

Romana ANTCZAK-JARZĄBSKA¹

ARCHITECTURAL GUIDELINES FOR STRENGTHENING STACK VENTILATION: PERFORMANCE INSIGHTS FROM URBAN HOUSING

Natural ventilation (NV) is a key energy-efficient strategy for improving indoor air quality and thermal comfort in residential buildings. In cold climates such as Poland, the dominant form of NV is stack (chimney) ventilation, whose effectiveness depends on temperature differences and wind conditions. The aim of this study was to evaluate the impact of different chimney configurations on air change intensity (ACH) in a real residential building in Gdańsk.

During a four-month measurement campaign, three solutions were compared: a traditional brick chimney (Type I), a solar chimney with a glazed extension (Type II), and a chimney equipped with a rotary cap (Type III). Results showed that, compared to the baseline configuration, the solar chimney increased the ACH by an average of 14% under favorable solar conditions, while the rotary cap improved ACH by up to 35% in moderate wind conditions.

The study confirms that even small passive modifications to chimneys can significantly enhance the stability and efficiency of stack ventilation. The findings provide practical design guidance for architects and urban planners, especially in the context of retrofitting existing buildings and designing new urban developments tailored to local climate conditions.

Keywords: stack ventilation, air change rate (ACH), solar chimney, chimney cap, urban housing

1. INTRODUCTION

Natural ventilation (NV) is a cost-effective and sustainable strategy for providing fresh air in residential buildings, contributing to thermal comfort, indoor air quality, and overall occupant well-being [Krishan 2001; Clarke 2001; Antczak-Jarząbska, Niedostatkiewicz 2017]. In urban environments, NV shapes the local microclimate and supports air circulation, enhancing comfort in densely built areas while improving environmental quality [Krishan 2001].

¹ WSB Merito University in Gdańsk, Faculty of Computer Science and New Technologies. ORCID: 0000-0002-6853-2041.

In cold climates, stack ventilation – driven by buoyancy (stack effect) and wind – is the most common form of NV [LBNL 2007]. While effective under favorable conditions, its performance can be variable due to fluctuating wind and temperature differences [PN-B-03430:1983/Az3:2000; Antczak-Jarząbska, Niedostatkiewicz 2017]. Chimneys, as core elements of stack ventilation, play a dual role: they ensure proper airflow while influencing building aesthetics and the urban roofscape [Antczak-Jarząbska, Krzaczek 2016].

Design variations, including traditional brick chimneys, solar chimneys, or chimneys with rotary caps, can significantly impact ventilation efficiency. Quantifying these effects using the air change rate (ACH) allows for a measurable evaluation of airflow performance, providing actionable insights for architects seeking to balance functionality, comfort, and urban integration.

This study focuses on a residential building in Gdańsk, Poland, comparing three chimney configurations. Using ACH as a key metric, it evaluates how geometric and material differences influence airflow intensity and natural ventilation performance. The findings aim to inform design strategies for sustainable, comfortable, and visually integrated urban housing.

While previous Polish research on natural ventilation has largely emphasized airtightness and heat recovery [Nantka 2005], the influence of chimney design on stack ventilation efficiency in urban contexts remains underexplored. Recent studies highlight that modifications in building envelope and fenestration can improve indoor air quality and thermal comfort in multi-family buildings [Kwiatkowski et al. 2014], while integrating natural ventilation with passive strategies – such as solar chimneys – can reduce energy demand [Wójcik 2012].

By systematically assessing different chimney designs with ACH measurements, this study provides evidence-based guidance for architects and designers, supporting best practices in the planning of naturally ventilated urban residences under Polish climatic and architectural conditions. The importance of energy efficiency and passive design strategies has also been discussed in recent studies on the Polish residential building stock [Attia et al. 2022].

2. QUALITY OF STACK VENTILATION

The effectiveness of stack ventilation systems in residential buildings is commonly assessed using the air change rate (ACH) as the primary performance indicator. The ACH quantifies the frequency with which the total volume of indoor air is replaced by fresh outdoor air within a given time period. It serves as a crucial parameter for evaluating indoor air quality and ensuring compliance with ventilation standards in habitable spaces [Nantka 2005].

The stack ventilation rate, $ACH(t)$ (h⁻¹), according to the governing equation, depends on the airflow volume $V(t)$ (m³/s), the room cubature VR (m³), and the dynamic

interaction of flow and pressure conditions within the system. Specifically, ACH is influenced by the instantaneous airflow leaving the ventilation system, the geometrical characteristics of the ventilated space, and the physical properties of the chimney configuration, including height, cross-sectional area, and surface roughness. The air change rate at a given moment t is calculated using the following equation (1):

$$\text{ACH (t)} = \frac{\dot{V}(t) \cdot 3600}{V_R} \quad (1)$$

This formulation enables real-time or average assessment of ventilation performance, which is particularly valuable when testing different chimney configurations in full-scale or simulation-based studies. In naturally ventilated buildings, where airflow is influenced by fluctuating environmental conditions, this parameter allows for objective evaluation of system responsiveness and effectiveness in maintaining indoor air quality.

3. MATERIALS AND METHODS

In order to determine the influence of passive energy systems on the efficiency of stack ventilation, a series of in situ experiments were conducted in a representative residential building located in Gdańsk, Poland. The measurements spanned four months, from August to November, thereby covering both summer and early autumn climatic conditions typical of northern Poland.

The experimental object was a single-family residential building, chosen as representative of post-war Polish urban housing stock. A dedicated test room was designated within the building, equipped with a controlled air inlet and connected to a vertical ventilation duct (chimney). This configuration isolated the internal airflow from other building influences and ensured that the results reflected primarily the impact of external climatic factors. Such a controlled approach is particularly relevant, as studies focusing on chimney-induced ventilation efficiency in Polish urban residential buildings remain limited, despite the system's widespread use in traditional housing.

To monitor the environmental boundary conditions, a microclimatic weather station was installed in the immediate vicinity of the building. It continuously recorded outdoor temperature, wind speed and direction, solar radiation, and atmospheric pressure – factors known to influence the performance of natural ventilation systems driven by buoyancy [Wójcik 2012; Zhai, Previtali 2010].

The central objective of the study was to measure and compare the air change rate (ACH) achieved under different chimney modifications designed to enhance stack-induced airflow. Three test configurations were implemented, each representing a distinct passive strategy relevant to contemporary architectural design (fig. 1 schematic representations of the three chimney types):

- TYPE I – Traditional Chimney Configuration: A baseline case with a conventional ceramic brick ventilation duct extending above the roof.
- TYPE II – Solar Chimney Configuration: The above-roof chimney section was enclosed with transparent glazing, allowing solar radiation to increase the temperature differential and strengthen buoyancy-driven ventilation.
- TYPE III – Chimney Cap Configuration: A rotary chimney cap was installed on the Type duct, intended to enhance airflow extraction through wind-induced suction.

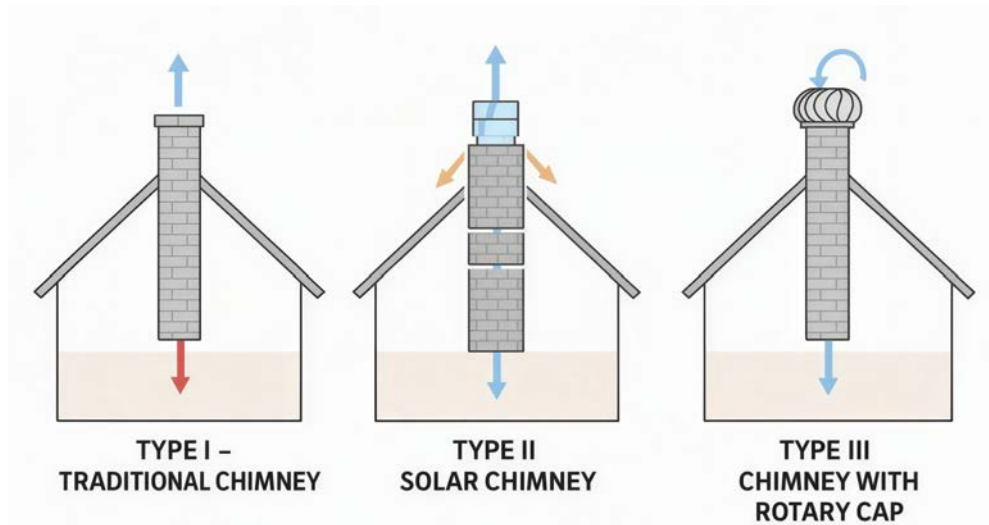


Fig. 1. Schematic representation of the three chimney configurations (Type I – traditional, Type II – solar, Type III – rotary cap) [from the author's collection]

Throughout all experiments, the positioning of airflow and temperature sensors inside the test room and along the ventilation duct remained constant, ensuring the comparability of results across different configurations.

The test building is a two-storey, two-apartment residential house located in Gdańsk (northern Poland, cold climate zone). The selected apartment (floor area $\approx 50 \text{ m}^2$) was situated on the first floor and included a kitchen, living room, bedroom, bathroom, and corridor. For measurement purposes, only the kitchen was designated as the test space, while other rooms were isolated from the ventilation system. The apartment remained inhabited during the campaign, with residents' activities occurring primarily in the morning and after 5:00 pm.

Constructed in the 1950s and renovated in 2012, the house represents a typical example of Poland's urban residential architecture, characterized by heavy-weight construction with concrete floor slabs and stone cavity walls. Table 1

presents the thermal properties (U-values) of the main structural components. The choice of such a case study reflects the prevalence of similar housing stock across Polish cities and underscores the relevance of stack ventilation solutions for everyday architectural practice.

By addressing real conditions in a representative Polish urban building, this study not only provides empirical evidence on the performance of stack ventilation systems but also highlights practical implications for architectural and urban design. The findings inform architects, engineers, and urban planners about the integration of passive ventilation strategies into both new construction and the modernization of existing housing stock. In particular, the inclusion of alternative chimney configurations – such as solar chimneys or chimneys equipped with rotary caps – can significantly strengthen the stack effect, enhance air exchange stability, and improve indoor air quality [Bręczewska-Kulesza 2009]. For designers, this underlines the importance of considering chimney geometry, materials, and additional aerodynamic elements already at the conceptual stage of the project [Antczak-Jarząbska, Krzaczek 2016].

The test apartment was equipped with a stack ventilation system with controlled air inlets and chimney ducts. The air inlets were small devices mounted in the casement or window frame, regulating the inflow of fresh air. This solution, first introduced in Scandinavia in the 1960s, has since been widely implemented across Europe [Andersen 1992: 23]. In Poland, inlet gaps are obligatory in buildings utilizing stack ventilation combined with multi-chimney ducts [PN-B-03430:1983/Az3:2000].

In the studied apartment, the air inlet to the chimney duct was additionally equipped with a controllable vent grill positioned 0.15 m below the room ceiling. The measurement system was restricted to the kitchen (fig. 2), with a usable area of 15.75 m² and an air volume of 40.95 m³. The simplified set-up – with one air inlet (rectangular gap integrated into the window frame) and one air outlet (kitchen chimney duct) – reduced the number of unknown variables influencing the air exchange process. The used air was removed through a vent with dimensions of 0.14 × 0.14 m. During the measurement period, all windows were closed, and internal doors remained shut during night-time and residents' work hours.

The case study demonstrates that, while conventional brick chimneys remain effective in standard residential conditions, the introduction of modern variations – solar-assisted chimneys, double-duct systems, or chimneys with aerodynamic caps – can offer architects additional design flexibility and higher robustness of natural ventilation under variable climate conditions [Bansal et al. 1994; Zhai, Previtali 2010]. As urban housing density increases, the deliberate choice of chimney type may become a key architectural tool for balancing aesthetic integration with functional performance.

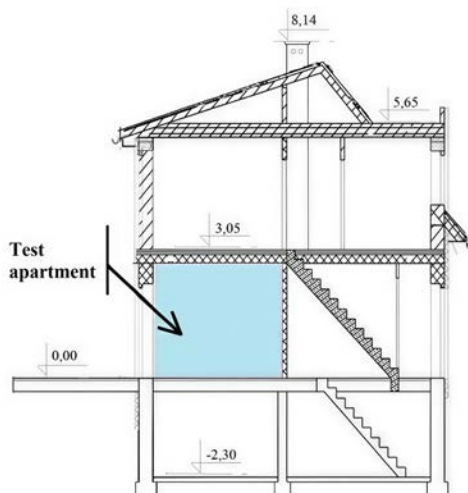


Fig. 2. The residential family test house vertical section of the first floor
[from the author's collection]

The test room was equipped with a single-chamber PVC window with dimensions 4/16/4 mm. The room had two doors, each opening to a heated adjacent space. When residents were absent, the doors were tightly sealed. The chimney itself was built using traditional full ceramic brick technology. In TYPE I, the chimney extended 1.04 m above the roof slope. The external wall was made of solid ceramic brick with a total thickness of 0.38 m, while internal partition walls were 0.12 m thick.

In TYPE II, the section of the chimney protruding above the roof was enclosed with a transparent float-glass cover, with a 0.04 m air gap. The glazing consisted of 5 mm thick glass panes. This design aimed to enhance buoyancy forces by utilizing solar radiation, while the remaining elements of the ventilation system were unchanged. The material and thermal parameters of the partitions for this configuration are summarized in table 1.

Tab. 1. The material and thermal parameters of the partitions in the ventilation system

Element	Thickness d [m]	Thermal conductivity λ [W/mK]	Emissivity ϵ [-]
Window joinery	0,024	1,4	0,95
External wall	0,38	0,77	0,84
Chimney wall	0,12	0,77	0,84
Glass wall	0,005	6	0,95
Air gap	0,04	0,025	—

Source: from the author's collection.

In TYPE III, a rotary-type chimney cap was installed on the traditional chimney described in TYPE I. The cap was expected to improve airflow extraction through wind-induced suction, offering a low-cost and practical modification for improving natural ventilation efficiency in existing residential buildings. Figure 3 representation of the three chimney types in reality:



Fig. 3. Real type of the three chimney configurations (Type I – traditional, Type II – solar, Type III – rotary cap) [from the author's collection]

By comparing these three configurations, the study addresses a significant research gap in Polish residential architecture, where experimental assessments of chimney-induced ventilation under real urban conditions are scarce. The findings are intended to guide architects and urban planners in evaluating how small-scale design interventions – such as solar chimneys or aerodynamic caps – can improve indoor air quality and contribute to more sustainable urban housing strategies. The measurement system enabled continuous monitoring of indoor and outdoor climate conditions, as well as airflow velocity in the vent inlets and outlets. It consisted of calibrated thermo-anemometers, pressure and temperature sensors, a weather station, and data acquisition software (LAB-EL LBX 2012). Measurements were logged in real time and stored in an SQL database. The local climate station was installed on the roof of the test building to record wind speed and direction, temperature, humidity, barometric pressure, and solar radiation. This setup ensured that airflow variations could be directly linked to external climate drivers [Shi et al. 2015; Wójcik 2012].

The experiment lasted from August to November, covering variable seasonal conditions in northern Poland. Outdoor temperatures ranged from -0.4°C to 32.8°C , with an average of 11.4°C . Wind conditions were generally weak, with an average velocity below 0.8 m/s . The dominant wind direction was north (58%), while solar radiation frequently exceeded 100 W/m^2 during daytime hours, favoring solar chimney performance [Zhai, Previtali 2010].

4. VENTILATION EFFICIENCY AND ARCHITECTURAL GUIDELINES

The comparative analysis of three chimney types – traditional, solar, and rotarycap – demonstrates that relatively simple passive modifications can significantly enhance stack ventilation efficiency in Polish urban housing. While the baseline configuration achieved an average ACH of 0.61-0.67 1/h, the introduction of a solar chimney improved airflow by approximately 14% under conditions of low wind and sufficient solar radiation, whereas the rotary cap increased performance by up to 35% in moderate wind conditions. These findings confirm that chimney geometry, materials, and aerodynamic adjustments directly affect ventilation stability and intensity [Liddament 1996; Bansal, et al. 1994; Ji, Cook, Hanby 2003; Antczak-Jarząbska, Niedostatkiwicz 2017; Zhai, Previtali 2010]. For architects and urban planners, the results highlight the need to consciously select chimney types suited to local climate, urban morphology, and building typology. Solar chimneys are particularly recommended in compact developments with limited wind exposure, while rotary caps are advantageous in areas with moderate wind, offering low-cost retrofitting opportunities. Furthermore, attention should be paid to chimney height (minimum 1 m above the roof ridge), material durability (ceramic, glass, or corrosion-resistant metals), and integration with architectural form, so that ventilation elements become both functional enhancers of air change rate and expressive accents of the roofscape. At the urban scale, the systematic application of such solutions can contribute to improved microclimate regulation, reduced reliance on mechanical ventilation, and mitigation of the heat island effect [Bręczewska-Kulesza 2009].

5. CONCLUSIONS

The analysis of three chimney configurations demonstrated that even relatively simple modifications can significantly enhance the efficiency of stack ventilation in Polish residential buildings. The traditional chimney (Type I) provided only limited performance under transitional climatic conditions, while both the solar chimney (Type II) and the rotary cap chimney (Type III) substantially improved air exchange rates. These findings lead to several practical guidelines relevant for architects and urban planners:

- Selection of chimney type should be aligned with local climatic and urban conditions. In dense urban areas with restricted airflow, solar chimneys allow the use of solar energy to reinforce the stack effect. Rotary caps, on the other hand, are effective in regions with moderate wind speeds, stabilizing system performance and reducing fluctuations in air exchange.
- Geometric and material parameters play a decisive role in system efficiency. Chimneys should extend at least 1 m above the roof ridge to ensure sufficient

draft. Materials with high thermal mass, such as ceramic brick, support stable airflow, while glazed surfaces in solar chimneys maximize solar heat gain and intensify buoyancy-driven ventilation.

- Architectural and aesthetic integration should be considered as both a technical and cultural issue. Chimneys – traditional or modern – contribute to the roofscape and urban identity. Rotary caps can introduce kinetic elements, highlighting the building's environmental responsiveness, while solar chimneys can serve as vertical accents, merging traditional forms with contemporary energy strategies.
- Urban-scale implementation of enhanced stack ventilation systems can improve microclimatic conditions. Systematic use across multiple buildings helps reduce reliance on mechanical ventilation, mitigate urban heat island effects, and contribute to sustainable urban planning.
- Operational and maintenance aspects must be anticipated at the design stage. Easy access to chimney elements enables cleaning and inspection, while the selection of durable, climate-resistant materials ensures long-term functionality under wind, frost, and snow loads.
- In summary, the design of chimneys should not be treated solely as a technical necessity but as an opportunity to consciously shape both residential environments and the wider urban landscape. Incorporating innovative chimney types – such as solar and aerodynamic systems – can enhance stack ventilation performance, enrich architectural expression, and support sustainable development strategies.

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WYTYCZNE ARCHITEKTONICZNE DOTYCZĄCE WZMACNIANIA WENTYLACJI KOMINOWEJ: WNIOSKI Z BADAŃ NAD WYDAJNOŚCIĄ W ZABUDOWIE MIEJSKIEJ

Streszczenie

Naturalna wentylacja (NV) stanowi kluczową, energooszczędną strategię poprawy jakości powietrza wewnętrznego i komfortu cieplnego w budynkach mieszkalnych. W klimacie chłodnym, takim jak w Polsce, dominującą formą NV jest wentylacja grawitacyjna (kominowa), której efektywność zależy od różnic temperatur oraz warunków wietrznych. Celem niniejszego badania była ocena wpływu różnych konfiguracji kominów na intensywność wymiany powietrza (ACH) w rzeczywistym budynku mieszkalnym w Gdańsku. W ramach czteromiesięcznej kampanii pomiarowej porównano trzy rozwiązania: klasyczny komin murowany (typ I), komin solarny z oszkloną nadbudową (typ II) oraz komin z obrotową nasadą (typ III). Wyniki wykazały, że w porównaniu do konfiguracji podstawowej komin solarny zwiększał ACH średnio o 14% przy sprzyjającym nasłonecznieniu, natomiast komin z nasadą – o 35% przy umiarkowanym wietrze. Badanie potwierdza, że nawet niewielkie, pasywne modyfikacje kominów mogą istotnie poprawić stabilność i wydajność wentylacji grawitacyjnej. Wyniki dostarczają wskazówek projektowych dla architektów i urbanistów, zwłaszcza w kontekście modernizacji istniejących budynków oraz projektowania nowej zabudowy miejskiej z uwzględnieniem klimatu lokalnego.

Słowa kluczowe: wentylacja, wskaźnik wymiany powietrza (ACH), kominy słoneczne, nasada kominowa, mieszkalnictwo miejskie