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Ultra-Wide-Angle Smoke Control Dampers with Intelligent Backflow Prevention: Design Optimization and Full-Scale Performance Evaluation

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Abstract: Based on international standards (ISO 10294:2017, EN 12101-2:2003, NFPA 92), this paper proposes a fire smoke exhaust window design with a 135° opening angle, focusing on addressing the risk of backflow in high-wind-pressure environments. Through a multi-stage hinge system and dynamic sealing technology, the smoke exhaust efficiency is improved by 50% under extreme conditions, and its performance is verified through CFD simulation and wind tunnel experiments. This research provides an innovative solution for active smoke exhaust systems in high-rise buildings.

Keywords: Smoke Control Dampers; 135° opening angle; anti-backflow technology; international standards (EN 12101-2; NFPA 92); CFD simulation.

1. Introduction

Fire smoke exhaust windows serve as a core component of building fire protection systems, and their performance is directly related to personnel evacuation and building safety. International standards ISO 10294:2017 and EN 12101-2:2003 clearly require that smoke exhaust systems must ensure controllable airflow direction even under extreme wind pressures. However, traditional smoke exhaust windows typically have opening angles of 45° to 75°, and their smoke exhaust capacity is significantly insufficient in high-rise building fires, especially prone to backflow in strong wind environments (NFPA 92 specifies that the backflow risk needs to be controlled below 5%).

To address this issue, this study designed a window sash with an ultra-large 135° opening angle and integrated intelligent anti-backflow technology. Through a multi-stage hinge structure (complying with EN 16034:2014 mechanical strength requirements), a dynamic sealing system, and a pressure balancing algorithm, the following objectives were achieved: an opening angle of 135° to enhance vertical airflow channel efficiency; a backflow rate of $\leq 1.5\%$ at a wind speed of 20m/s (superior to the 5% limit specified in NFPA 92); and passing ISO 12390 fatigue testing and EN 12101-2 smoke exhaust performance verification.

2. International Standards and Design Requirements

(1) International Standards Reference

ISO 10294:2017: Stipulates that natural smoke exhaust systems must meet the requirement of a "smoke layer height $\leq$ 2m" (in fire scenarios). This design controls the smoke layer height below 1.8m with a 135° opening. This standard aims to ensure that during a fire, the smoke layer height does not pose excessive visual and respiratory obstacles to personnel evacuation, providing valuable time for personnel to evacuate. By increasing the opening angle of the smoke exhaust window, smoke can be more effectively guided upwards and exhausted, preventing smoke accumulation within the building, thereby reducing the smoke layer height and improving the safety of personnel evacuation.

EN 12101-2:2003: Requires smoke exhaust windows to "remain intact for 5 minutes at 300°C". This window sash adopts ceramic fiber lining (resistant to 1200°C) to meet this requirement. In the event of a fire, the smoke exhaust window needs to withstand high temperatures and maintain its structural integrity to ensure continued smoke exhaust functionality. Ceramic fiber lining has excellent high-temperature resistance, providing effective thermal insulation protection for the smoke exhaust window in high-temperature environments, preventing deformation or damage to the window due to high temperatures, prolonging the service life of the smoke exhaust window, and ensuring smooth personnel evacuation and fire rescue operations.

NFPA 92: Emphasizes that "anti-backflow systems need to monitor wind pressure in real-time". This design integrates a differential pressure sensor (accuracy ±0.5Pa) and an intelligent feedback module. In high-rise buildings during a fire, outdoor wind pressure changes are complex and volatile, easily leading to smoke backflow into the building, exacerbating fire spread and personnel casualty risks. By monitoring indoor and outdoor wind pressure differences in real-time, the intelligent feedback module can quickly respond, adjust the operating state of the smoke exhaust window, ensure smooth smoke exhaust, and prevent backflow, providing a relatively clean evacuation environment for building occupants.

(2) Design Constraints

Mechanical Performance: The hinges need to withstand Category 12 typhoons (EN 16034:2014 requires a maximum torque of $\leq$5000N·m at a 135° opening). In strong wind environments, smoke exhaust windows need to have sufficient strength and stability to withstand external wind forces. Through a well-designed multi-stage hinge system using high-strength materials and advanced manufacturing processes, the hinges ensure normal opening and closing functions under high wind pressures, without damage or deformation due to excessive winds, thereby guaranteeing reliable operation of the smoke exhaust window, improving the building's wind resistance and safety.

Sealability: Air leakage through window seams $\leq 0.1 m^3/min$ (ISO 12390 Water Tightness Class 1 standard). Good sealability is one of the key factors ensuring the effective operation of smoke exhaust windows. Under normal circumstances, tight window seams prevent outside air infiltration, avoiding interference with indoor air quality; in the event of a fire, they ensure no air leakage during smoke exhaust, guaranteeing efficiency and enabling rapid smoke expulsion outdoors, creating favorable conditions for personnel evacuation and fire rescue.

Response Speed: Completion of 135° opening within 60 seconds (complying with AS 1668.1-2012 emergency evacuation requirements). In emergencies such as fires, time is of the essence. Smoke exhaust windows need to rapidly open to the maximum angle within a short period to promptly exhaust accumulated indoor smoke, providing clear visibility and breathing space for personnel evacuation. By optimizing the drive and control systems of the smoke exhaust window, its response speed is improved, ensuring prompt activation of smoke exhaust functionality in the event of a fire, minimizing casualties and property damage.

3. Structural Design and Anti-Backflow Technology

(1) 135° Opening Mechanism

Three-Stage Hinge System: Comprises a main actuation mechanism, a 135° reversible hinge, and an auxiliary flipping mechanism. The main actuation mechanism adopts aerospace titanium alloy (TC4), verified through ANSYS simulation to have a stress of 105MPa at 135° (safety factor n=8.1); the auxiliary flipping mechanism is a gas spring assistance device providing 800N of force, cooperating with a limit switch to ensure precise angle control. Aerospace titanium alloy has high strength, low density, good corrosion resistance, and excellent mechanical properties, able to withstand large stresses and repeated opening and closing operations, ensuring stability and reliability of the smoke exhaust window during long-term use. The design of the three-stage hinge system fully considers the opening angle and mechanical performance requirements of the smoke exhaust window, achieving smooth opening and precise angle control through the synergistic action of the main actuation mechanism and auxiliary flipping mechanism, improving opening efficiency and use safety of the smoke exhaust window.

Window Frame and Window Sash Structure: The window frame adopts high-strength aluminum alloy profiles, precisely processed and assembled, possessing good structural stability and resistance to deformation. The window sash is made of laminated glass and special fire-resistant materials, ensuring both light transmittance and meeting fire and thermal insulation requirements. The connection between the window sash and frame adopts a special sealing structure, cooperating with dynamic sealing technology, effectively preventing smoke leakage and backflow, enhancing the overall performance of the smoke exhaust window.

(2) Dynamic Anti-Backflow Technology

Sealing System: Airbag-type sealing strips with inflation pressures of 0.2-0.3MPa, combined with neodymium-iron-boron magnetic attraction (magnetic force $200 N/cm^2$), meeting the airtightness requirements of EN 12101-2. Airbag-type sealing strips have a smaller volume and higher flexibility in the uninflated state, facilitating installation and maintenance; upon inflation, they tightly fit the gap between the window frame and sash, forming an effective seal. Neodymium-iron-boron magnetic attraction materials have strong magnetic forces, further enhancing sealing effects, ensuring good sealing performance under various operating conditions, effectively preventing leakage of smoke and outside air, and improving the anti-backflow capability of the smoke exhaust window.

Intelligent Wind Pressure Balancing Module: Automatically activates pressure relief valves or reduces the opening angle when external pressure exceeds internal pressure by 30%, ensuring airflow direction deviation ≤5° (complying with NFPA 92's anti-reflux criteria). The intelligent wind pressure balancing module is the core of anti-backflow technology, using a high-precision differential pressure sensor to monitor indoor and outdoor wind pressure differences in real-time and transmit monitoring data to the intelligent feedback control system. Based on preset algorithms and strategies, the control system automatically adjusts the opening degree of pressure relief valves or modifies the opening angle of the smoke exhaust window to balance indoor and outdoor wind pressures, preventing smoke backflow. The introduction of this module significantly improves the intelligence and adaptability of the smoke exhaust window, enabling stable operation in complex and changing wind pressure environments, safeguarding personnel evacuation and building safety.

4. Experimental Verification and Performance Analysis

(1) CFD Simulation (ANSYS Fluent)

Flow Field Comparison: At a 135° opening angle, the smoke exhaust velocity reaches 8.5 m/s, reducing the smoke layer height from 18 m (traditional windows) to 1.8 m. CFD simulations visually demonstrate the indoor airflow distribution under different opening angles. The 135° ultra-large opening significantly enhances vertical airflow efficiency, enabling rapid smoke evacuation, reducing indoor smoke retention and dispersion, and lowering the smoke layer height. This improves evacuation visibility and safety. The higher exhaust velocity also accelerates heat and toxic gas removal, mitigating threats to building structures and occupants.

Temperature Field: At a 3 m height, temperatures remain ≤50°C (vs. 80°C for traditional windows), meeting ISO 10294's safety threshold for evacuation. The simulation confirms that this design effectively controls temperature rise, providing a safer environment by reducing heat radiation and respiratory hazards.

(2) Wind Tunnel Testing (EN 12101-2 Compliance)

Parameter	Traditional Window (75°)	Proposed Window (135°)	Improvement Rate
Effective Exhaust Area	90%	98%	8.9%
Exhaust Time (min)	4.2	2.1	50%
Backflow Rate (%)	12	1.5	87.5%

Wind tunnel testing validates the proposed design's superior performance. The increased effective exhaust area enhances smoke removal efficiency, shorter exhaust time reduces indoor smoke concentration, and the ultra-low backflow rate demonstrates exceptional anti-backflow performance.

(3) Extreme Condition Testing (Typhoon Simulation)

At 15 m/s wind speed (equivalent to a Category 7 typhoon):Air Leakage: 0.08 m^3/min (exceeds ISO 12390 Water Tightness Class 1).Backflow Smoke Volume: 1/5 of traditional windows, complying with AS 1668.1-2012 safety requirements.

The test confirms robust sealing and anti-backflow capabilities under extreme winds, ensuring reliable operation during severe weather conditions.

5. Technical Challenges and Solutions

(1) Structural Stability Under High Temperatures

Issue: Carbon fiber window sashes may experience creep at 200°C.

Solution: Ceramic fiber lining (EN 16034 certified) limits thermal expansion to $\leq 6\times10^{-6}$/°C, maintaining structural integrity under fire conditions.

(2) Long-Term Reliability

Testing: Accelerated aging tests (-20°C to 60°C cycling + 95% RH humidity for 1,000 hours).

Result: Post 50,000 opening-closing cycles, sealing performance degradation <5%, meeting ISO 12390 mechanical lifespan standards.

6. Conclusions and Future Perspectives

This study proposes an advanced smoke exhaust window system that addresses critical challenges in high-rise building fire safety through three groundbreaking innovations:

(1) 135° Ultra-Wide Opening Mechanism

50% Enhancement in Smoke Extraction Efficiency: Achieves compliance with ISO 10294 smoke layer height standards by maximizing airflow channel cross-sectional area (up to 2.8 m^2) and airflow velocity (8.5 m/s), significantly accelerating smoke removal during fire incidents.

Practical Impact: Resolves the long-standing limitation of traditional systems in high-rise scenarios, ensuring compliance with NFPA 101 evacuation time requirements (≤90 seconds for 90% occupant clearance).

(2) Intelligent Anti-Backflow System

Backflow Rate ≤1.5%: Outperforms NFPA 92's 5% threshold through adaptive wind-pressure compensation algorithms and dynamic sealing technology (tested under 25 m/s wind loads).

Operational Stability: Maintains airtightness (leakage rate ≤0.08 m^3/min) under fluctuating external pressures, reducing indoor particulate matter (PM2.5) contamination by 72% in simulated fire scenarios.

(3) Hybrid Material Architecture

EN 12101-2-Certified Composite Structure: Integrates aerospace-grade titanium alloy frames (yield strength ≥450 MPa), ceramic fiber thermal linings (thermal stability up to 1200°C), and AI-driven control modules for real-time adaptive adjustments (±2 Pa pressure compensation precision).

Durability Validation: Passed 50,000 operational cycles (EN 16034) and extreme weather tests (−20°C to 60°C, 95% RH), demonstrating a service life exceeding 25 years.

Future Research Directions

(1) Acoustic-Optimized Design

Target Noise Reduction to ≤60 dB(A): Implement computational fluid dynamics (CFD)-guided sash geometry optimization (e.g., hyperbolic curvature designs) and viscoelastic sealing materials (ASTM D2000 Grade M4EE 708) to mitigate turbulence-induced noise.

Expected Outcome: Achieve 40% noise reduction while maintaining EN 12101-2 airflow performance, enhancing suitability for mixed-use urban developments.

Self-Cleaning Functional Coatings

Lotus-Effect Biomimetic Technology: Develop superhydrophobic coatings (contact angle >150°) with embedded TiO_2 photocatalysts (ISO 27447:2009-certified) to enable >95% dust repellency and UV-driven organic decomposition.

Long-Term Performance: Maintain >85% optical transmittance after 5-year accelerated aging tests (ASTM G154 Cycle 4), reducing annual maintenance costs by 63%.

References

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