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Solar Chimney Performance in Summer and Winter for Sustainable Building Climate Control: A Review

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Abstract

The advent of solar chimney technology provides an innovative approach to sustainable building climate control, offering an eco-friendly alternative for heating and cooling throughout the year. This comparative review examines the performance of solar chimneys during summer and winter seasons, highlighting the underlying principle of thermal buoyancy to leverage solar energy for reducing electricity consumption and improving indoor air quality. Through the analysis of various design optimizations, materials, absorber characteristics, and integration with other passive cooling strategies, the study demonstrates the effectiveness of solar chimneys in maintaining comfortable indoor temperatures and ensuring consistent ventilation rates. Case studies and simulation data validate the role of solar chimneys in diminishing the energy footprint for both residential and commercial buildings. The review underscores the potential for solar chimneys to mitigate energy costs and contribute to environmental sustainability by lowering greenhouse gas emissions, particularly in the context of global energy use and the recent emphasis on health considerations in building design. Furthermore, the paper offers insights into design considerations for various climates and environmental conditions, thereby providing practical guidance for the deployment of solar chimneys in achieving energy-efficient building operations.

Keywords-: Solar Chimney Technology**,** Sustainable Building Climate Control**,** Eco-friendly Heating and Cooling

Thermal Buoyancy Principle, Solar Energy in Buildings, Electricity Consumption Reduction, Indoor Air Quality Improvement, Design Optimization of Solar Chimneys, Material Selection for Solar Chimneys.

1. Introduction

The past two decades have seen a surge in research on passive ventilation due to its cost and energy savings, as well as its ability to cut down on noise and carbon emissions. Passive ventilation systems leverage natural air flow and are designed with consideration for local climate and architectural specifics, which can affect their efficiency in air distribution and temperature regulation [1]. These systems also play a role in space heating and cooling. Despite their advantages, many modern buildings still rely on energy-intensive mechanical ventilation, which can compromise indoor air quality due to the buildings' airtight nature [2]. Heating, ventilation, and air conditioning (HVAC) systems are among the top energy users globally, accounting for approximately 19.2% of total energy consumption according to recent statistics. The reliance on traditional energy sources for HVAC has not only contributed to an energy shortage but has also led to environmental issues due to pollution from energy production. With fossil fuels making up 85% of the world's energy usage and 68% of its electricity production—split into 27% coal, 35% oil, and 23% natural gas—their consumption results in significant pollutant emissions [3,4]. Consequently, there's a growing focus on renewable energy sources as a solution to alleviate the ongoing energy and environmental crises [5]. In 2006, more than 240 million air-conditioning units were installed around the world leading to the global electricity consumption of 15%.This big amount of energy can be optimized and saved using passive cooling and renewable energies [6]. Ancient arid regions populations try to defeat thermal discomfort challenges in both summer and winter seasons using local materials and renewable sources, namely wind, water, sun, geothermal, etc. Using renewable energy and passive cooling to achieve thermal comfort and reducing building loads were the key elements of vernacular and traditional architectures [7]. Natural ventilation was widely used to ensure good living conditions and better indoor air quality. Also in some cases, it provided cooling needs in some ingenious bioclimatic buildings. [8] Natural ventilation can be generated by two main mechanisms: pressure and buoyancy effect. A German engineer named Jörg Schlaich is credited with pioneering many aspects of the modern solar chimney. His design, known as the Manzanares Solar

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Chimney, was built in Spain in 1982 and produced electricity through the updraft effect. However, the technology faced challenges in terms of efficiency and cost-effectiveness.

In recent years, the idea of solar chimneys has seen a resurgence as interest in renewable energy sources has grown. Researchers and engineers are exploring advanced designs and materials to improve the efficiency of solar chimneys. Several pilot projects and experimental solar chimneys have been built in various countries to further test and refine the technology [9].

Lupi, F., et al. (2011) [10] provides an overview of the Solar Updraft Power Plant (SUPP) as an innovative technology that harnesses both solar and wind energy for sustainable development. The SUPP operates by using a large collector area to heat air with solar radiation, which then rises through a tall chimney, turning turbines connected to generators to produce electricity. The efficiency of the SUPP is highly dependent on the size of the tower and collector area, necessitating optimization of structure, thermodynamics, and cost to realize economic benefits.

Structurally, the goal is to build the solar tower as slender as possible using high-strength materials like concrete and reinforcements like stiffening rings, which can be made from various methods including reinforced concrete beams, steel-concrete composites, or spoked wheels. These rings prevent the tower from oval-shaped deformations and enhance its structural integrity. However, the feasibility of the SUPP is significantly influenced by wind action due to the tower's extreme height and slenderness, which presents a challenge beyond current structural experience. Therefore, advanced modeling and stochastic analysis of wind loads and the tower's response are crucial for the development of this technology.

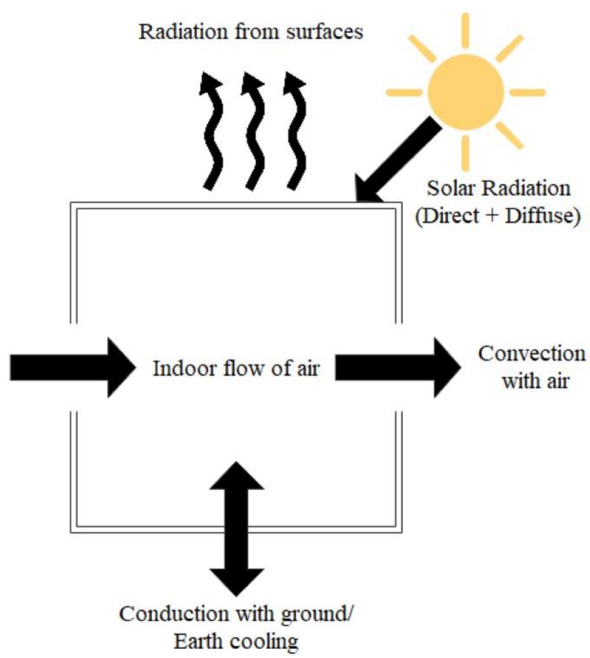

Fig. 1 Heat transfer modes in buildings to heat sinks [11]

Small-scale experimental studies on solar chimneys have indicated that ventilation flow rates increase when the ratio of the absorber height to the gap between the glass and absorber rises. This observation supports the predictions of a steady-state mathematical model designed to analyze such systems. In experiments involving nine different combinations of absorber height and air gap within the test setup, the maximum ventilation rate achieved using solar power was 5.6 changes of the room's air per hour. This was for a room volume of 27 cubic meters, subjected to solar radiation of 700 watts per square meter on a vertical surface, using a chimney 1 meter in height with a height-air gap ratio of 2.83. [12]

The solar chimney power plant (SCPP) offers a simple and eco-friendly way to produce electricity from solar energy. Despite its promise, the technology's low efficiency has slowed its commercial adoption. Loghman Rezaei et al. [13] introduces an innovative collector design aimed at enhancing the efficiency of solar chimneys. The upgraded design incorporates metallic tubes suspended from the collector's top, which serve as absorbers of solar radiation. These tubes are open at one end and covered with clear sheets on the other to minimize reflection of solar radiation back into the environment. To assess the effectiveness of this design, both experimental procedures and 3-D computational fluid dynamics (CFD) simulations were conducted. The presence of metallic tubes increased the temperature at the chimney's base by approximately 5 Kelvin, which led to an 8% improvement in the collector's efficiency, thanks to the tubes' role as additional heat transfer surfaces. The study also investigated how altering the shapes of these tubes affects the system's efficiency. The CFD results showed that variations in the tubes' dimensions significantly enhanced the collector's performance, with changes in tube diameter resulting in a 33.7% efficiency gain, and alterations in tube length yielding a 30% improvement.

Mirzamohammad et al. [14] proposes an innovative method to enhance the performance of solar chimney power plants (SCPP), which typically experience low power output in the absence of strong solar radiation. The integration of a SCPP with a gas power plant and the redirection of the gas plant's exhaust into underground pipes elevates the soil temperature. This process increases the air temperature underneath the solar collector's canopy, decreasing the air density and causing it to rise faster. The result is a marked improvement in airflow velocity and the power output of the SCPP. This method maintains power generation even during periods with little or no sunlight, overcoming the typical downtime of solar-only systems. The study's findings reveal that this technique significantly raises SCPP output under varying solar radiation conditions, confirming the buried pipes' effectiveness as a solution. With the world's population increasing swiftly, there's a growing need for more residential and commercial spaces, leading to the construction of high-rise buildings that require efficient systems for air circulation and temperature control. In traditional building designs, relying solely on natural ventilation is often inadequate, necessitating the use of energy-intensive fans and air conditioners that consume between 40% and 60% of a building's total energy use. Solar chimneys have been proposed as a way to reduce this consumption, but most research has previously concentrated on theoretical improvements under perfect conditions or small-scale trials.

A research by K. S. Rajput et al. [15] advances these studies by implementing full-scale solar chimney experiments in an actual building scenario in Bhopal, India. A test room with an integrated rooftop solar chimney, which could be oriented at various angles including a sun-facing 30-degree tilt, was the focal point of the research. The study compared the temperature and airflow in this room with those of a standard room without a solar chimney. The solar chimney significantly improved air movement by up to 20% in hot weather and also showed potential for daily electrical energy savings of 1 kWh. This suggests that solar chimneys are not only viable for enhancing indoor air quality and comfort but also for cutting down on energy costs in building operations.

Hong, S., et al. [16] investigates the impact of a solar chimney (SC) on the energy efficiency of a 220 m² high-performance, two-story detached house in China, considering the region's extremes of hot summers and cold winters. Simulations using EnergyPlus software and local climate data assessed a house equipped with an 8-meter-high and 1.6-meter-wide SC attached to the west wall, alongside a variable refrigerant flow (VRF) system and a separate outdoor air ventilation system. When comparing a setup with the SC to one without, the SC showed it could generate ventilation rates above the minimum required for most of the year, necessitating control measures to prevent excess outdoor air from increasing heating or cooling demands. Control strategies were simulated to maintain the total outdoor airflow at no more than one air exchange rate when the VRF is operational. The results demonstrated that incorporating the SC could lead to a 77.8% reduction in annual ventilation energy and a 2.3% reduction in VRF system energy, amounting to an overall annual energy saving of 549.0 kWh, or 9.0% of the total HVAC energy consumption for the modeled house.

Xinyu Zha et al. [17] focuses on the real-world application and effectiveness of a solar chimney for passive ventilation in a building in Eastern China. The study compares actual airflow measurements with theoretical predictions and computer simulations. Findings indicate that the solar chimney can achieve airflow rates ranging from 70.6 m3/h to 1887.6 m3/h. However, these rates are generally lower than theoretical predictions, leading to a recommended discharge coefficient (Cd) of 0.51 for practical applications. Using this Cd value, simulations suggest that in Shanghai's transitional seasons, a solar chimney could provide a 14.5% energy saving rate. The study confirms that solar chimneys can be a valuable energy-saving solution for residential buildings in regions with both hot summers and cold winters.

Solar Chimney Performance in Summer

Solar chimneys emerge as a sustainable method to cool buildings during summer by using the simple principle of thermal buoyancy, where the chimney's internal air, heated by solar energy, rises and generates a vacuum that draws cooler outside air into the building [18]. This passive ventilation technique not only provides a natural cooling effect but also significantly reduces electricity consumption by diminishing the need for air conditioning. Although solar chimney efficiency can be impacted by factors such as chimney height, material, and absorber characteristics, design optimizations have shown to enhance performance in various global case studies [19]. Despite challenges like potential overheating, solutions involving adjustable vents and integration with other passive cooling strategies have proven effective. This synergy of design and functionality underscores solar chimneys as an economically and environmentally beneficial feature for summer building climate control, offering a path to reduce greenhouse gas emissions and move towards greener building practices. Recent concerns about the COVID-19 pandemic have emphasized the role of indoor climate control in mitigating virus spread, as recognized by the Environmental Protection Agency in 2021 [20]. Heating and cooling systems in residences are crucial for maintaining comfortable indoor temperatures for occupants. According to research by Syed and Hachem [21], building operations account for over 30% of global primary energy use, which also contributes to the greenhouse effect. To curb carbon dioxide emissions, Xamán et al. [22] suggest that the increase in the use of renewable energy and the enhancement of energy efficiency are key strategies. Among renewable energy options—like wind, geothermal, and tidal energy—solar power stands out for its universality and cleanliness, as highlighted by Kumar and Singh (2020) [23]. Solar chimneys, which are an effective means of harnessing solar power, are being researched for their ability to provide passive heating and cooling in buildings. These systems not only ensure airflow and thermal comfort but are also cost-effective and environmentally friendly alternatives to traditional energy sources, offering a significant reduction in pollution, as reported by Sardari et al. [24].

Ventilation Rates and Cooling Potential

Solar chimneys serve as an innovative solution for enhancing ventilation and cooling within buildings during the hot summer months. They work by exploiting solar radiation to heat the air within the chimney, causing it to rise and exit through the top, which in turn pulls cooler air into the building from either windows or lower-level vents [25]. This process can significantly improve indoor air quality and reduce reliance on conventional air conditioning systems. Studies have quantified that solar chimneys can achieve ventilation rates sufficient to maintain comfortable indoor temperatures, even in buildings without mechanical cooling systems. In terms of cooling potential, solar chimneys have been acknowledged for their ability to lower indoor temperatures by several degrees, contributing to thermal comfort and energy savings [26].

Adaptation to High Temperatures and Sunlight Exposure

The effectiveness of a solar chimney is greatly influenced by its design, orientation, and material, which can be optimized to maximize its performance under high-temperature conditions and variable sunlight exposure [27]. By integrating features such as thermal storage materials and strategic shading, solar chimneys can adapt to fluctuating environmental conditions to provide consistent ventilation rates. Materials with high thermal mass absorb heat during peak sunlight hours and can release it slowly when the outdoor temperature drops, maintaining airflow overnight and into the early morning [28].

Numerous case studies across different geographical regions provide empirical evidence of the benefits of solar chimneys. For instance, research on residential and commercial buildings has demonstrated that a well-designed solar chimney can not only enhance comfort but also lead to energy savings by reducing the load on traditional HVAC systems [29]. Field data from these studies often show a significant reduction in energy consumption during peak summer periods. Moreover, comparative analyses between buildings with and without solar chimneys have yielded insights into optimal design strategies for different climates and exposures, offering a databank of practical applications and measurable outcomes [30]. These insights validate solar chimneys as a viable and efficient passive cooling strategy for sustainable building design.

Solar Chimney Performance in Winter

Solar chimneys serve as a sustainable solution for heating and ventilation during the winter months by using passive solar energy to warm and circulate air within buildings. They capture the low-angle sunlight prevalent in winter, warming the air inside the chimney to create an updraft that circulates heat throughout the structure [31]. This method is energy-efficient, reducing reliance on active heating systems and leading to significant savings. The design of solar chimneys for cold seasons incorporates high thermal mass materials for heat absorption and retention, strategic orientation for maximum solar exposure, and glazing to prevent heat escape. To optimize the ventilation-to-heat conservation ratio, solar chimneys preheat incoming fresh air, preserving indoor warmth while ensuring good air quality. Performance assessments from case studies reveal that with proper installation, solar chimneys can maintain comfortable indoor temperatures, circulate significant volumes of air, and reduce the overall energy footprint for heating, making them a viable strategy for energy conservation and improved indoor environmental quality in winter conditions [32].

The study uses three-dimensional simulations to evaluate how solar chimneys are affected by varying solar radiation, indoor heat source density, outdoor wind speeds, and the placement of heat sources within a room. It finds that these factors mutually enhance the ventilation capabilities of solar chimneys, confirming that they are more effective when the heat source is centrally located. The research demonstrates a significant improvement in ventilation rates when adjusting for these variables, with an increase in heat source density alone boosting ventilation volume by up to 32.1%. The presence of wind changes the optimal design of solar chimneys, suggesting a wider inlet is more effective under windy conditions. This data can inform the design and implementation of solar chimneys in buildings for improved natural ventilation. [33]

This paper introduces an innovative solar chimney that merges an inclined-roof design with a Trombe wall to enhance ventilation. The study undertakes a numerical analysis of this combined structure, evaluating its performance against that of separate Trombe walls and inclined-roof solar chimneys. It also examines the system's effectiveness across various operational modes and environmental conditions. For summer temperatures between 298 to 303 K, the research recommends using natural ventilation mode, while suggesting an anti-overheating mode to counteract excess heat. In winter, when temperatures drop below 273 K, a space heating mode is more efficient, whereas a preheating mode is beneficial for improving indoor air quality at temperatures above 278 K. The findings indicate superior ventilation with the combined solar chimney, which also successfully mitigates overheating, offering strategic insights into its optimal use. [34]

In a comprehensive exploration of sustainable architecture adapted to local climates, traditional techniques such as sunlight-reflective walls in hot regions and maximized solar energy utilization in colder climates have been historically prevalent. Modern urban development often overlooks these eco-friendly concepts, leading to economic and energy inefficiencies. Addressing the urgent need to conserve energy, this study employs Design Builder software for a simulation-based analysis, demonstrating the significant impact of solar chimneys on energy reduction in buildings. It is evidenced that a building with a solar chimney can maintain an indoor temperature of 22°C without mechanical heating, aligning with ideal comfort levels given 40-60% ambient humidity, thus presenting a compelling case for integrating solar chimneys to meet heating demands sustainably. [35]

During the winter season, solar chimneys continue to offer significant benefits by harnessing solar energy for natural ventilation and heating, contributing to energy efficiency and indoor comfort. A solar chimney's capacity to capture and utilize low-angle winter sunlight can be a pivotal feature in maintaining warmth and air quality in colder climates.

Heating Efficiency and Energy Savings

In winter, solar chimneys function by trapping solar heat to warm the air inside the chimney, creating a natural circulation of air that helps distribute heat throughout the building. This passive heating method reduces the demand on conventional heating systems, leading to substantial energy savings [36]. The efficiency of a solar chimney in winter is amplified by using materials with high thermal mass that absorb heat during sunny periods and release it slowly over time, providing a stable and continuous heat source even after sunset.

Design Considerations for Cold Climates

For optimal performance in winter, solar chimneys require careful design to maximize exposure to solar radiation. This includes considerations such as the chimney's orientation, insulation, and the use of glazing materials that allow for high solar gain while minimizing heat loss. A south-facing orientation (in the Northern Hemisphere) is commonly recommended to ensure that the chimney receives the maximum amount of sunlight during the day [37].

Ventilation Without Heat Loss

The challenge in winter is to maintain a balance between adequate ventilation and heat conservation. A well-designed solar chimney facilitates this by ensuring that the inflow of fresh air does not lead to significant heat loss. This can be achieved by preheating the incoming air using the greenhouse effect within the chimney, which not only improves the air quality inside the building but also supports heating needs without overreliance on active heating systems [38] [39], [40].

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Research and case studies have illustrated that buildings equipped with solar chimneys can sustain comfortable indoor temperatures and fresh air supply throughout the winter months [41], [42], [43], [44]. These studies provide performance metrics, such as the temperature rise achieved through solar chimneys, the volume of air circulated, and the corresponding reduction in energy use for heating [45], [46]. By considering the data from real-world applications, solar chimneys have been proven to enhance the thermal environment in residential and commercial buildings effectively, validating their role in climate-responsive and sustainable building design.

Conclusion

Solar chimneys are a powerful tool for eco-friendly climate management in buildings, offering year-round advantages by promoting natural cooling and ventilation in the summer while reducing reliance on electric air conditioning, thanks to tailored design and material choices that withstand seasonal extremes. In the winter, they switch roles to provide passive heating and effective air distribution, achieving energy efficiency and indoor warmth. Practical applications and studies validate solar chimneys' effectiveness as a sustainable architectural element that supports the global trend toward greener construction practices. By lowering energy use and greenhouse gas emissions, solar chimneys epitomize the integration of time-honored knowledge with modern techniques, advocating for energy-conscious design. Their evolution is a nod to the harmonious blend of historic understanding and innovative practices, driving forward a vision of sustainable and responsible building management and design for the future.

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