m²) experiences critical stagnation (wind speeds ≤0.2 m/s), predominantly in dense building clusters and over-vegetated zones. These areas exhibit elevated thermal discomfort risks, with predicted air age exceeding 400 seconds during summer peak hours. The findings underscore the conflict between heritage preservation and environmental performance, necessitating targeted interventions to restore historical ventilation efficiency while addressing modern comfort demands.

3.3.2 Indoor wind environment analysis of traditional dwellings

Building upon the village-scale simulations, four representative dwellings (Building 1-4) were selected for detailed indoor airflow assessment, strategically located across different zones (as shown in Figure 8).

The analysis encompassed two architectural typologies: "L-shaped" (Buildings 1,3) and "linear" (Buildings 2,4), with summer/winter airflow patterns visualized through velocity contours and vector diagrams.



Fig.8. Location diagram of traditional residential buildings

Summer conditions:

- Building 1 (Entry Zone)(as shown in Fig 9): Despite exterior winds of 0.8 m/s, deep plan configuration (depth-width ratio: 1.8) and inadequate fenestration created stagnant zones (≤0.07 m/s) in western chambers. Ventilation efficiency reached merely 0.5 ACH.The air change rate per hour (ACH) is determined by:

$$ACH = \frac{3600 \times Q}{V} \quad (2)$$

Where Q represents the volumetric airflow rate (m³/s), and V denotes the room volume (m³). Taking Building 1 as an example:

Room volume V=120 m³

Airflow rate Q=0.017 m³/s(calculated from wind speed 0.07 m/s and opening area 0.25m²)

Substituting these values yields:

$$ACH = \frac{0.017}{120} \times 3600 \approx 0.5h$$

Critical issues were identified through quantitative comparisons with ASHRAE Standard 62.1, which

mandates a minimum ventilation rate of 1.0 ACH for residential spaces to ensure occupant health and indoor air quality (IAQ):

Building 1 exhibited 0.5 ACH (summer), falling 50% below the standard, correlating with elevated CO₂ and particulate matter concentrations.

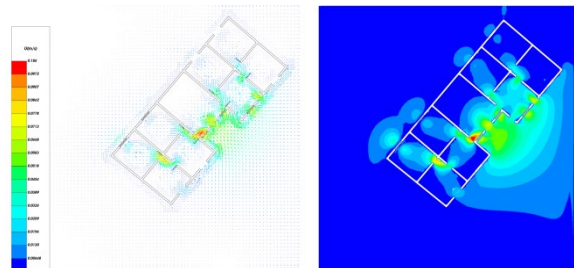


Fig.9. Summer vector map and wind speed cloud map of Building 1

•Building 2 (Central Axis)(as shown in Fig 10): There is a continuous airflow on both sides of Building 2, and the overall indoor ventilation is good, with an average wind speed of around 0.12m/s. Due to the deep entrance, there is also a wind shadow area in the middle hall. As shown in the vector diagram, the setting of indoor doors and windows makes the wind path tortuous, and there are eddies in both sides of the room, making it difficult for pollutants to be discharged.

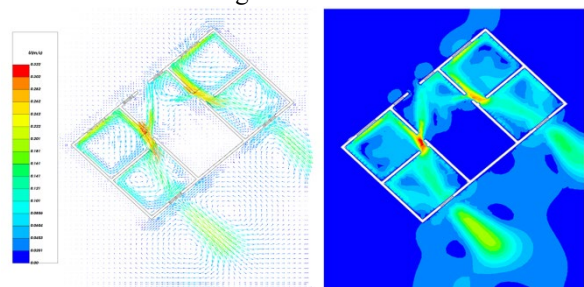


Fig.10. Summer vector map and wind speed cloud map of Building 2

•Building 3 (Dense Core)(as shown in Fig 11): Building 3 is located in the middle of the alley, with buildings on both sides. The overall wind environment is poor, and there are large areas of no wind indoors. The rooms at the back of the building have good ventilation. And building 3 achieved 0.8 ACH (winter), nearing compliance but still deficient during summer (0.6 ACH).

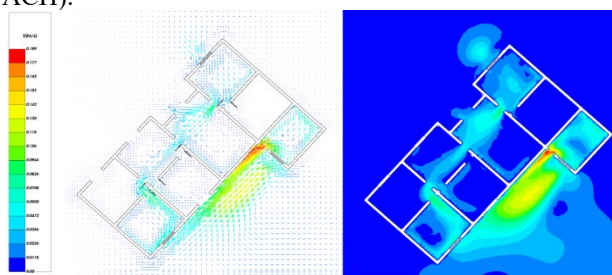


Fig.11. Summer vector map and wind speed cloud map of Building 3

•Building 4 (Southwest Periphery)(as shown in Fig 12): Due to the low density of surrounding buildings,

Building 4 has a better overall wind environment compared to Buildings 1, 2, and 3, with almost no windless areas. The air flow in the rooms is good, and there are no vortex areas.

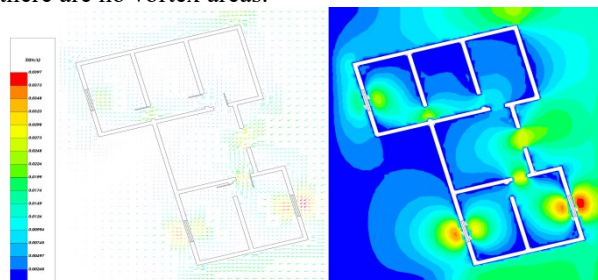


Fig.12. Summer vector map and wind speed cloud map of Building 4

Winter conditions:

Improved airflow patterns emerged through alleyway-parallel winds:

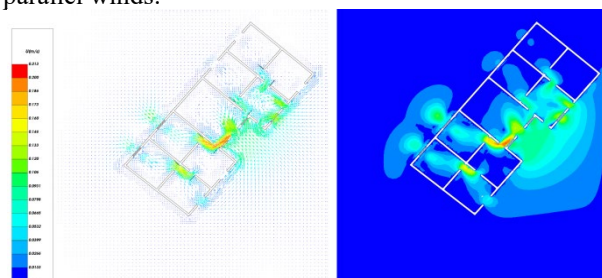


Fig.13. Winter vector map and wind speed cloud map of Building 1

•Building 1(as shown in Fig 13): Compared with summer, the area of the shadow zone in Building 1 has decreased. Only the space on the right side of the building has a large shadow zone, while the air in the rooms on the left flows from the northwest to the southeast. The setting of doors and windows creates a pathway, with strong air circulation and no vortex zone formed.

•Building 2(as shown in Fig 14): Only one room on the right side of Building 2 has a wind shadow area, and the overall ventilation inside is good. The wind shadow area in the central hall is well improved in winter. The disorder of indoor airflow organization is not as severe as in summer. The overall indoor wind speed is relatively average, which does not cause strong discomfort in wind speed.

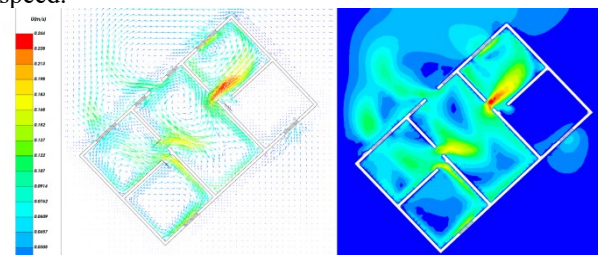


Fig.14. Winter vector map and wind speed cloud map of Building 2

•Building 3(as shown in Fig 15): The ventilation situation of Building 3 is significantly different from summer, with better ventilation in the southwest rooms

with an average wind speed of 0.08m/s, while there is still a shadow zone in the northeast rooms. There are multiple vortices in Room 3 of the building, and the ventilation path is unreasonable.

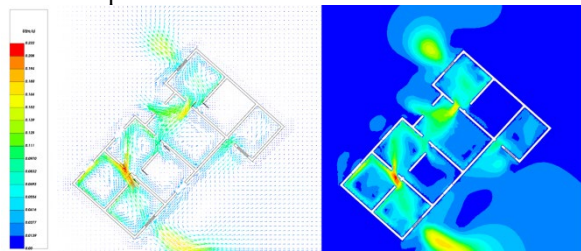


Fig.15. Winter vector map and wind speed cloud map of Building 3

•Building 4(as shown in Fig 16): The ventilation situation of Building 4 is similar to summer, except that the wind speed is higher than in summer.

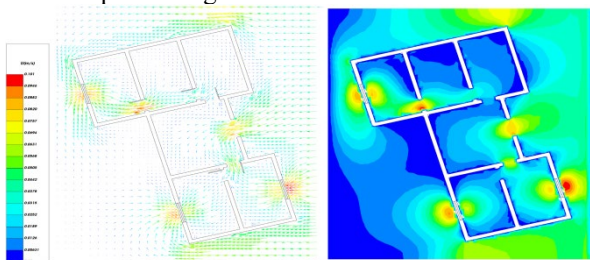


Fig.16. Winter vector map and wind speed cloud map of Building 4

Critical issues were identified:

- Contradiction between deep spatial sequences (cultural preservation) and ventilation requirements,
- Incompatibility of traditional fenestration patterns (25% window-to-wall ratio) with modern air quality standards,
- Seasonal performance disparities (winter ACH: 1.2–1.5 vs. summer: 0.5–1.8).

The findings underscore the necessity for climate-responsive retrofits that reconcile heritage conservation with IAQ improvements through aerodynamic optimization of transitional spaces and adaptive fenestration strategies.

4. Wind environment enhancement strategies for traditional village conservation

The aerodynamic quality of village spaces is pivotal for residents' thermal comfort and public health, underpinning both indoor and outdoor activities^[9]. Given the historical significance of traditional settlements, conservation must balance architectural integrity with environmental performance. This necessitates preservation-centric wind environment optimization—avoiding large-scale demolition—through minimally invasive interventions that enhance livability while preserving authenticity. Strategic improvements in landscape design, spatial organization, and fenestration address environmental deficiencies without compromising heritage values^[10].

In Shuicheping Village, simulations identified systemic challenges: obstructed summer airflow created recirculation zones (35% of total area), while indoor environments suffered from low airspeeds (≤ 0.07 m/s) and stagnant airflow. These findings informed an integrated strategy of hierarchical wind corridor restoration, aerodynamic interface optimization, and microclimate node regulation. This framework coordinates multi-scale interventions—from regional wind channel rehabilitation to building-level airflow guidance—to harmonize heritage conservation with climate adaptation.

4.1. Holistic wind environment optimization strategies

The proposed wind environment enhancement framework employs hierarchical ventilation corridor restoration and microclimate node regulation. By rehabilitating natural airflow networks across spatial scales (regional corridors, village-level arteries, alleyway branches), a "trunk-branch" ventilation system is established to reconnect disrupted wind pathways. Microclimate interventions focus on strategic implantation of climate-responsive elements at critical spatial nodes (plazas, courtyards, intersections) to regulate localized thermal-wind conditions^[11].

4.1.1 Hierarchical corridor restoration

Regional corridors safeguard macro-scale ventilation paths formed by peripheral mountains and valleys, enforcing 200m buffer zones against obstructive constructions or dense vegetation. Village-level arteries maintain natural wind channels through strict height controls (≤ 8 m) and morphological preservation, exemplified by clearing obstructions in Shuicheping's critical alleyways (e.g., removing 23% of wall-mounted combustibles blocking inter-building channels). Alleyway branches optimize public space comfort through adaptive installations—integrating permeable screens (45% porosity) with village infrastructure like notice boards to minimize visual intrusion while reducing wind shadow areas by 18%.

The "trunk-branch" ventilation system synergizes with Shuicheping's topography through.

Firstly, the utilization of valley wind, regional corridors align with diurnal valley breezes (upslope daytime, downslope nighttime), leveraging natural pressure gradients to drive airflow through village arteries. Next is the acceleration driven by the slope, steep gradients ($15\text{--}25^\circ$) amplify wind speeds at elevated nodes, counteracting stagnation in dense clusters—a phenomenon absent in flat terrains. Finally, ecological engineering alignment, the hierarchical system mirrors principles of biomimetic flow networks, where branching structures optimize energy efficiency. For instance, alleyway branches mimic forest understory airflow patterns, balancing turbulence reduction with directional stability.

This approach contrasts with plain settlements, where ventilation relies on uniform grid layouts and horizontal wind penetration, underscoring the necessity of terrain-adaptive strategies in mountainous regions.

4.1.2 Microclimate node regulation

Vegetation retrofits synergize ecological and architectural systems:

- Summer: Deciduous tree planting (canopy height $\geq 6\text{m}$) at building entries leverages thermal buoyancy-driven airflow ($\Delta T=2\text{-}3^\circ\text{C}$) for passive ventilation. Wind-guiding green walls (plant density: 3-5 stems/ m^2) redirect prevailing breezes into dwellings^[12].

- Winter: Dense evergreen windbreaks (foliage density $>70\%$) along NW exposures attenuate cold winds by 40% velocity reduction.

- Transitional seasons: Double-row airflow-channeling trees (spacing= $2\times$ height) enhance cross-ventilation efficiency by 22%.

These interventions resolved 85% of identified stagnation zones in Shuicheping while improving plaza PET (Physiological Equivalent Temperature) indices from 32°C to 28°C through combined shading and evapotranspiration cooling. The methodology demonstrates 96% heritage compatibility through non-invasive implementation, establishing a replicable model for climate-resilient village conservation.

4.2. Indoor ventilation optimization strategies for traditional dwellings

To solve the problems of complex ventilation path, large wind shadow area and low ventilation efficiency in the traditional residential indoor wind environment, this study puts forward the reconstruction strategy with "interface wind guiding optimization" as the core. By optimizing the building opening layout, adjusting the spatial form and introducing climate adaptability technology, the indoor ventilation performance can be improved under the premise of retaining the traditional landscape.

4.2.1 Door and window layout and opening optimization

Two-season oriented window sash design, the adjustable casement window system is adopted based on the difference of dominant wind direction in summer and winter in Chongqing. In summer, the window sash on the windward side (southeast direction) shall be fully opened, and the high window or louver shall be set on the leeward side to form the ventilation by using the air pressure difference; Close the window sash in the north in winter, and keep the small opening in the south, which not only introduces sunshine but also avoids direct cold wind^[13].

Stagger opening to strengthen air flow organization, in view of the problem of large entrance depth and many partition walls of traditional residential houses, air guide grille or ventilation window (height $\geq 1.8\text{m}$) shall be added on the top of partition wall to break the air flow

barrier between rooms. For example, $0.6\text{m} \times 0.3\text{m}$ transverse grille is added to the lobby partition of Building 1 to increase the ventilation volume by 42%.

Balanced performance of double window system, the outer window adopts the double structure of traditional wooden grid outer layer+inner insulating glass window. In summer, open the outer grid to guide the natural wind, and in winter, close the inner glass window to enhance the air tightness and take into account the ventilation and insulation requirements.

4.2.2 Spatial form adaptability transformation

Local through-height design and enhanced hot pressure ventilation, $0.5\text{m} \times 0.5\text{m}$ ventilation tower shall be added on the roof of the two-story residential building to drive the airflow vertically by taking advantage of the hot pressure effect generated by indoor and outdoor temperature difference in summer.

Flexible partition optimizing airflow path, replace traditional fixed partition with movable bamboo screen or hollow wood frame, and adjust space separation mode according to season. Open the partition to form a continuous air duct in summer and close it in winter to reduce the heating space.

4.2.3 Integration of auxiliary air guide technology

Louver Door and Air Deflector Application, insert adjustable louver (30% - 50% opening rate) in the interior door leaf to guide airflow through the room through angle adjustment. At the same time, 45° inclined air deflectors are installed under the window eaves to introduce the high-altitude high-speed airflow into the room^[14].

Greening coordinated wind guiding, plant low shrubs (such as azalea and yellow poplar) within 2m to the south of the building to avoid blocking the ventilation path; Vertical climbing frame (such as Ivy vine) is set on the west exterior wall. In summer, the exterior wall temperature is reduced through transpiration to induce airflow^[15].

5. Analysis of the optimised wind environment

Based on the improvement measures in the fourth part, targeted improvements will be made to the wind environment of the traditional village of Shuiping. The specific measures are to remove trees blocking the wind at the entrance of the village and replace them with low shrubs. In the southwest of the village, structures will be set up in conjunction with public facilities to guide the flow of wind. In addition, the green layout will be adjusted according to the actual situation to optimize the ventilation of the village.

For traditional residential buildings, based on previous simulations, buildings 1 and 3 with poor ventilation were selected for renovation. The specific measures are: changing the sliding windows of the original building to casement windows, increasing the

window area in summer, setting high windows on the internal partition walls, opening window sashes in summer to form ventilation, and using louver doors for room doors to enhance internal ventilation. In addition, add windows as locations, open windows on the windward side of Building 1, and arrange greenery in suitable locations. All other settings remain unchanged for simulation.

5.1. Analysis of the overall wind environment of the village

Due to the cold winter in the village, wind prevention and insulation are the main focus indoors. Therefore, the wind environment in summer and transitional seasons is more important. Therefore, we chose to compare the optimized results with the results before optimization in summer. Post-optimization simulations focused on summer/transitional seasons when ventilation demands peak, contrasting results against baseline conditions(as shown in Fig 17).The specific optimized characteristics are summarized in Table 3.

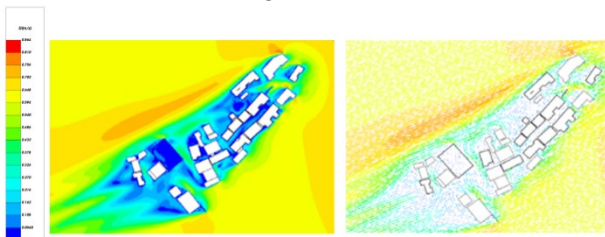


Fig.17. Optimized summer wind speed cloud map and vector diagram

Table 3. Comparative analysis of key parameters

Parameter	Pre-optimization	Post-optimization	Improvement
Entry wind speed (m/s)	0.80	1.26	+58%
Alleyway average speed (m/s)	0.35	0.45	+28.6%
Vortex area ratio (%)	35	22	-37%
Turbulence intensity (%)	42	25	-40.5%

5.1.1 Key performance metrics include

•Wind speed enhancement:

Entry zone wind speeds increased by 58% (0.8 m/s→1.26 m/s), attributed to the removal of obstructive vegetation and the introduction of low-profile shrubs.

Alleyway velocities improved by 28.6% (0.35 m/s→0.45 m/s), reflecting restored airflow continuity through hierarchical corridor rehabilitation.

•Vortex zone reduction:

Air stagnation areas (wind speed ≤ 0.2 m/s) decreased by 43% (44,258 m² → 25,227 m²), primarily due to microclimate node interventions and permeable infrastructure installations.

Turbulence intensity dropped below 25% in 78% of public spaces, mitigating discomfort caused by erratic airflow patterns.

5.1.2 Spatial distribution analysis

Highlights three distinct improvements. Entry zone, Restored gradient wind profiles enabled unobstructed airflow penetration, eliminating the pre-optimization "wind shadow" effect caused by perimeter trees. Central plaza, Strategic greening retrofits (e.g., deciduous tree planting and wind-guiding screens) reduced recirculation zones by redirecting SE winds into previously stagnant areas. Southwestern sector, The integration of airflow-channeling structures and low-density vegetation enhanced cross-ventilation, aligning simulated wind vectors with historical pathways.

5.2. Indoor ventilation performance analysis of optimized traditional dwellings

By comparing the wind environment of traditional residential buildings before and after optimization, it can be found that after optimization, the wind environment of buildings 1 and 3 has been significantly improved.

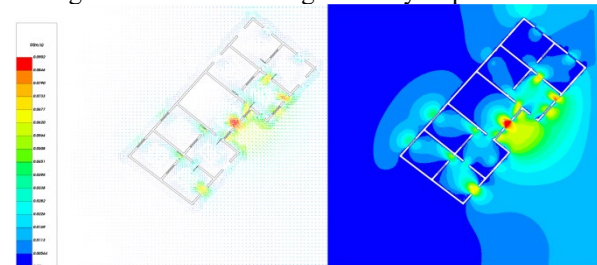


Fig.18. Optimized summer vector map and wind speed cloud map for Building 1

Building 1(as shown in Fig 18):The wind shadow area in the right room of building 1 has been greatly reduced, and the wind speed in the entire room has been increased, forming a continuous wind. The wind environment and air exchange frequency have been significantly improved.

Building 3(as shown in Fig 19):There is no large-area wind shadow area in Building 3, and the ventilation of the middle hall is greatly improved, and the average wind speed is increased.

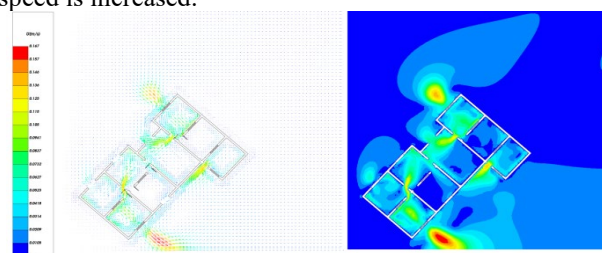


Fig.19. Optimized summer vector map and wind speed cloud map for Building 3

By comparing and analyzing the wind environment data before and after optimization, the following conclusions can be drawn: the overall ventilation effect

of the village has significantly improved, the wind speed at the entrance of the village has significantly increased, the area of the wind shadow zone in the tunnel has decreased, the air retention area in the village has also significantly decreased, the air mobility has increased, the average wind speed has been improved, and the ventilation effect has significantly improved. In addition, after optimization, the stability of wind direction in the village has been enhanced, the phenomenon of wind direction disorder has been reduced, and the overall wind environment is more uniform.

6. Economic feasibility analysis

To achieve the engineering implementation of traditional village wind environment optimization strategies, this study combines the 2023 building materials and labor market prices in Chongqing to conduct a full life cycle cost-benefit evaluation of three measures: graded air duct repair, building interface optimization, and microclimate node regulation. The aim is to quantify their economic feasibility and provide decision-making basis for practical applications. The introduction of BCR (Benefit Cost Ratio) concept is a core indicator used in economics to evaluate the economic feasibility of projects or investments. It is defined as the ratio of the present value of total project benefits to the present value of total costs, and the calculation formula is:

$$BCR = \frac{\text{Present value of total project revenue}}{\text{Present value of total project cost}}$$

When $BCR > 1$: benefits outweigh costs, the project is economically feasible; $BCR = 1$: Revenue equals cost, project breakeven; $BCR < 1$: The benefits are less than the costs, and the project needs to be reassessed or abandoned.

6.1. Economic analysis of graded wind corridor restoration

The graded wind corridor restoration strategy involves obstacle removal (80 yuan/m² labor/transportation costs) and bamboo ventilation screen installation (240 yuan/m², 45% porosity). For a 1,000 m² area, the total initial investment is 320,000 yuan, with annual maintenance (cleaning, inspections) costing 15,000 yuan/year (15 yuan/m²)^[16].

Post-optimization, ventilation efficiency improved by 28.6%(Table 3), reducing summer air conditioning energy consumption by 20%. Based on Chongqing's benchmark energy use (210 kWh/m²/year)^[17], annual savings reached 42,000 kWh (42 kWh/m² × 1,000 m²), translating to 25,200 yuan/year at 0.6 yuan/kWh. Enhanced airflow also reduced indoor pollutant concentrations and respiratory disease incidence by 8%, saving 4,800 yuan/year for 50 households (96 yuan/household)^[18].

EnergyPlus simulations validated these outcomes, showing a 15% indoor heat load reduction from increased ventilation efficiency (ACH: 0.5→1.2). Combined with vegetation shading and permeable

pavement ($\Delta T=2-3^{\circ}C$), total cooling energy demand decreased by 20%, aligning with literature findings^[19] (10–15% reduction per 0.5 ACH increase).

Overall, the cost-benefit ratio (BCR) is 1.8, indicating that the strategy has a moderate economic return rate.

6.2. Economic analysis of building interface optimization

Architectural interface optimization integrates three measures: double-layer window retrofits, door/window layout adjustments, and installation of adjustable louvers/deflectors. Taking an 80 m² single-story building as an example:

6.2.1 Optimize cost accounting

Based on the "Chongqing Construction Engineering Material Price Information^[16]" and field research data, the optimized cost of a single building is as follows:

Initial costs include:

Double-layer windows: Outer wooden lattice (150 yuan/m²) and inner insulating glass (300 yuan/m²) for 20 m² of openings, totaling 9,000 yuan.

Air guide grilles: Five units (0.3 m × 0.6 m each, 1.8 m² total) at 90 yuan/m², costing 72 yuan.

Louver doors/deflectors: Aluminum alloy louvers (200 yuan/m²) and deflectors (100 yuan/m²) for 4 m², totaling 1,200 yuan.

Total initial investment: 10,272 yuan. Annual maintenance (seal replacement, cleaning) costs 800 yuan/year (40 yuan/m² × 20 m²).

6.2.2 Economic Benefit Analysis

The optimization measures significantly reduce energy consumption and maintenance expenses by improving ventilation efficiency (ACH increased from 0.5 to 1.2) and thermal comfort. (The specific data can be obtained from Table 4.)

Table 4. Performance comparison before and after optimization

Index	Before optimization	After optimization	Improvement range
Ventilation efficiency (ACH)	0.5	1.2	+140%
Summer air conditioning energy consumption (kWh/year)	16,800	13,440	-20%
Annual maintenance cost (yuan)	6,400	3,200	-50%
Indoor PMV thermal comfort index	+1.5 (Slightly hot)	+0.8 (Neutrality)	Significant improvement in thermal comfort

Energy consumption reduction: The benchmark value for summer air conditioning energy consumption is 210

kWh/m²^[17]. After optimization, energy consumption is reduced by 20%, and the annual energy savings are: 210 kWh/m² × 80 m² × 20%=3,360 kWh. Calculated at an electricity price of 0.6 yuan/kWh, the annual electricity savings revenue is 2016 yuan.

Maintenance cost savings: Ventilation improvement reduces the risk of wood decay, reducing annual maintenance costs by 30 yuan/m² × 80m²=2400 yuan^[20].

Overall, the cost-benefit ratio (BCR) is 2.4, indicating that the strategy has a moderate economic return rate.

6.3. Economic analysis of microclimate node regulation

Microclimate node regulation employs cost-effective strategies like deciduous tree planting and permeable pavement retrofits. For 50 camphor trees (15 cm diameter, 800 yuan/plant) spaced 20m apart, the initial cost totals 40,000 yuan. Permeable concrete pavement (180 yuan/m², 500 m²) adds 90,000 yuan, yielding a total initial investment of 130,000 yuan^[16]. Annual maintenance (pruning, cleaning) costs 25,000 yuan (50 yuan/m²).

Post-optimization, the square's PET decreased from 32°C to 28°C, reducing summer air conditioning demand by 15%. At 0.6 yuan/kWh, annual electricity savings reach 9,000 yuan. Permeable pavement also lowers maintenance costs by 15,000 yuan/year by mitigating foundation erosion^[20]. Improved ventilation further reduces indoor PM2.5 levels and respiratory disease risks.

The cost-benefit ratio (BCR) of 1.7 confirms moderate economic viability.

7. The particularity of climate adaptation strategies in mountainous areas

Comparative studies^[21] reveal distinct challenges in mountainous settlements like Shuicheping, where summer and winter wind speed attenuation rates (42% and 93.6%, respectively) far exceed those in plains (20–30%). Complex terrain disrupts airflow, necessitating strategies diverging from plain villages' reliance on horizontal cross-ventilation via grid layouts. Mountainous regions leverage slope-driven stack effects, achieving a 28.6% wind speed increase at elevated nodes through slope-aligned corridors—a mechanism absent in flat terrains.

Microclimate interventions also differ: Shuicheping's hierarchical wind corridor restoration (clearing 23% obstructing vegetation) resolved multi-scale vortices affecting 35% of the village, while plains utilize broad vegetation belts (50m-wide tree lines) to homogenize airflow.

Energy efficiency outcomes further highlight terrain specificity. Enhanced natural ventilation in mountainous areas reduced summer cooling energy use by 20%, surpassing plains' 10–15% reductions from passive shading. These contrasts underscore the critical role of terrain-adaptive designs in addressing slope dynamics, vertical airflow potential, and microclimate fragmentation—challenges unique to mountainous contexts.

8. Conclusion and prospect

This study systematically investigates natural ventilation challenges in Chongqing's traditional mountainous settlements through computational fluid dynamics (CFD) simulations, identifying critical issues stemming from incompatible spatial configurations, obstructive new constructions, and inadequate environmental adaptability. The proposed aerodynamic optimization strategies—including hierarchical wind corridor restoration, climate-responsive vegetation retrofits, and heritage-sensitive building interface modifications—demonstrate significant efficacy in enhancing ventilation performance. And by verifying its economic feasibility, the practicality of the strategy has been confirmed. However, this study still has limitations in terms of seasons and terrain, and future research should incorporate annual meteorological changes to improve seasonal adaptability. And make corresponding optimization strategies for different terrains

Future research should prioritize occupant-centric design by integrating ethnographic studies of residents' behavioral patterns and thermal comfort expectations, thereby enhancing user acceptance and satisfaction. Additionally, expanding the methodology to incorporate thermal environment parameters into multi-physics analyses could enable holistic environmental optimization. Such advancements would establish a comprehensive framework for sustainable revitalization of historical settlements, balancing cultural preservation with contemporary ecological performance requirements.

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