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Examining Wind Flow's Impact on Multi-Storey Buildings: A Quest for Quality Improvement

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Abstract
This scientific article delves into the intricacies of wind flow's impact on multi-storey buildings, presenting results from a series of experimental investigations. The research encompasses an examination of wind interactions with buildings of varying heights and geometric profiles. Furthermore, it unveils the effects of tall structures on the natural ventilation and smoke evacuation systems of shorter edifices, considering different wind flow directions. The study leverages specialized wind tunnel and measurement techniques for a comprehensive analysis of wind-induced loads on buildings. The acquired insights furnish crucial input for the design of single-story temporary modular constructions within densely populated urban areas, subject to wind-induced stresses. Additionally, they hold potential applicability in the advancement of energy-efficient technologies and strategies within the realm of construction. The acquired dataset underscores the criticality of scrutinizing wind flow's impact on structures of varied typologies and dimensions and will allow to significantly improve the quality and efficiency of modern buildings in the future.

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1. Introduction

Presently, particularly in the course of reconstructing the housing sector following the destruction caused by Russia's aggressive war against Ukraine, the scrutiny of wind loads has evolved into an increasingly pivotal undertaking for engineers and architects. Heightened emphasis is placed on contemporary approaches for ascertaining these loads, encompassing both computer modeling and experimental examinations conducted within wind tunnels. Accurate evaluation of the aerodynamic properties of buildings, notably within micro-districts characterized by multi-story edifices, facilitates the implementation of pertinent measures for thermal modernization and the enhancement of the efficacy of heating and natural ventilation systems. This stands as a significant stride towards diminishing energy consumption and augmenting the environmental sustainability of buildings.

Primarily, for a more complete understanding of the interaction between the building and the wind, and to discern the influence of wind forces on their stability and operational performance, it is expedient to undertake research utilizing wind tunnel models. This approach facilitates the precise determination of pressure values exerted on the building's surface at varying wind velocities and in conditions of turbulent airflow (Hubová et al., 2022; Vita, et al., 2020). Research of this nature enables the identification of critical pressure coefficient values, denoting the threshold beyond which wind loads pose a critically perilous risk to the structural integrity of the building (Abdelfatah, et al., 2022). Furthermore, wind tunnel experiments provide a comprehensive understanding of how winds influence the building from diverse directions, with consideration for the correlation between wind speed and flow turbulence, particularly in scenarios involving complete turbulence (Ikegaya et al., 2022; Yuan et al., 2023; Huang et al., 2021). This holds paramount significance in the architectural design of buildings, particularly in the case of high-rise structures (Shen et al., 2023). Another pivotal aspect influencing pressure distribution on the building's surface encompasses the presence of natural obstructions, the geometric dimensions of the building, and the reciprocal influence of neighboring structures. A body of scientific literature presents findings from wind tunnel studies regarding the impact of pre-existing obstacles, be they other buildings or natural topographical features, on the stability and functionality of the building (Jóźwiak et al., 1995; Chauhan et al., 2022; Y. Zheng et al., 2011). It has been ascertained that these pre-existing external factors hold the potential to substantially alter the direction and magnitude of wind-induced pressure. Furthermore, differing geometric dimensions and their relative positioning can engender intricate aerodynamic circumstances, the intricacy of which is contingent upon the concentration of buildings in proximity (Kim et al., 2017; Quan Yong et al., 2010). Such interplay among structures contributes to the configuration of pressure distribution and concomitant aerodynamic phenomena within a particular building (Nagar et al., 2022; Fontes-Silva. et al., 2022).

The application of computer modeling presents itself as a more cost-effective approach for investigating aerodynamic phenomena pertaining to airflow around buildings. This mode of simulating building aerodynamics, inclusive of the evaluation of natural and hybrid ventilation, stands as a pivotal component in the examination of wind pressure effects (Tominaga et al., 2016; Zhai et al., 2011; Chu, 2023; Van Hooff et al., 2017; Zhang et al., 2023; Perén et al., 2015; Shirzadi et al., 2018; Myroniuk et al., 2023; Hirose et al., 2022; Voznyak et al., 2022).

A crucial facet of this process involves the anticipation of the aerodynamic coefficient, serving as an indicator of the extent to which wind exerts influence on the building. This insight enables an understanding of potential aerodynamic phenomena that may transpire (Huang et al., 2022). Particular emphasis should be placed on the outcomes of aerodynamic investigations employing computer modeling, specifically in evaluating the influence of wind on high-rise edifices, buildings of diverse architectural configurations, and those with varying degrees of infiltration (Giachetti et al., 2022; Li et al., 2023; Feng et al., 2019; Elshaer et al., 2016). In the realm of computer modeling, the interplay between buildings assumes a significant role, given that their arrangement and configuration can alter the aerodynamic circumstances in densely populated urban areas. Additionally, evaluating the impact of external elements such as terrain and natural features holds import, as they can markedly influence and configure the wind patterns around the building (Chen et al., 2023; Blocken, 2018; Zhang et al., 2023; Hirose et al., 2022). This methodology, focusing on the evaluation of external factors' influence on aerodynamic phenomena, enables the modeling of urban microclimates at a pedestrian scale. It further allows for estimations of the maximum allowable concentrations of harmful substances in residential areas (Potsis et al., 2023; Vita, et al., 2020). This holds significant importance in the orchestration of both natural and urban ventilation. While computer modeling stands as a potent instrument for investigating external aerodynamics, it may not invariably account for every facet of the authentic natural environment. Consequently, a pivotal aspect in aerodynamic research continues to be the juxtaposition of outcomes derived from computer modeling with those obtained through wind tunnel experiments (Gaur et al., 2021).

In this context, wind tunnel research assumes paramount significance, as it establishes conditions closely mirroring real-world scenarios. Such studies serve to enhance the precision of modeling and validate the findings derived from computer-based methodologies (Zhao et al., 2023). Furthermore, they afford avenues for testing and refining widely employed modeling techniques. They offer a platform for scrutinizing results garnered from computer-based analyses against those derived from actual measurements, thereby discerning potential disparities (Li et al., 2020; Chu, 2023; Gough et al., 2018). This approach engenders greater dependability in ascertaining the impact of wind flow on buildings. To conduct an exhaustive and precise analysis of the nuanced aerodynamic interplay between the building and its surroundings, the field study method remains pertinent. This approach facilitates the comprehensive consideration of all factors that may influence the building's behavior and the functioning of internal engineering systems under the sway of wind flow. This encompasses local topographical idiosyncrasies, the placement and configuration of adjacent structures, as well as meteorological conditions (Tong et al., 2016; Gough et al., 2018).

A crucial aspect of contemporary construction lies in comprehending the impact of wind flow on cross-ventilation and natural ventilation. This facet is assuming escalating importance in the realm of energy-efficient and sustainable housing quality (Tong et al., 2017). Contemporary scientific endeavors in the domain of building aerodynamics underscore the imperative of harnessing wind as a force to facilitate natural air exchange within rooms. A substantial body of scholarly work is dedicated to identifying and modeling this phenomenon, aimed at refining the operation of ventilation systems and augmenting their efficacy (Jiang et al., 2023; Carrilho da Graça et al., 2016; Zhong et al., 2022).

Hence, the advancement of energy-efficient solutions, along with the implementation of systems for their control—particularly in the integration of heat recovery apparatus within natural ventilation systems—becomes an imperative within the evolving landscape of escalating demands for energy efficiency and environmental preservation (Litovko et al., 2021; Chen et al., 2019). Particularly in megacities, where dense urban construction, cityscape, and climatic factors can exert substantial influence on the performance of ventilation systems (Chen et al., 2017; Chu, 2023; Tong et al., 2016; Ikegaya et al., 2018).

Thus, the examination of wind's impact on natural ventilation and its effects on exhaust and smoke ducts assumes paramount significance in the realm of sustainable construction and energy conservation for future urban developments. Consequently, this study presents the findings of scientifically conducted experimental research within a wind tunnel setting. Its focus is dedicated to discerning the influence of wind patterns on the functionality of natural ventilation systems within multi-story edifices. This request remains extremely relevant, especially in the context of densely populated high-rise buildings, and becomes particularly important in the planning of temporary modular communities, such as structures on construction sites as offices, canteens and working spaces for staff, temporary retail spaces or service points during fairs or special events, temporary medical centers or dispensaries in regions where additional medical infrastructure is needed, facilities for organizing temporary educational events, workshops or trainings. Most crucially, in emergency scenarios such as natural disasters or evacuations, modular buildings assume the pivotal function of providing temporary housing for individuals temporarily displaced from their original places of residence.

An essential aspect pertains to the evaluation of optimal sites for temporary structures comprising modular buildings. These constructions primarily cater to temporarily resettled individuals and are predominantly characterized by single-story configurations and straightforward modular architectural designs.

In the current context of full-scale conflict in Ukraine, the establishment of modular towns takes precedence, often integrated into pre-existing microdistricts characterized by well-established infrastructure and high-density multi-story urban structures. Consequently, it becomes imperative to meticulously evaluate the efficacy of microclimate management systems within modular constructions. This includes a specific focus on natural ventilation systems and gravity-driven smoke removal systems. Notably, the substantial influence of high-rise edifices on the functionality of these systems, particularly under the influence of varying wind pressures and directional shifts, demands careful consideration.

This scientific work primarily focuses on the determination of aerodynamic coefficients distributed across the entire roof surface of residential sectors. The research was conducted through comprehensive experimental studies employing a model of a commercial and residential complex within a wind tunnel. The results provide valuable insights for enhancing the understanding of aerodynamic interactions in complex urban environments. This study delves into the intricate interplay of wind flow patterns between high-rise and low-rise buildings, particularly focusing on the distribution of pressure coefficients on the roof surface of the latter. The presence of high-rise structures significantly alters the airflow dynamics over low-rise counterparts, inducing reverse turbulent flows that impede the natural movement of air. This phenomenon restricts the operational efficacy of ventilation channels within the natural ventilation system, rendering them nonfunctional in specific wind directions. Through meticulous wind tunnel experiments, regions marked by excess static pressure and areas of rarefaction have been delineated, providing valuable insights into the aerodynamic behavior of such configurations.

2. Experimental

The pivotal determinant in the design of a natural exhaust ventilation system and a smoke extraction system lies in the accurate computation of the cross-sectional area and height of the exhaust duct. The channel's cross-section is contingent upon the mandated air exchange rate, while its height is contingent upon factors such as the roof configuration, the placement of the channel atop the residence, and the existence of a wind support zone surrounding the dwelling.

The wind support zone refers to the area delineated by the roof and any protruding structures above it, bounded by an imaginary plane inclined at an angle of 45 degrees to the horizontal axis extending from the uppermost point of the projecting structure. Figure 1 illustrates different approaches for ventilating exhaust ducts on the house roof contingent upon the wind support zone.

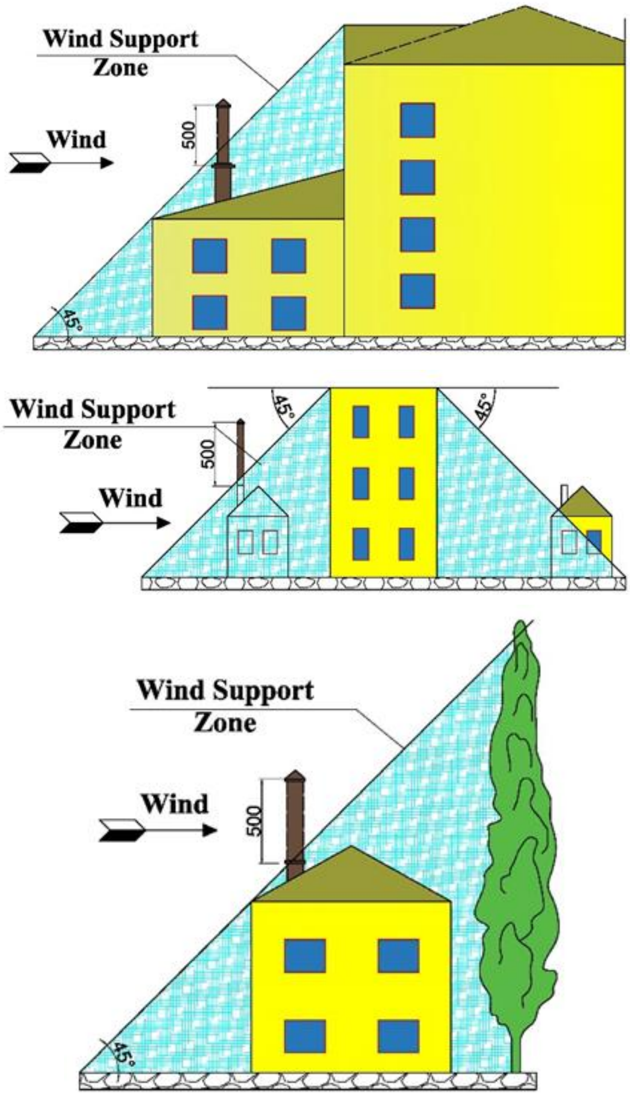


Fig. 1. Identification of the wind support zone in the context of air stream dynamics around a residential structure

The physical emulation of wind-induced loads on residential structures entails the examination of house models within a wind tunnel. A wind tunnel is a specialized facility engineered to replicate the impact of wind forces on building edifices. Within the operative segment of the tunnel, an airflow with predetermined attributes is generated, accommodating the installation of the subject model. Empirical techniques for simulating the aerodynamic behavior of structures through wind tunnel experimentation have been frequently employed. Nonetheless, the synthesis of this data proves challenging, given the diverse configurations and spatial placements of buildings within residential areas.

In the computation of wind-induced loads on a structure, as well as in the determination of pressures at specific locations on its external facade, the aerodynamic coefficient "c" is used. This coefficient delineates the relationship between the surplus static pressure at a designated point on the building's outer surface and the dynamic wind pressure.

$$\pm c = \frac{P}{\frac{\rho \cdot v^2}{2}} \tag{1}$$

Aerodynamic coefficients are typically ascertained through experimental procedures conducted in wind tunnels, utilizing scale models of buildings. The magnitude and sign of the aerodynamic coefficient are contingent upon factors including the specific location of the point on the building's surface, the building's geometrical configuration, and the direction of the prevailing wind. Furthermore, the value of this coefficient is subject to alteration due to the presence of adjacent buildings and structures, as well as the topographical characteristics of the surrounding area. The energetics inherent to the aerodynamic coefficient lies in its capacity to denote, in fractional units, the proportion of the flow's specific kinetic energy transmuted into specific potential energy. The aerodynamic coefficient's value can be delineated in terms of flow velocities proximate to discrete points in the vicinity of the building, employing the Bernoulli equation. In the case of a cuboid-shaped building, the aerodynamic coefficient manifests the subsequent values: on the windward side facade, $c_w=0.6...0.8$, and on the leeward side facade, $c_l=-0.2...-0.3$.

The aerodynamic coefficient's value is contingent upon the aperture of windows within the edifice and the orchestration of cross-ventilation, characterized by aeration induced by the influence of wind.

Experimental investigations were carried out within an open-section wind tunnel at Lviv Polytechnic National University.

A fundamental prerequisite for achieving congruence in aerodynamic processes between the natural environment and the model lies in geometric similarity. This condition dictates that the dimensions of the actual building and the scale model maintain a consistent linear scale (Zhao et al., 2023).

Given the actual dimensions of the residential complex and the specific configuration of the wind tunnel's working section (with a diameter of 1.0 meter), it was imperative that the maximum area of the model fell within the range of 5-15% of the cross-sectional area of the wind tunnel's working section. Consequently, a meticulously scaled model of the residential complex was fashioned at a 1:250 ratio. In our particular instance, contingent upon the angle of attack, the model's cross-sectional area represented 13% of the working section's pipe area.

Throughout the course of the experimental investigation, the building model was positioned within the operational domain of the wind tunnel. Employing a specialized measuring apparatus, all requisite parameters were ascertained to establish the existence of a wind support zone and assess the potential occurrence of backdraft within the natural exhaust ventilation systems of the residential sector of the specified complex (Fig. 2).

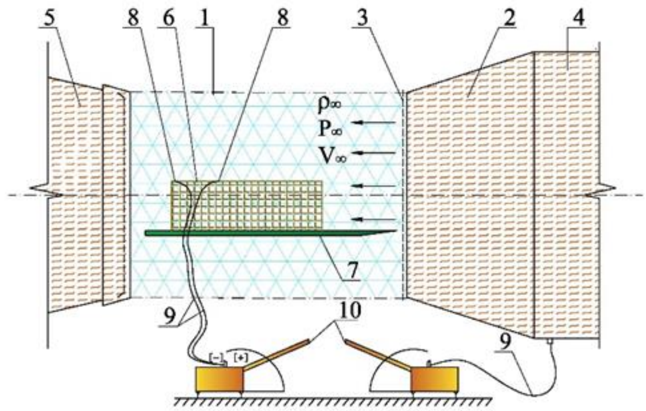


Fig. 2. Scheme of the Experimental Setup for Investigating the Commercial and Residential Complex. 1 – working section of the wind tunnel, 2 – nozzle, 3 – leveling grid, 4 – pre-chamber, 5 – diffuser, 6 – model of a commercial and residential complex, 7 – lower surface of the model, 8 – static pressure sampling points, 9 – flexible tubes, 10 – micro-manometer mmn

The subsequent control and measurement instruments were employed to assess physical parameters throughout the experimental research:

- Micromanometer MMN-2400(5)-1.0, Serial Numbers 2000 and 2220, exhibiting an accuracy level of ±0.5 mm.
- Pitot-Prandtl Tube, designated as No. 77, is characterized by a sensitivity angle of ±5o and a local resistance coefficient of ζ=0.983.
- BAMM-1 Aneroid Barometer, Serial Number 8795, with a measurement range spanning from 80000 to 106000 Pa, and a precision of ±200 Pa.
- Thermal Anemometer ATT-1004, featuring a measurement range for air flow velocity of 0.5-20 m/s, with an accuracy of ±(0.2+0.05V) m/s, and a measurement range for air temperature of 0-50 °C.

The study was conducted at three distinct air flow velocities within a range $V_\infty = 13-20\ m/s$ that corresponds to $Re = 2 \cdot 10^5 - 3 \cdot 10^5$ varying angles of wind incidence upon the house model (Fig. 3).

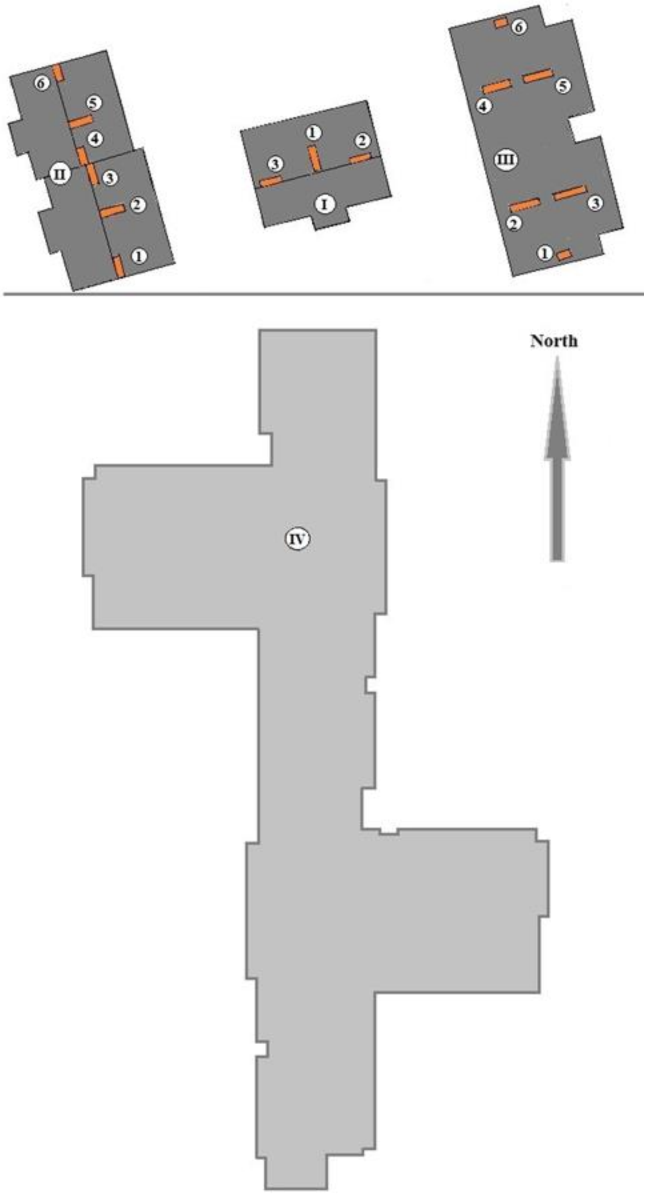


Fig. 3. Layout of the studied buildings: I, II, III - modular buildings that can be affected by the residential and commercial complex IV

The velocity of the undisturbed air flow V_∞ within the working section of the pipe was determined based on the micromanometer readings, following this formula:

$$V_\infty = \varepsilon \cdot \mu \cdot \sqrt{\frac{2 \cdot \Delta h \cdot K \cdot n}{\rho}} \qquad (2)$$

Here,
ε - denotes the field coefficient of the tube,
μ - represents the consumption coefficient,
Δh - stands for the disparity in micromanometer readings
K signifies the slope coefficient of the micromanometer tube,
n - embodies the coefficient of the pneumatic tube,

ρ_∞ denotes air flow density, ascertained through the formula.

$$\rho_\infty = \rho_{st.c} \cdot \frac{P_b}{P_{st.c}} \cdot \frac{T_{st.c}}{T_\infty} \qquad (3)$$

Here,

$\rho_{st.c.}$ denotes the air flow density under standard conditions

P_b represents the barometric pressure measured by an aneroid barometer,

$P_{st.c.}$ signifies the pressure under standard conditions,

T_∞ stands for the air flow temperature in the working section of the wind tunnel, and $T_{st.c.}$ embodies the air temperature under standard conditions, expressed in Kelvins (K).

3. Results and discussion

A photo of a geometrically similar model is shown in Fig. 4.

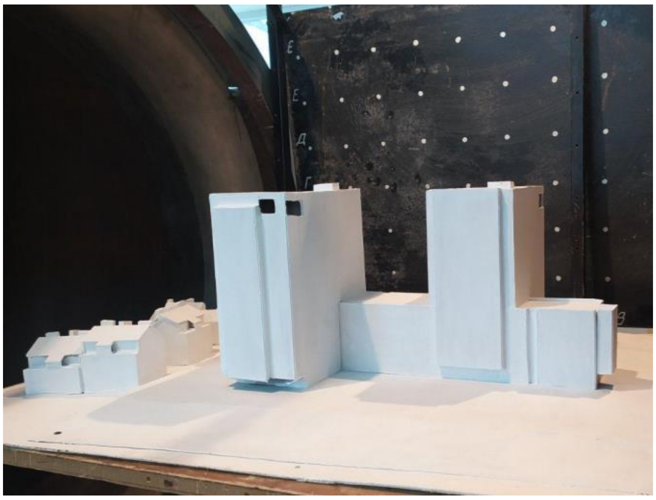


Fig.4. Representation of a Geometrically Equivalent Model of a Commercial and Residential Complex

The findings from the experimental investigations of the commercial and residential complex at various angles of the air flow are presented in Fig. 5, 6, and 7. In order to maintain the same drawing scale, different reference points were adopted.

Section #1

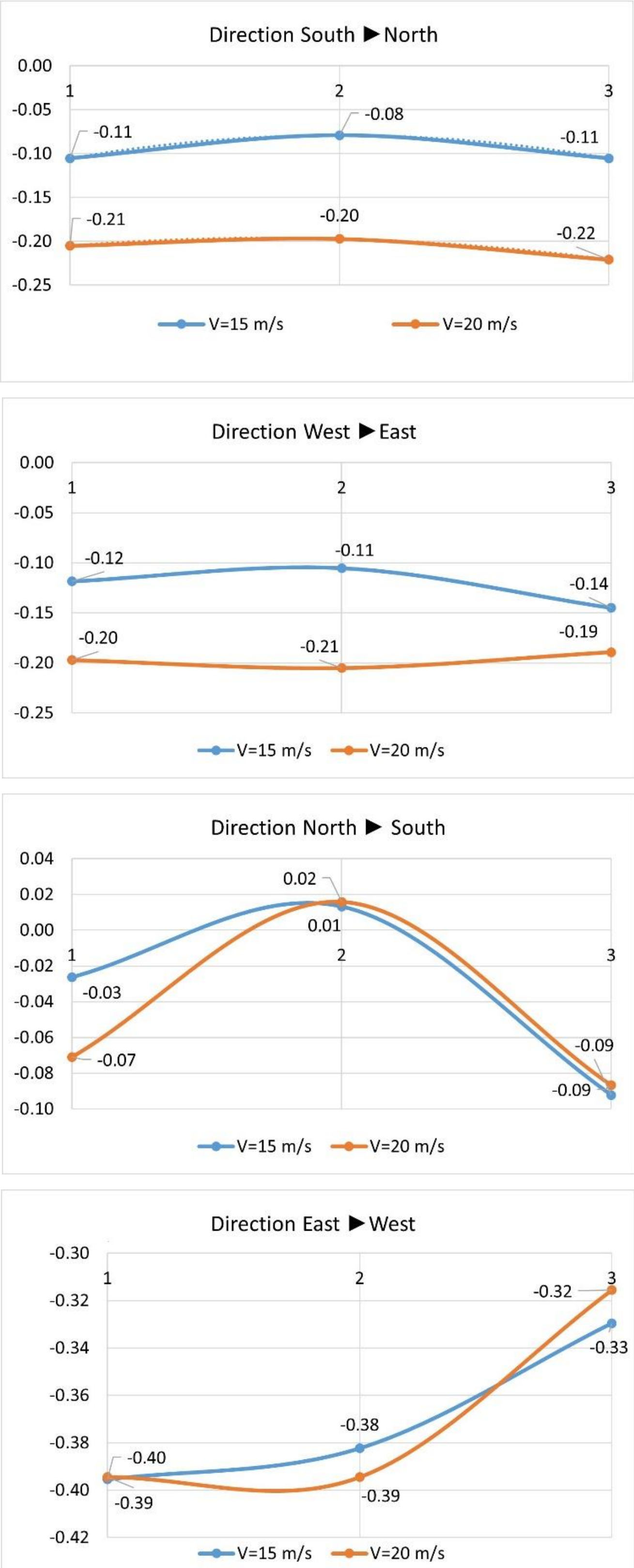
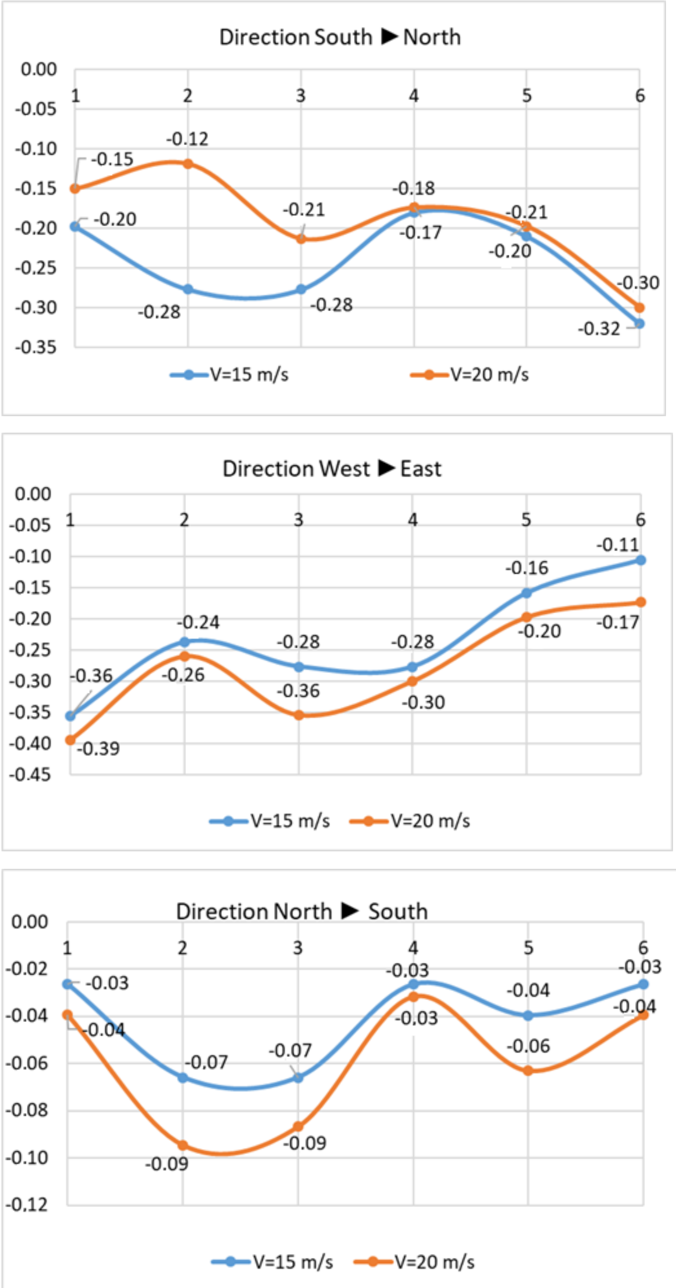
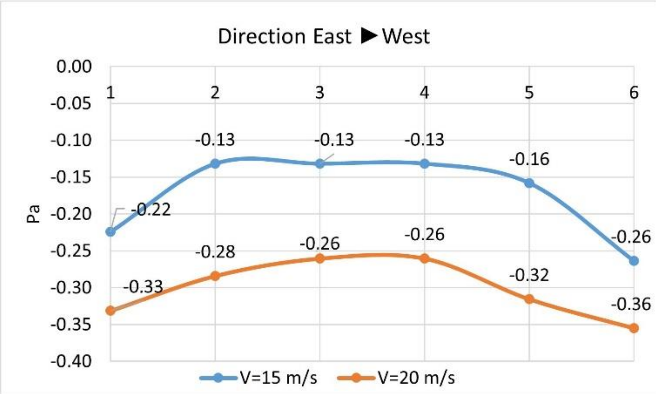


Fig. 5. Results of experimental studies for section #1.

As depicted in Fig. 5, for section #1, the wind direction North – South is unfavorable, as a positive pressure coefficient of +0.02 was recorded at a wind speed of 20 m/s on ventilation channel #2. For the rest of the ventilation channels, at different wind directions and speeds from 15 to 20 m/s, negative pressure coefficients are observed, namely in the range from -0.12 to -0.40.

Section #2





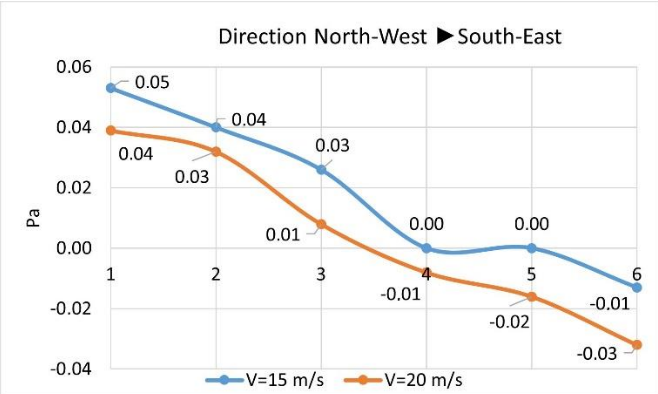
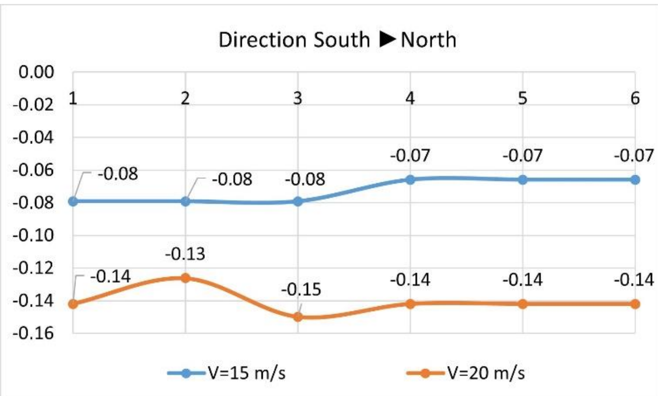
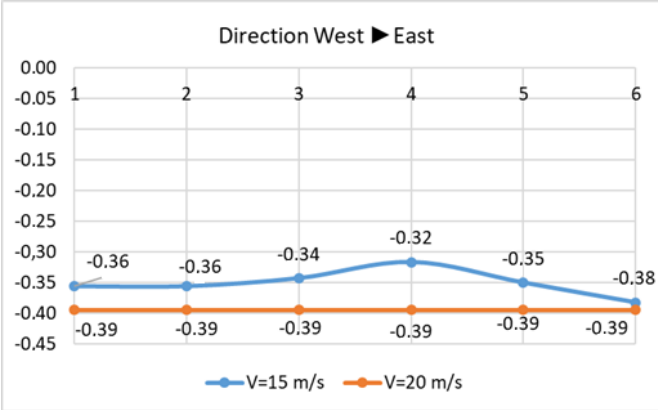


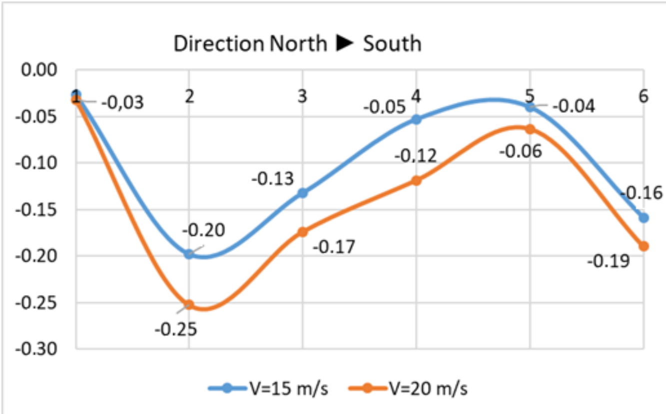
Fig. 6. Results of experimental studies for section #2

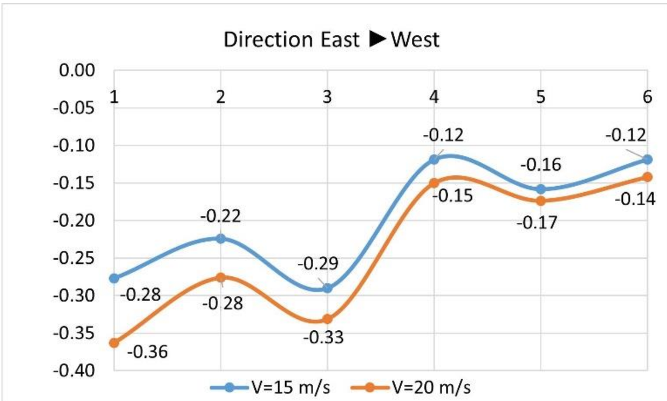
As illustrated in Figure 6, for section #2, the wind direction is unfavorable from the Northwest to the Southeast, as positive pressure coefficients were recorded for ventilation channels #1, 2, 3, 4, and 5, which range from 0 to +0.05 at a wind speed of 20 m/s. At a wind speed of 15 m/s, positive pressure coefficients are observed for channels #1, 2, 3 and are at range from +0.01 to +0.04. For all other wind directions and speeds from 15 to 20 m/s, negative pressure coefficients are observed, namely in the range from -0.01 to -0.39 for ventilation channels #1,2,3,4,5,6.

Section #3









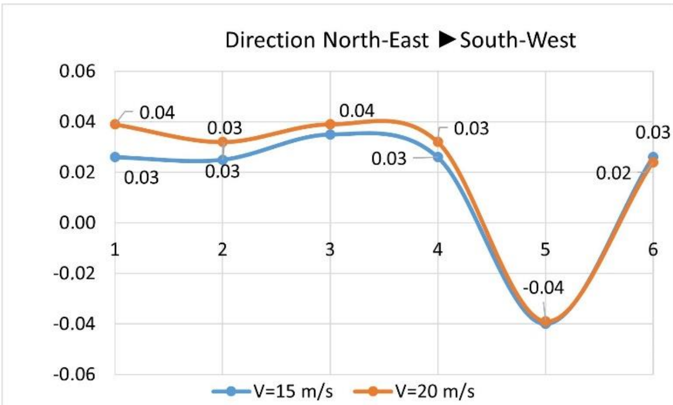


Fig. 7. Results of experimental studies for section #3

As demonstrated in Fig. 7, for section #3, the wind direction is unfavorable from the Northeast to the Southwest, as positive pressure coefficients were recorded for ventilation channels # 1, 2, 3, 4, and 6, which range from 0.02 to +0.04 at a wind speed of 20 m/s. At a wind speed of 15 m/s, positive pressure coefficients are observed for channels # 1, 2, 3, 4, 6 and are at range from +0.02 to +0.03. For all other wind directions and speeds from 15 to 20 m/s, negative pressure coefficients are observed, namely in the range from -0.03 to -0.39 for ventilation channels #1, 2, 3, 4, 5, 6.

The allocation of aerodynamic coefficients across the roof surface of the residential sectors was determined through experimental investigations conducted on the model of the commercial and residential complex within the wind tunnel. Regions characterized by surplus static pressure as well as areas of rarefaction have been delineated.

Within the realm influenced by excessive static pressures, where aerodynamic coefficients exceed zero, adverse conditions emerge for the functionality of both natural exhaust ventilation and the smoke evacuation system. Under such circumstances, there exists a risk of backdraft occurring within both ventilation and smoke channels.

However, it should be noted that within the scope of the conducted experiment, an analysis of other parameters, such as ambient temperature or atmospheric pressure, was not carried out. It is essential to acknowledge that these mentioned parameters may undergo variations during different times of the day and seasons. The experiment was designed and conducted in a stationary mode, involving the fixation and analysis of specific conditions during its implementation. Consideration of the influence of temperature and atmospheric changes may necessitate additional investigations, as these factors can impact the results of the experiment in diverse contexts.

4. Summary and conclusion

Summarizing the obtained research results for three different sections, it can be determined that the negative impact of wind on ventilation ducts is specific depending on their location.

In Section #1, a north-to-south wind direction proves particularly disadvantageous, notably impacting ventilation channel #2, as evidenced by a recorded positive pressure coefficient of +0.02. Within Section #2, an unfavorable impact is discerned in the scenario of wind flowing from the Northwest to the Southeast, affecting ventilation channels # 1, 2, 3, 4, and 5, with pressure coefficients ranging from 0 to +0.05 at a wind speed of 20 m/s. However, at a wind speed of 15 m/s, positive pressure coefficients are observed for channels # 1, 2, and 3, varying from +0.01 to +0.04. In Section #3, characterized by a wind direction from Northeast to Southwest, positive pressure coefficients are recorded for ventilation channels #1, 2, 3, 4, and 6, spanning from 0.02 to +0.04 at a wind speed of 20 m/s. At a wind speed of 15 m/s, positive pressure coefficients are observed for channels #1, 2, 3, 4, and 6, ranging from +0.02 to +0.03. With the exclusion of these specified wind directions, negative pressure coefficients ranging from -0.01 to -0.40 were identified in all other instances, across various wind speeds from 15 to 20 m/s for all ventilation channels.

This study highlights the adverse conditions faced by natural exhaust ventilation and smoke removal systems in areas subject to excessive static pressure, resulting in aerodynamic coefficients surpassing zero. Such circumstances pose a potential risk of backdraft occurring in both ventilation and smoke ducts. Consequently, this research emphasizes the need to scrutinize the functionality of ventilation systems in low-rise buildings and evaluate the efficiency of the smoke removal system, taking into consideration the detrimental effects of wind pressure on their operation. Therefore, based on the analysis of the obtained results of experimental studies, the following configurations of ventilation systems were proposed for use in modular houses in this case:

1. Mechanical exhaust ventilation with natural inflow, which is a meticulously designed system engineered to maintain superior indoor air quality while concurrently ensuring energy efficiency. It relies on a strategically positioned fan to expel contaminated air from the room, fostering an environment conducive to the unhindered ingress of fresh air. Importantly, this innovative ventilation approach obviates the necessity for mechanical supply systems, representing an impactful advancement in sustainable building practices. By meticulously orchestrating airflow dynamics, this system stands as an efficacious solution for enhancing indoor environmental conditions and curbing energy consumption.

Mechanical exhaust ventilation with natural inflow encompasses distinctive attributes that distinguish it as an advanced ventilation system. Central to its operation is an exhaust fan, meticulously engineered to extract contaminated air from the room. This action induces a controlled vacuum effect, facilitating the inflow of fresh outdoor air through designated air intake apparatus integrated within the building's outer envelope. Concurrently, the system enables the ingress of supply air through purpose-built ventilation apertures, windows, or other compatible devices, all without reliance on external mechanical supply mechanisms. This dual functionality underscores the system's efficacy in optimizing indoor air quality and energy conservation. This type of ventilation can be quite effective in providing the necessary air circulation in the premises and reducing energy consumption compared to fully mechanical ventilation systems.

2. Mechanical tidal ventilation with natural exhaust represents a ventilation system characterized by the coordinated operation of fans for the introduction of fresh outdoor air and a natural exhaust mechanism for the expulsion of contaminated air. By synergizing these dual functions, this system achieves optimal air exchange, thereby preserving the requisite microclimatic conditions within the enclosed spaces. This approach stands as a pivotal strategy in safeguarding indoor air quality and sustaining an environment conducive to occupant well-being.

Mechanical tidal ventilation with natural exhaust is distinguished by the integration of purpose-built mechanical tidal systems to facilitate the influx of fresh tidal air. Concurrently, a natural exhaust mechanism, employing gravitational principles, expels contaminated air through strategically positioned exhaust vents or ducts located at the uppermost section of the room. This system proves highly effective in upholding indoor air quality and establishing an environment conducive to optimal living and working conditions.

3. Mechanical supply and exhaust ventilation represents a ventilation system employing fans to facilitate the introduction of fresh external supply air into the room, while concurrently expelling exhaust air from it. This approach ensures a harmonized air exchange within the room, contributing to the preservation of essential microclimate parameters.

The fundamental characteristics of mechanical supply-exhaust ventilation encompass the utilization of fans to facilitate the ingress of fresh air into the designated space through designated supply vents or systems. Concurrently, it orchestrates the expulsion of stale air via dedicated exhaust vents or ducts. This system exhibits adaptability for automation and regulation, thereby enabling precise control over air exchange rates. This control ensures alignment with established sanitary and hygienic standards governing the microclimate parameters within the room, as well as accommodating its specific operational exigencies.

4. The decentralized mechanical ventilation system constitutes a configuration wherein each discrete room or designated zone is endowed with its autonomous fan apparatus for the facilitation of fresh air intake and the expulsion of used air. Within this system framework, each fan operates autonomously and is amenable to individualized regulation. This decentralized paradigm affords the capability for singularized control over air exchange rates within specific rooms or delineated zones.

The principal attributes of the decentralized mechanical ventilation system encompass the incorporation of discrete fans allocated to each room, the capacity to fine-tune air inflow and extraction within distinct zones, along with the autonomous controllability of the system for each room. This system variant finds particular applicability in scenarios necessitating differential air exchange levels across various sectors of the edifice or where disparate air quality standards pertain to distinct chambers. Decentralized mechanical ventilation systems have the potential to engender the requisite milieu for diminishing energy consumption, particularly when outfitted with high-efficiency ventilation units and heat recovery apparatus for exhaust air.

The experimental outcomes lay the foundation for enhancing design and construction methodologies, particularly focusing on optimizing natural ventilation and smoke extraction systems in low-rise buildings situated in densely populated urban areas. This leads to a substantial enhancement in the quality and efficiency of modern building design.

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