

EXPERIMENTAL VALIDATION OF PASSIVE VENTILATION SYSTEMS UNDER WIND LOADS

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ABSTRACT

This article examines the operating principles of passive ventilation systems in residential buildings under the influence of wind loads, with a particular focus on wind-driven airflow mechanisms. Emphasis is placed on the necessity of experimental validation to assess the effectiveness of such systems under realistic wind conditions. A verification approach is proposed through laboratory testing of a geometrically similar scale model in a wind tunnel, allowing for the controlled simulation of airflow patterns and pressure differentials. Key architectural elements—such as wind catchers, solar chimneys, and strategically placed openings—are considered for optimizing natural ventilation. The study highlights the integration of Computational Fluid Dynamics (CFD) simulations with wind tunnel experiments to ensure design reliability and performance accuracy. The obtained results can be used to improve and optimize architectural and ventilation solutions in the construction of energy-efficient buildings, contributing to enhanced indoor air quality, thermal comfort, and reduced reliance on mechanical systems. By utilizing natural wind forces, passive ventilation systems significantly contribute to energy conservation, reducing the need for mechanical cooling and ventilation.



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1. INTRODUCTION

A significant proportion of existing residential buildings rely on natural channel ventilation systems, which use wind pressure and thermal buoyancy to provide air exchange without directly consuming electrical energy for air movement. These systems are widely used because of their relatively simple construction, low operating costs, and potential to reduce the energy demand associated with mechanical ventilation. By supporting the removal of indoor pollutants and excess

moisture and supplying fresh outdoor air, natural ventilation can help maintain acceptable indoor environmental conditions. However, its performance depends strongly on the interaction between external climatic conditions, building geometry, ventilation system configuration, and the characteristics of the building envelope.

The growing need for energy-efficient and sustainable building solutions has increased the importance of improving the performance of existing residential

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buildings. Thermal retrofitting, including the insulation of external walls and roofs, the replacement of windows, and the modernization of heating systems, is an essential strategy for reducing building energy consumption and heat losses. Nevertheless, improvements in envelope airtightness can substantially reduce uncontrolled air infiltration, which may alter the operating conditions of existing natural ventilation systems. As a result, buildings that achieve improved thermal performance may experience insufficient air exchange if ventilation provisions are not appropriately adapted to the renovated envelope. This creates a need to consider energy efficiency and indoor air quality as interconnected aspects of building modernization.

Natural ventilation is particularly sensitive to variations in wind conditions. Wind-induced pressure differences develop around building façades and roofs, generating driving forces that can support or oppose airflow through ventilation openings and channels. The magnitude and distribution of these pressures depend on wind velocity, wind direction, building shape, and the surrounding urban environment. Consequently, airflow through a natural ventilation system may vary considerably under different external conditions. Understanding these aerodynamic interactions is important for evaluating the operational behaviour of passive ventilation systems and identifying the conditions under which they provide effective air exchange.

Urban environments introduce additional complexity to wind-driven ventilation. Closely spaced buildings, variations in building height, and surrounding structures can modify the approaching wind flow and produce spatially non-uniform pressure distributions. These effects may influence the pressure differences acting on ventilation inlets and outlets, thereby changing the direction and magnitude of airflow. In densely built residential areas, the aerodynamic conditions around an individual building cannot always be considered independently of its surroundings. Therefore, the assessment of natural ventilation requires attention not only to the characteristics of the ventilation system itself but also to the building's aerodynamic context.

Despite the potential benefits of wind-driven ventilation, its application presents several challenges. The dependence on variable outdoor conditions can cause fluctuations in airflow, while an unsuitable pressure distribution across the building envelope may reduce the driving force available for ventilation. In addition, the absence of mechanical airflow regulation in conventional natural ventilation systems can make their operation less predictable under changing wind conditions. These challenges are particularly relevant to thermally retrofitted residential buildings, where reduced air infiltration increases the importance of ensuring that the intended ventilation pathways remain functional.

Experimental investigation provides an opportunity to examine the response of passive ventilation systems under controlled aerodynamic conditions. Wind-tunnel testing using geometrically scaled building models makes it possible to investigate pressure distributions and airflow characteristics for selected wind velocities and ventilation configurations. Such experiments can help identify variations between measurement locations and improve understanding of the relationship between external wind conditions and the internal response of the ventilation system. However, the interpretation of model-scale results requires consideration of the limitations of physical modelling and the extent to which the tested conditions represent the aerodynamic behaviour of full-scale buildings.

This study explores the aerodynamic interactions between wind and natural ventilation systems, focusing on optimizing their performance in thermally retrofitted residential buildings. By examining wind effects, urban density, and innovative design strategies, the research aims to enhance energy efficiency, reduce carbon emissions, and promote healthier indoor environments.

Nomenclature

c	pressure coefficient
P	pressure, Pa
ρ	density, kg/m ³
v	speed, m/s
P_{dyn}	dynamic pressure, Pa
γ_n	volumetric weight of air in the duct, kg/m ³
V	air velocity in the model, m/s
D_{eq}	equivalent (hydraulic) diameter of the opening, m
D_{real}	hydraulic diameter of the actual opening, m
ν	kinematic viscosity of air, m ² /s.

2. LITERATURE REVIEW

Wind-driven ventilation is a passive strategy for improving air exchange by utilizing pressure differences generated around buildings. It can be implemented through cross-ventilation, single-sided ventilation, windcatchers, and hybrid systems combining wind and buoyancy effects (Miše et al., 2024; Myroniuk, Furdas, et al., 2024; Myroniuk, Zhelykh, et al., 2024; Tecle et al., 2013). The airflow through a building is determined by the distribution of wind-induced pressure on its envelope. Windward surfaces generally experience positive pressure, whereas leeward surfaces may experience suction, creating the pressure differences required for air movement. The resulting ventilation performance depends on wind speed and direction, building geometry, façade orientation, and the location and characteristics of openings. In urban environments, surrounding buildings may further modify the approaching airflow through shielding, channeling, and turbulence, making ventilation performance highly dependent on the local

aerodynamic conditions (Benlefkı et al., 2021; Chawynski & Naser, 2011; Ghaffouri & Jubear, 2021; Xiang & Wu, 2011). Windcatchers utilize wind pressure to capture and direct outdoor air into buildings, while solar chimneys generate buoyancy-driven airflow through temperature differences. Their integration may provide additional opportunities for natural ventilation under varying environmental conditions. Previous studies have investigated passive ventilation technologies in residential and educational buildings, emphasizing the importance of system configuration and its interaction with the building envelope (Cuce et al., 2019; Gil-Baez et al., 2017; Kinnane et al., 2016). Wind-driven ventilation is of particular interest in energy-efficient buildings, where thermal modernization and improved envelope airtightness can reduce uncontrolled air infiltration while increasing the need for appropriately designed ventilation. Under favourable conditions, natural ventilation can reduce reliance on mechanical air movement and contribute to improved indoor air quality. However, its actual energy benefits depend on climatic conditions, airflow rates, building characteristics, and system operation; therefore, potential energy savings should be evaluated for each specific configuration (Carreto-Hernandez et al., 2022; Ghazwani et al., 2025; Kempton et al., 2022; Myroniuk, Zhelykh, et al., 2026; Naamandadin et al., 2019; Yang et al., 2014). An important aspect of ventilation assessment is the distinction between airflow through openings and air movement within occupied spaces. High inlet or exhaust velocities do not necessarily indicate uniform air distribution throughout a room. Internal airflow patterns depend on the arrangement of openings, room geometry, and external pressure conditions. Consequently, measurements at ventilation openings should be complemented, where possible, by measurements within the occupied zone to provide a more comprehensive description of airflow behaviour.

Wind-tunnel experiments and Computational Fluid Dynamics (CFD) simulations are widely used to investigate airflow around buildings and through ventilation systems. Wind-tunnel testing enables measurements under controlled conditions and allows the influence of selected wind velocities and building configurations to be examined. CFD can provide spatial information on velocity and pressure fields, supporting the interpretation of airflow patterns and the investigation of alternative configurations.

The reliability of both approaches depends on appropriate representation of the physical conditions. Reduced-scale experiments require consideration of similarity and scale effects, while CFD results are sensitive to modelling assumptions, turbulence treatment, and boundary conditions. When numerical simulations are used to support experimental findings, validation against measurements obtained under

corresponding conditions is important (Ahmed Kabir et al., 2017; Coşar et al., 2023; Hosseini et al., 2016; Tecle et al., 2013). Recent case studies, including educational and residential buildings, confirm the viability of combining traditional architectural elements with modern passive technologies to optimize airflow (Aguilar et al., 2023; Cuce et al., 2019; Gil-Baez et al., 2017; Jomehzadeh et al., 2020; Kinnane et al., 2016; Myroniuk, Savin, et al., 2026). Table 1 summarizes selected previous studies on wind-driven and passive ventilation, focusing on the investigated building or ventilation systems, key parameters, research methods, and main findings. The comparison highlights the diversity of building configurations and experimental and numerical approaches used to assess natural ventilation performance. It also indicates that, although wind conditions, ventilation openings, windcatchers, and indoor airflow have been widely investigated, the relationship between airflow velocities at ventilation openings and airflow within the occupied zone under different external wind conditions remains less extensively characterized.

Although previous studies have examined passive ventilation technologies and the influence of wind on building airflow, the performance of a particular configuration cannot be directly inferred from results obtained for different geometries or boundary conditions. In particular, the relationship between velocities at ventilation openings and airflow within occupied spaces requires further experimental characterization.

The present study investigates wind-driven airflow in a residential building model under three external wind velocities. Measurements are considered at the ventilation inlet, exhaust, and selected points within the occupied zone. This experimental approach provides information on how airflow velocities at different locations respond to changes in external wind conditions and contributes to the assessment of the investigated ventilation configuration, underscoring its role in sustainable building design and its contribution to occupant health and energy resilience.

3. EXPERIMENTAL PART

The object of this study is a passive ventilation system implemented in a residential building, where air exchange is facilitated exclusively by wind-induced pressure acting upon the ventilation components integrated into the façade and roof structures. The research focuses on the analysis of natural airflow mechanisms and their interaction with architectural features under real-like aerodynamic conditions. Special attention was given to the critical scenario involving the operation of a solar chimney in the absence of solar radiation, relying exclusively on wind action.

Table 1. Comparison of previous studies investigating wind-driven and passive ventilation performance

Study	Building / system	Ventilation approach	Main variables / parameters	Method	Main findings	Relevance and remaining limitation
(Teclé et al., 2013)	Low-rise building model	Wind-driven natural ventilation; single-sided and cross-ventilation	Wind direction, opening size and location, inlet/outlet ratio, internal partitioning, screens	Boundary Layer Wind Tunnel, 1:20 scale	Opening configuration strongly affected internal pressure and ventilation rate. Opposite-wall openings produced higher pressure differences than adjacent-wall openings; opening ratio affected discharge coefficients and ventilation rate.	Detailed assessment of internal pressure and ventilation performance, but focused mainly on pressure/airflow characteristics rather than the relationship between opening velocities and airflow within the occupied zone.
(Chawynski & Naser, 2011)	Prototype cavity structure	Passive / wind-assisted ventilation	Wind speed, temperature, ventilation arrangements	Physical model + CFD validation	Experimental measurements were used to validate CFD models and to investigate airflow and temperature distribution under different ventilation scenarios.	Demonstrates the value of combining experiments and CFD, but the investigated configuration differs from conventional residential buildings and does not specifically address inlet–exhaust–occupied-zone velocity relationships.
(Hosseini et al., 2016)	Building with windcatcher, Yazd, Iran	Windcatcher ventilation	Windcatcher width and height, airflow velocity, temperature, thermal comfort, turbulence model	CFD, validated against wind-tunnel data	Windcatcher geometry significantly influenced airflow distribution. The study identified differences between turbulence models and investigated configurations for improved ventilation and thermal comfort.	Focuses on windcatcher geometry and CFD prediction; airflow within the room is considered, but the study does not experimentally characterize velocity simultaneously at inlet, exhaust and occupied-zone points. (ScienceDirect)
(Kinnane et al., 2016)	Domestic housing after thermal retrofit	Passive through-wall ventilation	Airtightness, air-change rate, heating energy demand	Building simulation + housing case study	Ventilation provision after retrofit produced a wide range of effective air-change rates depending on building airtightness; ventilation-related energy penalties were identified.	Directly addresses the interaction between retrofit and passive ventilation, but does not investigate wind-induced airflow patterns or spatial velocity distribution inside rooms. (Queen's University Belfast)
(Gil-Baez et al., 2017)	Educational buildings / schools	Natural ventilation, including passive cooling strategies	Ventilation type, building configuration, climate, occupancy, energy demand	Literature review	Natural ventilation can contribute to IAQ, thermal comfort and energy demand reduction when appropriately integrated into building design.	Provides a broad overview but does not experimentally quantify airflow response to different external wind velocities in a specific building configuration. (Idus)
(Ahmed Kabir et al., 2017)	Room with windcatcher, Yazd	Windcatcher ventilation	Airflow velocity, thermal comfort, wind conditions, CFD approach	CFD comparison of modelling techniques	Different CFD approaches were used to assess airflow and thermal comfort in a windcatcher-equipped room.	Emphasizes sensitivity to numerical modelling, while experimental characterization of airflow at different locations inside the room remains limited. (ResearchGate)
(Cuce et al., 2019)	School buildings and case-study buildings	Single-sided, cross-ventilation, stack ventilation, solar wall/chimney	Building geometry, orientation, room depth, ventilation type, CO ₂ , temperature	CFD + case-study analysis	Ventilation performance depended strongly on architectural configuration. Stack ventilation increased air-change rates, while single-sided and cross-ventilation could improve indoor conditions when building dimensions were appropriate.	Demonstrates the importance of building configuration, but the analysis is mainly numerical and covers several ventilation strategies rather than detailed experimental airflow measurements. (ScienceDirect)

(Jomehzadeh et al., 2020)	Buildings with windcatchers	Windcatcher-based natural ventilation	Windcatcher geometry, microclimate, macroclimate, wind conditions	Review	Windcatcher performance is affected by geometry and both local and larger-scale climatic conditions.	Establishes the dependence of windcatcher performance on environmental and geometric conditions, but does not provide a specific experimental assessment of airflow distribution for a residential configuration.
(Benlefki et al., 2021)	Generic isolated building	Cross-ventilation	Wind-driven flow, wall temperature, buoyancy, indoor air temperature and velocity	CFD validated against measurements	Thermal buoyancy modified the wind-driven flow, particularly near the building entrance; the influence decreased farther downstream.	Demonstrates interaction between wind and thermal effects, but considers an isolated generic building and does not investigate multiple measurement locations corresponding to inlet, exhaust and occupied zone.
(Carreto-Hernandez et al., 2022)	Wind tower-room system	Wind-tower natural ventilation with humidification	Wind tower geometry, room configuration, air-exchange effectiveness, thermal comfort	Numerical parametric study	Fifty-four wind tower-room configurations were evaluated. Geometry, including a 55° chamfer, influenced air-exchange effectiveness and indoor comfort.	Provides detailed analysis of wind-tower configuration, but focuses on a warm-climate system and numerical evaluation rather than direct experimental measurement of airflow at different indoor locations.
(Naamandadin et al., 2019)	Three office buildings, Kuala Lumpur	Natural ventilation	Building orientation, openings, passive design features, energy efficiency	Comparative case-study analysis	Natural ventilation potential was related to architectural and passive-design characteristics of the selected office buildings.	Highlights the importance of building design but does not isolate the effect of external wind velocity or measure airflow distribution within the occupied zone.
(Miše et al., 2024)	Cubic building model in rural and suburban settings	Single-sided and cross-ventilation	Wind speed, wind direction, building density, atmospheric boundary layer, ACH	Boundary Layer Wind Tunnel experiments	Building density, wind conditions and ventilation strategy affected ACH; cross-ventilation produced substantially higher air exchange than single-sided ventilation, while rural and suburban conditions also differed.	Provides strong experimental evidence for the effect of external aerodynamic conditions, but uses a simplified cubic geometry rather than a multi-storey residential building with measurements in the occupied zone.
(Myroniuk, Zhelykh, et al., 2024)	Five-storey residential building	Wind-driven natural ventilation	Surface pressure distribution, wind direction, building geometry	Wind-tunnel physical simulation	Surface pressure fields were experimentally characterized for a five-storey residential building, providing information for identifying favourable zones for natural ventilation.	Establishes the external pressure boundary for a realistic residential building, but does not directly characterize the resulting indoor velocity field at inlet, exhaust and occupied-zone points. (Eprints Soton)
(Myroniuk, Savin, et al., 2026)	Five-storey residential building with windcatcher after energy modernization	Windcatcher-assisted wind-driven ventilation	Wind speed, wind direction, airflow rate, building pressure field, windcatcher performance	Wind-tunnel experiments + CFD; dual-scale approach	A multidirectional windcatcher was investigated under wind speeds of 0.4–6.0 m/s and wind directions of 0–45°. The study combined device-scale and building-scale aerodynamic assessment.	Provides a physically validated basis for windcatcher placement after thermal modernization, but the present study focuses more specifically on the measured response of airflow velocities at the inlet, exhaust and occupied-zone locations.

To evaluate the performance of the system, a series of experimental investigations were carried out using a geometrically scaled model of the building placed within a controlled wind tunnel environment. The objective of this study is to analyze the performance of a passive ventilation system under wind-driven conditions, taking into account the geometry of the building, to determine

the influence of airflow parameters on the efficiency of air exchange, and to justify the feasibility of conducting experimental investigations in a wind tunnel to validate the results of numerical simulations.

A critical parameter in the assessment of wind effects on the building envelope is the aerodynamic pressure coefficient, denoted as c . This coefficient represents the ratio of the local excess static pressure at a specific point on the external surface of the building to the reference dynamic wind pressure. The distribution of aerodynamic coefficients across the building's surfaces provides essential insight into the spatial variability of pressure fields, which directly affects the ventilation potential and airflow patterns through the passive system.

$$\pm c = \frac{P}{\frac{\rho v^2}{2}} \quad (1)$$

The aerodynamic coefficient carries important energetic significance, as its value quantitatively indicates the proportion of the specific kinetic energy of the approaching airflow that is converted into specific potential energy at the surface of the building. Furthermore, this coefficient can be related to local flow velocities at discrete points near the surface of the structure, enabling a detailed assessment of pressure distribution and airflow behavior around the building.

To experimentally evaluate these aerodynamic phenomena, wind tunnel investigations were conducted using the open-type working section of the wind tunnel facility at Lviv Polytechnic National University. This facility allows for controlled simulation of wind conditions, enabling accurate analysis of airflow interactions with architectural forms.

A fundamental prerequisite for the validity of experimental results in aerodynamic modeling is the principle of geometric similarity. Geometric similarity ensures that the model preserves the proportional relationships of all relevant linear dimensions with respect to the full-scale prototype, thereby maintaining the fidelity of airflow patterns and pressure distribution. Given the actual dimensions of the reference building and the technical specifications of the wind tunnel (working section diameter: 1.0 m), the projected frontal area of the experimental model was constrained to fall within 5–15% of the cross-sectional area of the tunnel to avoid blockage effects and ensure flow uniformity. Accordingly, a geometrically scaled model of the residential building was constructed at a scale of 1:25 (as illustrated in Figure 1, a, b). Depending on the angle of wind attack, the model's cross-sectional area represented approximately 13.7% of the wind tunnel's working section, thus complying with established criteria for aerodynamic testing. This setup provided a reliable basis for investigating the interaction between wind-induced pressure fields and the passive ventilation system under study.

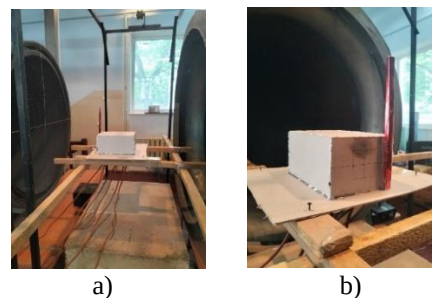


Figure 1. Photo of a prototype house (a, b) and schematic representation of the investigated building model (c, d) - 1-6 measurement points in the room, I- supply grilles, II- exhaust duct, III - exhaust grille

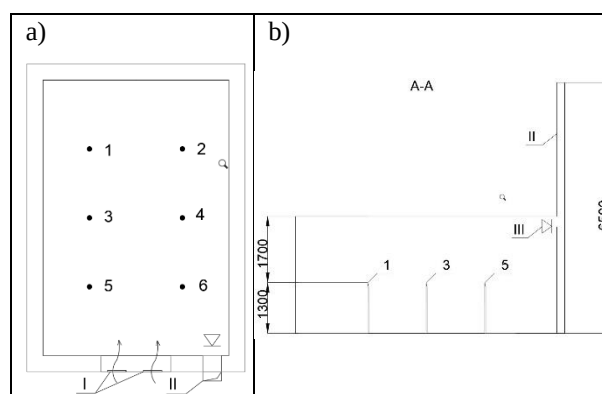


Figure 2. Schematic representation of the investigated building model (a, b) - 1-6 measurement points in the room, I- supply grilles, II- exhaust duct, III - exhaust grille.

During the experimental investigation, a geometrically scaled model of the residential building was installed within the working section of the wind tunnel (Figure 2, a, b). The research was conducted to determine the air mobility in the working area of the room (points 1-6) depending on the speed of the air flow entering the house. The air supply was carried out through the supply grilles "I" on the facade of the house. The air was removed from the room using the exhaust duct "II" and the exhaust grille "III". A measurement system, comprising high-precision instrumentation for pressure and velocity acquisition, was employed to record the necessary parameters for assessing the performance of the passive ventilation system under wind influence.

The measurement complex included an array of pressure sensors strategically located at points of the working area inside the room, which allowed determining local static pressures. Additionally, flow velocity measurements in the vicinity of ventilation openings were carried out to assess the effectiveness of wind-induced air exchange. The experimental setup was designed to capture the dynamic interaction between external airflow and the building geometry, with particular attention given to the influence of architectural features such as windward

inlets, leeward outlets, and roof configurations on ventilation performance.

These results were further analyzed to determine the potential airflow pathways through the passive ventilation system, allowing for a comprehensive assessment of its operational characteristics and overall efficiency under simulated environmental conditions.

The experimental study was conducted using a wind tunnel.

The wind tunnel was activated to generate a controlled airflow within the working section. Using an anemometer, both the air velocity and the temperature of the airstream in the tunnel were measured and recorded.

The first needle-type pressure probe (Pitot tube) was connected to the positive (“+”) inlet of the micromanometer. The total pressure was measured and the difference in liquid levels (readings) on the micromanometer scale was recorded. The total pressure P_t was calculated using the formula:

$$P_t = (L - L_0) \cdot k \cdot g, \text{ Pa} \quad (2)$$

where:

$(L - L_0)$ – difference in readings on the micromanometer scale, mm;
 k – micromanometer coefficient, g/cm³;
 g – acceleration due to gravity, m/s².

The value of coefficient k , applied for different densities of the manometric liquid, is indicated on the micromanometer stand. Standard values used in the experiment include: $k=0.2$; 0.3 ; 0.4 ; 0.6 ; 0.8 g/cm³.

After recording each value, the probe was removed, allowing the fluid in the micromanometer to return to its zero position. This procedure was repeated for the remaining five probes, ensuring consistent data collection from all six measurement zones.

A Prandtl tube and a differential pressure meter (Testo) were used to measure the total pressure within the channel, on the building facade, and in the inlet openings. For comparison, similar measurements were taken using a Testo 510i differential manometer at all six probe points.

The experiment was conducted at three different flow velocities: $v=12.5$ m/s; $v=15.0$ m/s; $v=18.5$ m/s. Assuming the dynamic pressure is equal to the total pressure, the air velocity in each of the six measured

zones was determined using the Darcy–Weisbach equation:

$$V = \sqrt{\frac{2 \cdot P_{\text{dyn}}}{\gamma_n}}, \quad (3)$$

where:

P_{dyn} – dynamic pressure, Pa; γ_n – volumetric weight of air in the duct, kg/m³.

To extrapolate the experimental results from the model (scale 1:25) to the full-scale building, the Reynolds number similarity criterion was applied:

$$Re = (V \cdot D_{\text{eq}}) / 1.5 \cdot 10^{-5}, \text{ Pa} \quad (4)$$

where:

V – air velocity in the model, m/s;
 D_{eq} – equivalent (hydraulic) diameter of the opening, m;
 $1.5 \cdot 10^{-5}$ – kinematic viscosity of air, m²/s.

From the calculated Reynolds number, the real-scale airflow velocity was determined using the formula:

$$V_{\text{real}} = \frac{Re \cdot v}{D_{\text{real}}}, \quad (5)$$

where:

D_{real} – hydraulic diameter of the actual opening, m;
 v – kinematic viscosity of air, m²/s.

This methodology ensures the accurate scaling of model test results to real-world applications, providing a reliable basis for assessing the performance of passive ventilation systems under wind-induced conditions.

As shown in Figure 3, at an incoming flow velocity of $V = 12.5$ m/s, the air velocity at the supply grilles within the room reached 1.26 m/s. This ensured air movement within the occupied zone of the space in the range of approximately 0.09 to 0.13 m/s.

As illustrated in Figure 4, at an incoming airflow velocity of $V = 15.0$ m/s, the air movement within the occupied zone of the room was observed to be within the range of 0.14 to 0.15 m/s. Under these conditions, the air velocity at the supply grilles inside the room reached 1.6 m/s.

As shown in Figure 5, at an incoming airflow velocity of 18.5 m/s, the air velocity across all six zones ranged between 0.17 and 0.18 m/s. This indicates improved airflow balance throughout the space and reduced presence of stagnant zones (Table 2).

An increase in inlet airflow velocity is accompanied by a corresponding increase in exhaust velocity, which confirms the proper functioning of the system and its capability to sustain air exchange without mechanical assistance (such as fans).

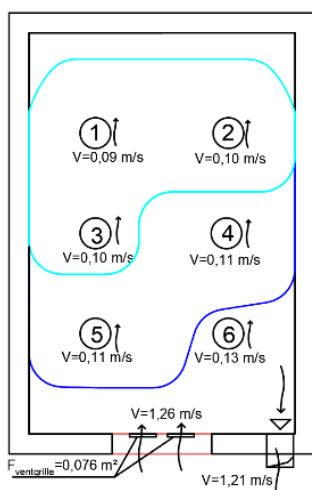


Figure 3. Velocity distribution profiles within the occupied zone of the investigated room at an external airflow velocity of $V = 12.5$ m/s.

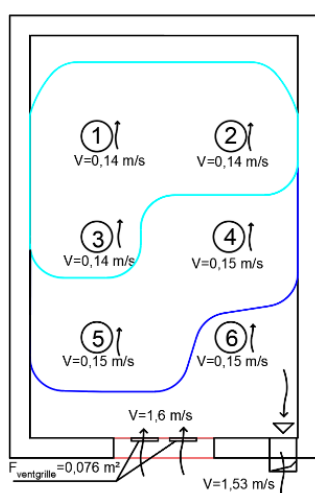


Figure 4. Velocity distribution profiles within the occupied zone of the investigated room at an external airflow velocity of $V = 15$ m/s.

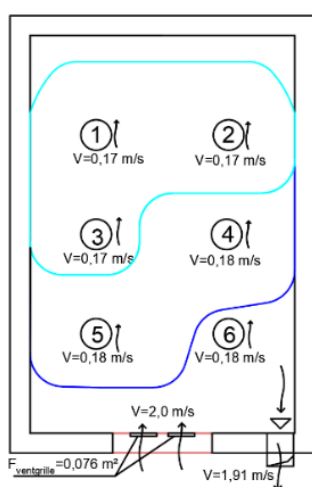


Figure 5. Velocity distribution profiles within the occupied zone of the investigated room at an external airflow velocity of $V = 18.5$ m/s.

Table 2. Airflow velocity distribution analysis.

Parameter	Fig. 3	Fig. 4	Fig. 5
Wind speed on the façade, m/s	12.5	15	18.5
Air speed at the entrance to the room, m/s	1.26	1.6	2.0
Air speed at the hood, m/s	1.21	1.53	1.91
Air speed at the control points, m/s	0.09-0.13	0.14-0.15	0.17-0.18

As the area of the ventilation grille (0.076 m^2) remains constant throughout the experiment, the observed increase in airflow velocity can be attributed solely to the rise in dynamic wind pressure, rather than to any changes in the cross-sectional area of the airflow path.

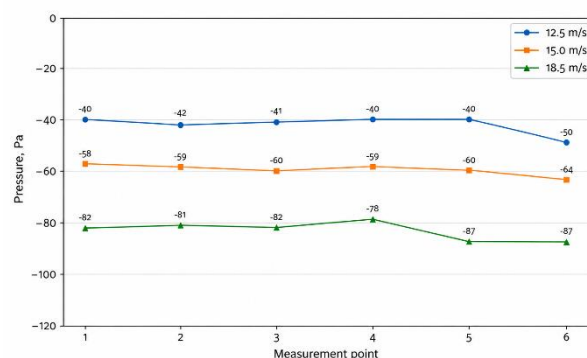


Figure 6. Pressure distribution at six indoor measurement points under different external wind velocities.

Figure 6 presents the static pressure distribution at six indoor measurement points for external wind velocities of 12.5, 15.0, and 18.5 m/s. Negative pressure values were recorded at all measurement locations, with pressure becoming generally more negative as external wind velocity increased. The broadly similar spatial distribution across the three conditions, together with local variations between points, illustrates the response of the indoor pressure field to changing wind loads. These results support the analysis of pressure conditions within the model building; however, additional airflow measurements are required to quantify the corresponding ventilation performance.

The experimental results have potential implications for the preliminary design of wind-driven ventilation systems in residential buildings. The observed increase in inlet and exhaust velocities with increasing external wind velocity indicates that the ventilation response depends on the aerodynamic conditions surrounding the building. For building designers, this highlights the importance of considering the location of ventilation openings in relation to the external airflow and the building geometry. The placement of inlet and exhaust openings should be assessed together, since the ventilation response depends on the pressure conditions acting on the building envelope and the characteristics of the internal airflow path.

The measurements within the occupied zone also demonstrate the importance of evaluating airflow beyond the ventilation openings themselves. Air velocity at the inlet or exhaust does not fully describe the distribution of air within a room. Measurements at multiple locations can provide additional information about internal air movement, although the available ranges in the present study do not allow a detailed point-by-point assessment. For thermally retrofitted buildings, the findings support the need to consider ventilation as an integral part of the building modernization process. Improvements in envelope airtightness may change the role of purpose-provided ventilation openings and the pathways through which air enters and leaves a building. However, the present experiment did not directly compare pre-retrofit and post-retrofit conditions, and therefore does not quantify the effect of thermal modernization itself.

The results may be used as preliminary experimental evidence when considering wind-driven ventilation configurations. They should not be used alone to establish annual ventilation performance, energy savings, indoor air quality compliance, or thermal comfort. These assessments require additional measurements and building-specific calculations under a broader range of environmental conditions.

No artificial intelligence (AI) tools were used during the experimental work, data collection, processing, or analysis of the experimental data presented in this manuscript.

4. LIMITATIONS AND FUTURE WORK

The present study has several limitations that should be considered when interpreting the experimental findings. First, the investigation was conducted using a geometrically scaled residential building model with a scale of 1:25. Although geometric similarity provides a basis for physical modelling, it does not by itself guarantee complete aerodynamic similarity between the model and the full-scale building. The transfer of the measured results to real buildings should therefore be considered with caution.

Second, the experimental programme included three external wind velocities: 12.5, 15.0, and 18.5 m/s. This limited number of conditions does not allow a comprehensive characterization of the system response over a wider range of wind conditions or the establishment of a general relationship between external wind velocity and internal airflow.

Third, the available results for the occupied zone are reported as velocity ranges across six measurement points. Individual numerical values for each point are not available. Consequently, a detailed spatial analysis, including the identification of local maxima and minima and the calculation of point-to-point variability, could not be performed.

Fourth, repeated measurements and the complete primary pressure dataset were not available for the present analysis. Therefore, measurement uncertainty and statistical significance could not be fully evaluated. The reported differences should be interpreted as observed experimental results rather than statistically established effects.

Finally, CFD simulations were not performed for the investigated configuration. The study therefore does not provide a direct numerical validation of the experimental results. In addition, the experiment did not directly assess indoor air quality, annual energy performance, or the effects of thermal retrofitting through a comparison of pre-retrofit and post-retrofit conditions.

Future research should extend the experimental programme to a wider range of wind velocities and wind directions and include repeated measurements to improve the assessment of measurement variability. Recording individual velocity values at all measurement points would enable a more detailed investigation of the airflow distribution within the occupied zone.

Further work should also include measurements of volumetric airflow rates and pressure differences across the ventilation system. These data would support a more comprehensive assessment of ventilation performance. CFD simulations could be conducted for the same geometry and boundary conditions, followed by a comparison with experimental measurements at corresponding locations.

Finally, investigations under combined wind and buoyancy effects, as well as studies involving full-scale or in-situ measurements, would help establish the applicability of the findings to residential buildings under real operating conditions.

5. CONCLUSION

The present study experimentally investigated the response of a wind-driven passive ventilation system under different external wind conditions using a geometrically scaled residential building model in a wind tunnel. The experimental programme considered three external wind velocities of 12.5, 15.0, and 18.5 m/s. The results provide insight into the pressure distribution and airflow behaviour within the model building and demonstrate the potential of wind-driven ventilation for further application in energy-efficient residential buildings.

The main findings can be summarized as follows:

1. The experimental results demonstrated a consistent response of the ventilation system to increasing external wind velocity. The measured airflow velocities at the control points increased with wind speed, indicating that stronger wind conditions can enhance the air movement induced by the investigated passive ventilation

configuration. However, because only three wind velocities were examined, the observed trend should not be interpreted as evidence of a universal linear relationship between external wind velocity and internal airflow.

2. The pressure measurements revealed a clear dependence of the indoor pressure field on external wind conditions. Negative pressure values were recorded at all six indoor measurement points for the three investigated wind velocities. As the external wind velocity increased, the measured pressures generally became more negative. This indicates that the pressure conditions within the model changed systematically with the applied wind load. The observed differences between measurement points also demonstrate that the pressure field was not entirely uniform throughout the model building.

3. The spatial distribution of pressure provides additional information for interpreting the ventilation process. Although the overall pressure response followed a similar pattern under the three tested conditions, local variations were observed between measurement locations. These differences highlight the importance of considering the spatial distribution of pressure when evaluating passive ventilation systems rather than relying exclusively on measurements at a single control point.

4. The experimental approach provides a basis for investigating the aerodynamic behaviour of passive ventilation systems. Wind-tunnel testing using a scaled building model makes it possible to examine the response of a defined building and ventilation configuration under controlled wind conditions. Such experiments can contribute to the assessment of design alternatives and support the identification of configurations requiring more detailed investigation. Nevertheless, the transfer of

the obtained results to full-scale buildings requires consideration of aerodynamic similarity, model-scale effects, and actual operating conditions.

5. The findings support the further investigation of wind-driven passive ventilation in energy-efficient residential buildings. The observed changes in airflow velocity and pressure distribution indicate that external wind conditions are an important factor affecting the operation of the investigated system. This is particularly relevant when considering ventilation strategies for buildings with improved envelope airtightness. However, the present experiment did not directly evaluate indoor air quality, annual energy performance, or the system's operation in pre-retrofit and post-retrofit buildings. Therefore, the practical benefits for thermally modernized buildings require further quantitative assessment.

Overall, this study provides experimental evidence of the relationship between external wind conditions and the pressure and airflow response of the investigated passive ventilation configuration. The results establish a basis for further research combining extended wind-tunnel experiments, detailed airflow measurements, and CFD simulations. Future investigations should include a wider range of wind velocities and directions, repeated measurements, and validation against full-scale or in-situ data. Such work would enable a more comprehensive assessment of the system's performance and its applicability under real residential building conditions.

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