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SOLAR CHIMNEY: AN INNOVATIVE APPROACH TO PASSIVE VENTILATION

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The article explores the effective implementation of energy-efficient technologies in passive ventilation systems for residential buildings. As energy efficiency and environmental sustainability become more critical in construction, ensuring natural air exchange is essential for a comfortable indoor microclimate. The study analyzes contemporary ventilation systems, evaluates climatic factors, and applies numerical modeling to assess passive ventilation effectiveness. Findings show that solar chimneys, wind catchers, and hybrid ventilation systems improve natural air exchange and reduce reliance on mechanical systems. Despite advances in renewable energy technologies, solar chimneys are underutilized, particularly in multi-story buildings, due to limited research and the lack of validated methodologies. The article also offers recommendations for integrating passive ventilation technologies into modern construction for more sustainable and energy-efficient designs.

Keywords: solar chimney, solar energy, interactive simulations, convection, passive ventilation, natural ventilation.

Introduction

An increasing number of European countries are transitioning to renewable energy sources, incentivizing their citizens to modernize building engineering systems and prioritizing the development of energy-efficient buildings (Arce et al., 2009; L. Yang et al., 2014). A key aspect of this process is the proper organization of natural ventilation, which plays a vital role in maintaining indoor air quality and overall building performance (Broderick et al., 2017; Chen et al., 2017; Coggins et al., 2022; López Plazas & Sáenz De Tejada, 2024; Sukholova et al., 2024; Voznyak et al., 2020; B. Wang et al., 2023).

The issue of ensuring adequate passive ventilation in residential buildings is widespread; however, it is often underestimated and overlooked. Insufficient ventilation leads to the accumulation of harmful substances, increased humidity levels, and a decline in indoor air quality, all of which negatively impact the health and comfort of occupants (Cakyova et al., 2021; Chenari et al., 2016; Haverinen-Shaughnessy et al., 2018; Jia et al., 2021; Liu et al., 2023; Rodrigues et al., 2000; Rojas et al., 2024; Y. Wang et al., 2017; Zaniboni & Albatici, 2022). Beyond human well-being, natural ventilation is essential for preserving the integrity of building materials and structural stability. Furthermore, a well-designed airflow system facilitates the uniform distribution of temperature within indoor spaces, enhancing overall thermal comfort.

Properly calculated air exchange not only ensures optimal microclimatic conditions for occupants but also prevents detrimental effects on building structures, including moisture accumulation in protective layers, corrosion, and the degradation of construction materials. Consequently, the implementation of effective passive ventilation strategies is integral to both occupant well-being and the long-term durability of buildings (Chenari et al., 2016; Etheridge, 2015; Tognon et al., 2023; Zaniboni & Albatici, 2022; T. Zhang & Yang, 2019).

A key factor in the organization of indoor ventilation is the phenomenon of free convection, which enables air movement without reliance on mechanical systems (Walker et al., 2011; D. Yang et al., 2013; Ziskind et al., 2002). The effectiveness of natural ventilation driven by convection is influenced by the temperature differential between indoor and outdoor environments, the height of ventilation ducts, and the strategic placement of ventilation openings. Enhancing ventilation efficiency can be achieved through the implementation of specialized design solutions, such as the integration of dedicated ventilation shafts or thermally insulated ducts (Bansal et al., 1994; Kalidasan et al., 2014; Sornek et al., 2023; T. Zhang & Yang, 2019).

One of the most innovative approaches to optimizing passive ventilation technologies is the utilization of solar chimneys, also referred to as thermal chimneys. A solar chimney is a passive system that harnesses solar energy to facilitate ventilation within buildings (Letan et al., 2003; Matsunaga et al., 2021; Monghasemi & Vadiee, 2018; H. Zhang et al., 2021). This advanced design leverages solar thermal energy to generate natural air circulation through the principle of free convection. As solar radiation heats the air within the chimney, the warmed air rises, creating an upward airflow. This process induces the removal of warm indoor air through the chimney while simultaneously drawing in fresh air from lower ventilation openings, thereby enhancing indoor air exchange and thermal comfort.

Solar chimneys enhance the efficiency of natural ventilation, operating on principles similar to those of Trombe walls by utilizing solar energy to facilitate air exchange (Ali et al., 2024; Arce et al., 2009; Myroniuk et al., 2024; Rabani et al., 2019; Shi et al., 2016; Simões et al., 2021). This technology not only optimizes indoor climate regulation but also contributes to overall energy conservation. Specifically, the implementation of solar chimneys can lead to a reduction in the average daily electricity consumption of air conditioning systems, thereby decreasing reliance on mechanical ventilation (Ardila et al., 2023; Chew et al., 2022; Hassan, 2023; Khanal & Lei, 2011; Punyasompun et al., 2009; Zamora & Kaiser, 2010).

As a passive ventilation solution, solar chimneys effectively ensure adequate air exchange and cooling in summer. This significantly enhances a building’s energy efficiency without incurring additional operational costs. Consequently, the integration of solar chimneys presents a highly effective strategy for addressing two fundamental challenges in energy-efficient construction – maximizing energy efficiency and promoting environmental sustainability.

Materials and Methods

This study aims to highlight the significance of investigating and further researching the application of solar chimneys in temperate climates. Solar chimneys represent a promising solution for enhancing building energy efficiency and optimizing ventilation processes through the utilization of solar energy. However, due to the variability of climatic conditions, their operational effectiveness may fluctuate significantly, necessitating comprehensive research and analysis.

For numerical modeling in this study, the Energy2D software was employed – an interactive multiphysics simulation program designed to analyze thermal processes in dynamic conditions. This program models three fundamental heat transfer mechanisms – thermal conduction, convection, and radiation – along with their interactions, which are crucial for examining thermal and hydrodynamic phenomena in solar chimneys. The use of Energy2D enables the visualization of heat transfer processes, the assessment of system efficiency, and the identification of key parameters influencing performance.

Results and discussion

This article presents the results of a numerical simulation analyzing the performance of a solar chimney as a component of a passive ventilation system for residential buildings. The implementation of this ventilation technology is a highly effective strategy under stringent energy conservation requirements, as it leverages natural mechanisms – such as temperature and pressure differentials – to facilitate efficient air exchange. This ensures the maintenance of appropriate sanitary and hygienic conditions within indoor environments without relying on electrically powered fans. Consequently, this approach reduces operational costs and contributes to lowering the building's overall carbon footprint.

The study investigates convection phenomena and hydrodynamic processes within an enclosed space using the Energy2D software. As part of the modeling process, scenarios were developed to replicate real-world conditions for utilizing a solar chimney in natural ventilation. The simulation demonstrated that the establishment of an airflow between supply and exhaust ventilation openings, positioned on opposite walls of the building, was driven by pressure differences. This enabled the implementation of one of the fundamental forms of passive ventilation – cross-ventilation – further enhancing the system's effectiveness (Benlefki et al., 2021).

The modeling results provided a comprehensive assessment of the hydrodynamic processes governing natural convection, the distribution of air temperature within the solar chimney, and the impact of the room's geometric characteristics on airflow dynamics. Utilizing the interactive Energy2D approach enabled the visualization of temperature fields, airflow trajectories, and the effects of variable external climatic conditions. This analysis was based on the fundamental physical equations of heat transfer and hydrodynamics, ensuring a rigorous evaluation of the system's performance.

1. Heat conduction equation (Fourier's Law)

$$\frac{\delta T}{\delta t} = a\nabla^2 T\,, \tag{1}$$

where T – temperature, K; t – time, s; $\alpha = \frac{k}{\rho c_p}$ – thermal conductivity coefficient, m²/s; k – thermal conductivity coefficient, W/(m K; ρ – material density, kg/m³; c_p – specific heat capacity, J/kg·K.

2. Convection heat transfer equation.

Convection is modeled by the Navier – Stokes equation for an incompressible fluid in combination with the energy equation:

$$\rho\left(\frac{\delta T}{\delta t} + \vartheta \times \nabla\right) = -\nabla P + \mu\nabla^2\vartheta + \rho g, \tag{2}$$

where P – pressure, Pa; μ – dynamic viscosity, Pa·s; g – acceleration of gravity, m/s².

3. Stefan-Boltzmann law, which describes heat transfer by radiation between surfaces:

$$q = \varepsilon\sigma T^4, \tag{3}$$

where q – radiation power, W/m²; ε – surface emissivity; σ – Stefan-Boltzmann constant (5.67×10^{-8}), W/m²·K⁴; T – surface temperature, K.

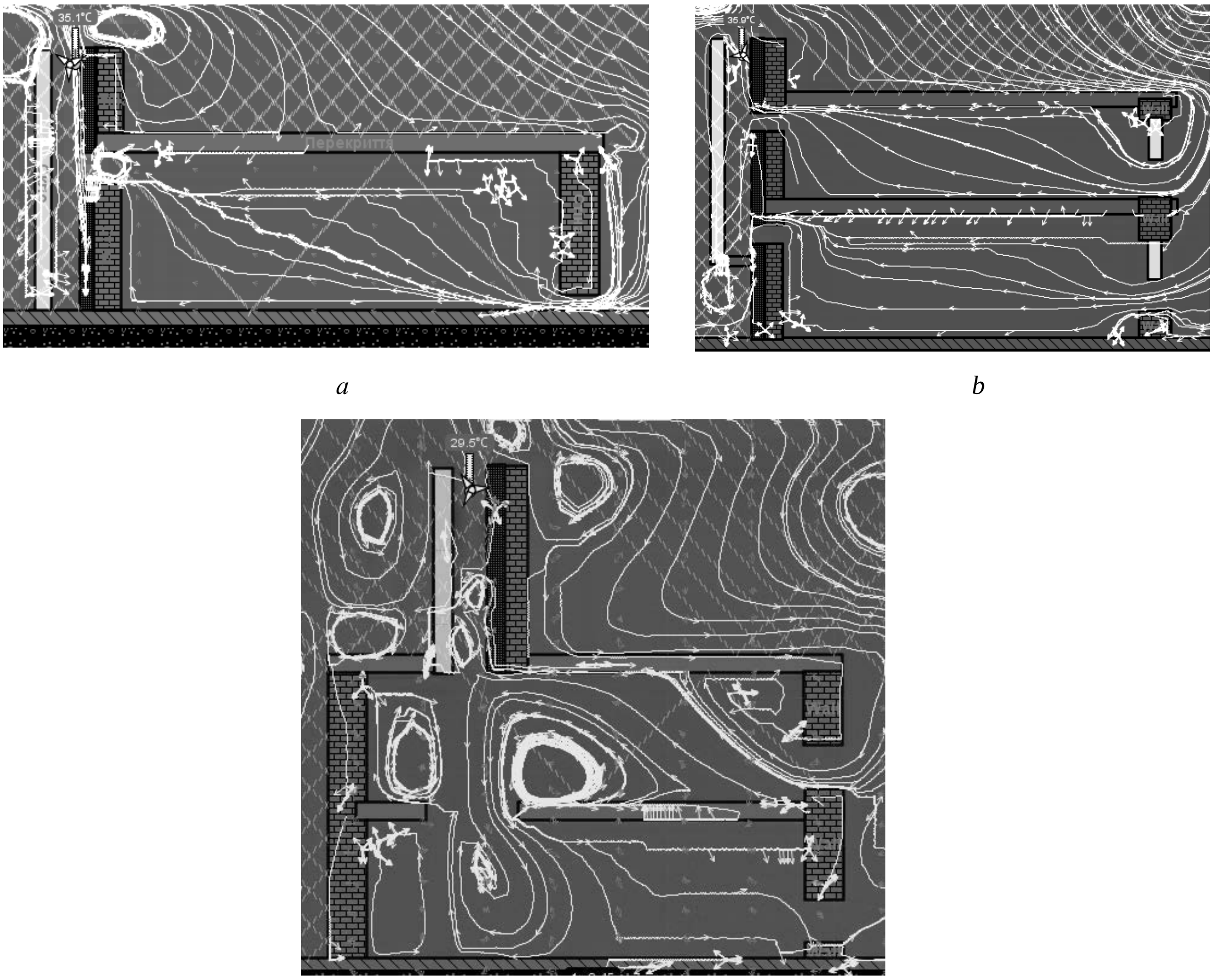
4. Dependence of buoyancy force (Archimedes' Law). Takes into account the effect of temperature on the change in air density, which causes natural convection:

$$F_b = \rho g\beta(T - T_0), \tag{4}$$

where β – coefficient of thermal expansion, 1/K; T_0 – ambient temperature, K.

During the modeling process in the Energy2D software package, finite difference discretization and explicit numerical schemes were employed to enable interactive simulations. This approach allowed for real-time analysis of heat transfer, convection, and radiation within complex thermodynamic systems incorporating solar chimneys and cross-ventilation. The following data and assumptions were adopted.

The solar chimney design included a glass layer with a high heat absorption coefficient to maximize the utilization of solar radiation for heating the air inside the chimney. To prevent excessive heating of the structural walls, an insulation layer was incorporated, with properties corresponding to mineral wool in accordance with DSTU 9191:2022. The angle of incidence of solar radiation was set at 45°, while the solar energy density was considered under ideal conditions at 1000 W/m² (Venhryn & Shapoval, 2019). The ambient air temperatures were assumed to be 25 °C. The results of the visualization are presented in Fig. 1.



a *b*

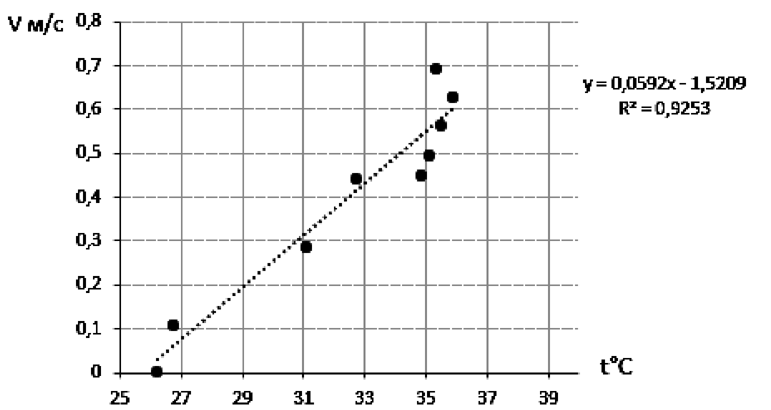
c

Fig. 1. Diagram of airflows around a building equipped with a Solar Chimney: a – a single-story building with an attached Solar Chimney and cross-ventilation; b – a two-story building with an attached Solar Chimney and cross-ventilation; c – a two-story building with a Solar Chimney integrated into the roof structure

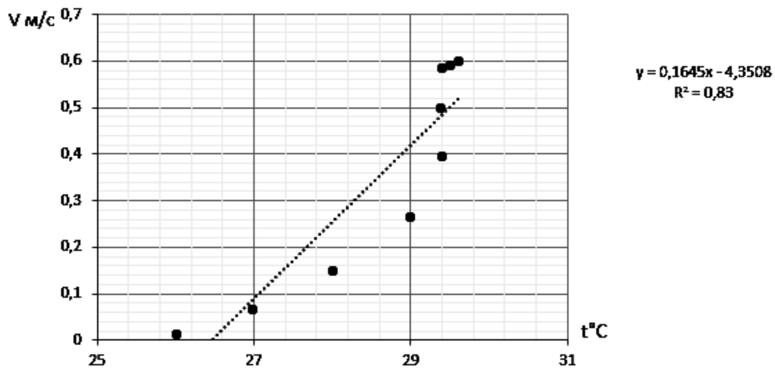
The simulation results obtained using the Energy2D software, as illustrated in Fig. 1, confirm the effectiveness of natural ventilation facilitated by a solar chimney under varying climatic conditions. The analysis of temperature distribution and airflow dynamics indicates that solar radiation induces an upward movement of warm air within the vertical channel, thereby enhancing the performance of passive ventilation through the process of convection. The red arrows in the diagram depict the direction of airflow, demonstrating the formation of stable air circulation that ensures efficient air exchange within the indoor environment. The temperature contour lines illustrate a uniform heat distribution, thereby minimizing localized overheating and preventing air stagnation. Simultaneously, external air enters the building through window openings and ventilation grilles, moves through the interior space, gradually heats up, and follows the preceding airflow. As the air temperature within the solar chimney increases, its density decreases, generating an upward airflow. A higher temperature within the chimney results in a greater pressure differential, thereby increasing the velocity of air movement within the room.

Based on the obtained data, graphical dependencies were established, illustrating the relationship between air velocity under cross-ventilation conditions and the temperature of the heated air at the outlet of the Solar Chimney (Fig. 2). These dependencies enable the assessment of the efficiency of the passive ventilation system under varying thermal conditions and different geometric configurations of the Solar

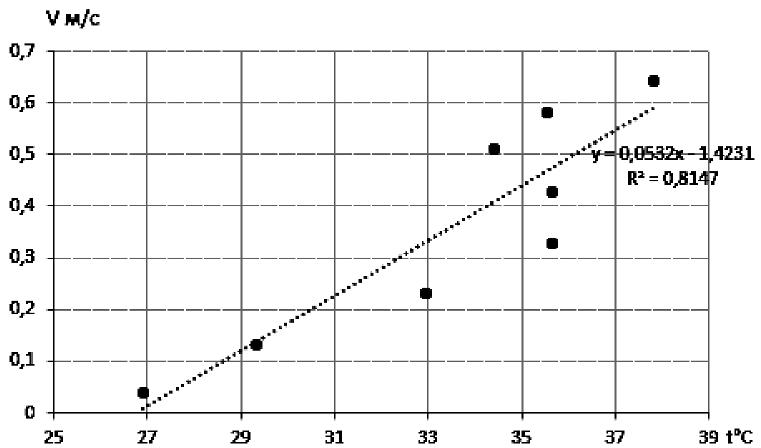
Chimney. Furthermore, they facilitate the prediction of air exchange rates necessary to maintain optimal indoor conditions, ensuring thermal comfort and adequate ventilation within the living space.



a



b



c

Fig. 2. Graph of air velocity change at the outlet of the solar chimney shaft versus exhaust air temperature
a – one-story house with an attached solar chimney and cross-ventilation;
b – two-story house with a solar chimney on the roof;
c – two-story house with an attached chimney and cross-ventilation

The graphical dependencies of air velocity on the temperature of heated air at the outlet of the solar chimney, as presented in Fig. 2, illustrate the linear nature of airflow parameter variations across different building configurations. In the case of a single-story house with an attached solar chimney and cross-ventilation, a consistent increase in air velocity with rising temperature is observed, as evidenced by a high coefficient of determination (R^2 = 0.9253). For a two-story house with a rooftop solar chimney, the airflow velocity also increases with temperature; however, the steeper slope of the regression line suggests an enhanced chimney effect, despite a slightly greater dispersion of experimental data (R^2 = 0.83). In contrast, for a two-story building with an attached chimney and cross-ventilation, the relationship between air velocity and temperature is less pronounced, with the regression line exhibiting the smallest slope among the analyzed cases. This indicates a more uniform distribution of airflow, though with a diminished temperature-driven influence on air velocity (R^2 = 0.8147). The obtained results confirm the effectiveness of the solar chimney in augmenting natural ventilation, while also demonstrating that the degree of temperature influence on air circulation is significantly dependent on the architectural and design characteristics of the building.

Conclusions

The results of numerical modeling in the Energy2D software confirm the effectiveness of utilizing a solar chimney to enhance the performance of passive ventilation systems under varying climatic conditions. Analysis of temperature distribution and airflow patterns indicates the formation of stable air circulation, which facilitates efficient air exchange within indoor spaces through convection-driven processes.

The graphical dependencies of air velocity on the temperature of heated air at the solar chimney outlet reveal a linear relationship across different building configurations. The most pronounced effect of air heating is observed in a one-story house with an attached solar chimney and cross-ventilation, as evidenced by a high coefficient of determination (R^2 = 0.9253). In a two-story house with a rooftop solar chimney, a more pronounced stack effect is achieved, albeit with slightly greater variability in the data (R^2 = 0.83). In contrast, a two-story building with an attached chimney and cross-ventilation exhibits the lowest slope of the regression line (R^2 = 0.8147), suggesting a more uniform airflow distribution with a reduced influence of temperature on air velocity.

The findings provide a comprehensive assessment of the effectiveness of passive ventilation systems under varying thermal conditions and structural configurations. While the solar chimney proves to be an efficient mechanism for enhancing natural ventilation, its performance is highly dependent on the architectural design and structural characteristics of the building.

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СОНЯЧНИЙ ДИМОХІД: ІННОВАЦІЙНИЙ ПІДХІД ДО ПАСИВНОЇ ВЕНТИЛЯЦІЇ

У статті розглянуто питання ефективного застосування енергозберvirзбережних технологій у системах пасивної вентиляції житлових будинків, що має велике значення в умовах зростання вимог до енергоефективності та екологічної стійкості будівель. Із огляду на це, важливим аспектом є забезпечення природного повітрообміну для створення комфортного мікроклімату. Дослідження охоплює аналіз сучасних вентиляційних систем, а також оцінювання впливу кліматичних факторів на їх ефективність. Важливою складовою є застосування числового моделювання для визначення ефективності пасивної вентиляції в різних кліматичних умовах.

Результати показують, що технології, такі як сонячні димоходи, стіна Тромбе, оптимальне розміщення вентиляційних отворів та радіаційні панелі, здатні істотно покращити природний повітрообмін і знижують потребу в механічній вентиляції, що дає змогу значно зменшити енергоспоживання та підвищити ефективність вентиляційних систем, забезпечуючи комфортний мікроклімат у приміщеннях.

Попри розвиток технологій відновлюваної енергії, сонячні димоходи залишаються недостатньо вивченими, їх рідко застосовують, зокрема, в багатоповерхових будинках. Це пояснюється обмеженими інженерними дослідженнями, відсутністю науково обґрунтованих методик їх розрахунку та недостатньою адаптацією до різних кліматичних умов. Необхідні додаткові дослідження для вивчення ефективності та оптимальних умов застосування сонячних димоходів у різних кліматичних зонах.

У статті також наведено рекомендації щодо інтеграції пасивних вентиляційних технологій у сучасну будівельну практику, зокрема щодо оптимального проєктування та розміщення вентиляційних систем для максимального використання природних ресурсів.

Ключові слова: сонячний димохід, сонячна енергія, інтерактивне моделювання, конвекція, пасивна вентиляція, природна вентиляція.