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Experimental Studies of Solar Chimneys; a Survey of Performance, Design, and Applications for Power Generation

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Article

Experimental Studies of Solar Chimneys; A Survey of Performance, Design, and Applications for Power Generation

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Abstract

This paper provides a comprehensive review of experimental solar chimney research, focusing on methods to improve power generation performance. These studies are systematically categorized based on parameters that include component dimensions, innovative structures, materials, environmental conditions, and combined mechanisms. Furthermore, an analysis of component dimensions and their interrelationships is presented. Additionally, the paper proposes a set of recommendations for future experimental endeavors aimed at addressing gaps in the exploration of experimentally investigated parameters and configurations. By unifying empirical findings within a scholarly framework, this review contributes to the ongoing literature of solar chimney power plants, facilitating further understanding and optimization of these systems for enhanced sustainability and efficiency. Investigations confirm that the key parameters discussed significantly influence solar chimney performance, emphasizing the importance of an optimal design balance.

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1. Introduction

Among available solar thermal systems, solar chimneys are of particular importance due to their power production functionalities, the simplicity of the structure, and natural convection operation. In addition to these attributes, solar chimneys have been recognized for their cost-effectiveness relative to solar photovoltaic (PV) systems, making them a competitive alternative in renewable energy portfolios. Their ability to generate electricity in areas where wind resources are insufficient is particularly noteworthy, as it allows for effective power production even in low-wind environments. Moreover, functioning as a self-contained power generation mechanism, solar chimneys harness solar thermal energy directly, thereby enhancing their applicability in a diverse range of geographical and climatic conditions. In spite of autonomous power production capability, using air with a low thermal conductivity as the working fluid impacts the thermal efficiency of the system and renders the system ineffective. It should be noted that, like any mechanism, solar chimneys face several implementation challenges. These include extensive land use and wildlife disruption, safety concerns for chimneys exposed to hurricanes and earthquakes, and the need for locations with appropriate latitude and solar radiation intensity. Numerous research studies have been carried out to optimize the performance of the system by implementing analytical, experimental, and computational methods. We provide a comprehensive review of experimental studies that assessed the performance of a solar chimney for power generation. While review papers have been previously published that focused on experimental works for power generation [1] and natural ventilation [2], this review aims to update this study and investigate the most recent experiments related to the power generation application of solar chimneys as well as possible correlations between dimensional parameters and outputs of solar chimneys.

This review is outlined as follows: Section 2 describes the working principle and fundamental components of a typical solar chimney. Section 3 provides an overview of studies that assessed the

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impact of solar chimney geometry on the system's performance. Sections 4 and 5 investigate several paths to optimize the design and enhance the performance of solar chimneys through variations in the conventional structure of collector and chimney components. Section 6 focuses on a broad spectrum of materials utilized in the construction of solar chimneys to further improve solar energy absorption while minimizing energy losses to the environment, which is followed by Section 7 focused on optimizing the optical properties of the collector component. Section 8 discusses studies that integrate energy storage into the structure of solar chimneys to deal with performance fluctuations due to variations in the incoming solar energy. In Section 9, the impact of environmental conditions on systems' performance is evaluated, which is then followed by Section 10, which investigates the proposed innovative structures of solar chimneys. In section 11, novel configurations that integrate solar chimneys with different systems, including photovoltaic and desalination, have been examined.

2. Solar Chimney Working Principles and Fundamental Components

The solar chimney, also called a solar updraft tower or solar power tower, operates on the principle of harnessing and capturing solar energy to generate electricity through natural convection. The history of solar chimney goes back to 1903, when the idea was introduced as "solar engine project" [3]. The first and only industrial unit was built in Manzanares, Spain in 1981. Since then, nearly all systems have been built on a smaller scale, exclusively for research purposes. A conventional solar chimney is generally made of a solar collector, a wind turbine, and a chimney. The solar collector is typically a large, transparent canopy that covers a wide area, allowing sunlight to heat the absorbing surface and, consequently, the air trapped underneath the collector. As the heat transfers from ground to air, the air becomes less dense and moves towards the top of the chimney. Air is drawn in from the base as a result of this natural convection flow, consequently creating a pressure gradient in the chimney. This upward flow of air drives turbines located at the base of the chimney, converting the kinetic energy into electricity.

The working principle of the solar chimney is based on the density difference as a result of the temperature difference between the heated air in the collector and the cooler air at the base of the chimney, which is shown in Figure 1. This temperature gradient creates a continuous flow of air in the chimney, driving the turbines and generating electricity without the need for additional fuel or mechanical systems. This natural airflow harnesses solar energy to generate a pressure differential, which serves as the driving force for the system's operation and energy production. The total pressure difference across the chimney, commonly referred to as the "stack effect," is calculated by integrating the buoyancy-driven pressure gradient along the chimney height. This difference drives the airflow, enabling the system's operation [4]:

$$\Delta p_{tot} = \int_0^{H_{ch}} g \cdot (\rho_a - \rho_{ch})\, dz \tag{1}$$

where H_{ch} is the chimney height, g is gravitational acceleration, and ρ is air density. The turbine's power output is proportional to the pressure drop across the turbine, the air's volumetric flow rate, and the turbine-generator system's efficiency. This equation highlights the energy conversion from airflow to usable power and is expressed as:

$$P_o = \frac{2}{3} \cdot \Delta p_{tur} \cdot \dot{V} \cdot \eta_{tur\text{-}gen} \tag{2}$$

where $\dot{V}$ is the volumetric flowrate of air and η is the efficiency of the turbine-generator system. The collector efficiency quantifies how effectively it converts incoming solar radiation into thermal energy in the air. It depends on air properties, flow velocity, and temperature rise across the collector which can be computed as:

$$\eta_{coll} = \frac{\rho \cdot v_{ch} \cdot A_{ch} \cdot c_p \cdot \Delta T}{G \cdot A_{coll}} \tag{3}$$

where v is the air velocity, A is the area, c_p is the specific heat capacity of air, ΔT is the temperature difference, and G is the solar radiation intensity. The chimney efficiency represents how effectively it converts thermal energy into kinetic energy of the air. This depends on the chimney height, gravitational acceleration, and the ambient temperature, given by:

$$\eta_{ch} = \frac{g \cdot H_{ch}}{c_p \cdot T_a} \tag{4}$$

where T_a is the ambient temperature. These equations form the foundation for understanding the energy conversion and efficiency of solar chimney power plants, providing insights into their design and performance optimization. Solar chimneys have the potential to provide a sustainable and clean energy source, especially in regions with abundant sunlight, offering an environmentally friendly alternative to conventional power generation methods. This mechanism has other applications as well, including natural ventilation in buildings. Researchers have covered all these applications in recent years, specifically natural ventilation[5]. Power generation is only discussed in this paper and specifically encompasses experimental research. Figure 2 shows the location of each experiment as well as its reference number.

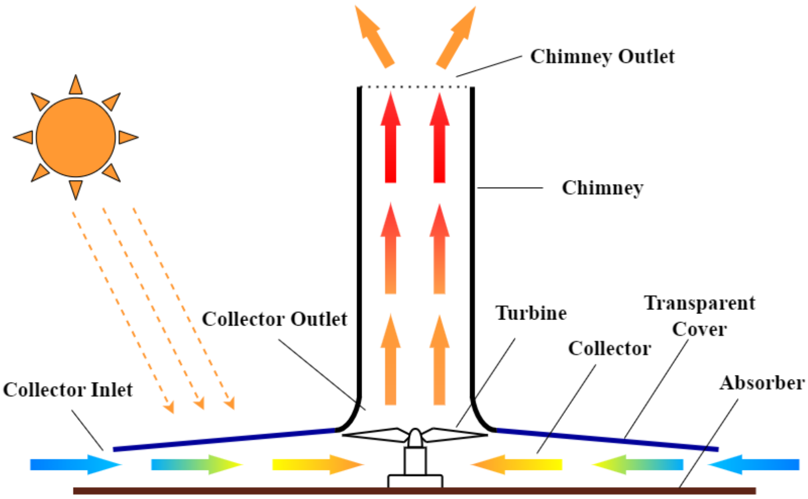

Figure 1. Schematic of conventional solar chimney working principles. The incoming solar radiation heats the absorber surface and the air in its vicinity. The heated air has a lower density, creating an upward airflow (the stack effect) within the chimney. The airflow is sustained by the existence of an energy source, diminishing as solar energy fluctuates and dissipates.

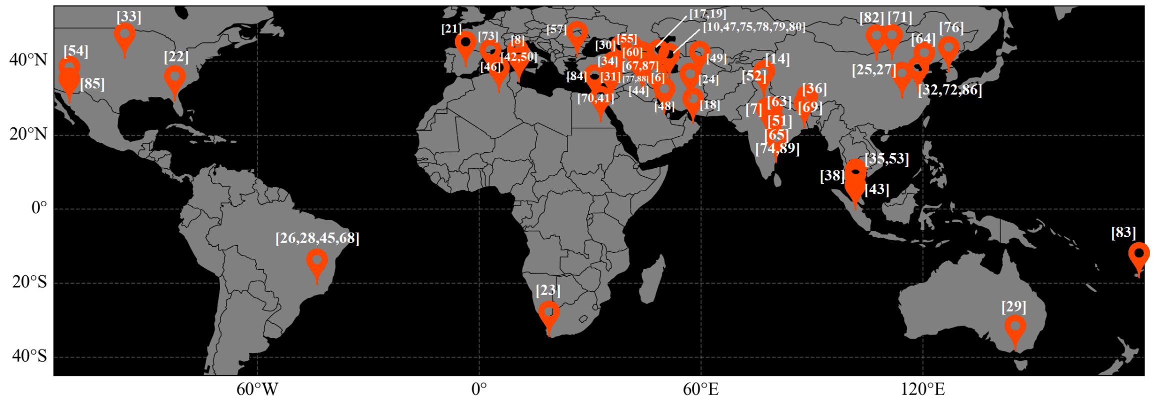

Figure 2. Global distribution of experimental setups for solar chimney studies, represented by their respective reference numbers as listed in the references.

The performance of solar chimneys is affected by a wide spectrum of parameters, from geometrical specifications such as chimney height and collector radius to environmental conditions such as solar irradiation intensity to ambient relative humidity. The system's performance can be improved by modifying the design of different components (such as the wind turbine or collector), by introducing new components into the system (e.g., guide vanes), or even integrating conventional solar chimneys with other systems (i.e., desalination system or PV panel) to increase economic viability and add new functionalities. Within the scope of this study, we are examining each of the aforementioned parameters and configurations and assessing their impact on the performance of solar chimneys in the context of experimental studies. Figure 3 provides an overview of these parameters and configurations; whereas the frequency of each subject examination is visually represented by increasing the designated bubble size.

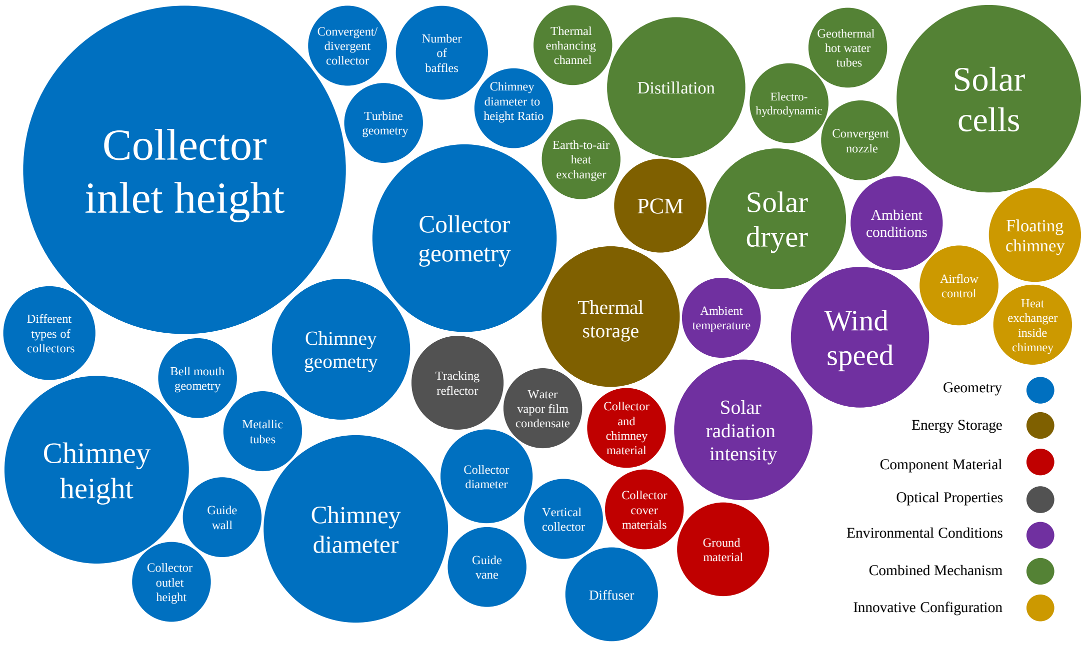

Figure 3. Distribution of experimentally investigated parameters in recent years. The size of each bubble corresponds to the frequency in which the parameter is studied in the literature.

3. Geometrical Characteristics of Solar Chimney Components

The following sections explore the first category of experimental studies, which have concentrated on understanding the impact of various dimensional parameters of the solar chimney, such as the height and diameter of the collector and the chimney on its performance. This exploration is essential as even subtle variations in these dimensions can lead to notable differences in the efficiency and effectiveness of solar chimneys. By examining these geometric factors, we can gain insights into optimizing solar chimney designs for maximum energy generation and operational efficiency. Furthermore, this examination helps identify gaps in the literature, providing a direction for future research on these parameters.

3.1. Chimney Height

The chimney height stands out as a particularly influential factor. The increased height of a solar chimney can offer positive effects on performance. Firstly, it enhances the stack effect, promoting more significant updrafts due to greater temperature and pressure differences between the base and top of the chimney. This increased stack effect leads to improved airflow, driving the turbines more efficiently and resulting in enhanced power generation and system efficiency. Studies conducted by Rishak et al. [6], Bansod et al. [7], and Jemli et al. [8] all highlight the positive impact of taller chimneys on the performance of solar chimney power plants. These studies were conducted in Iraq, India, and Tunisia, respectively. In the aforementioned studies, the height of the studied chimneys varied, spanning from 1 to 6 m.

While taller chimneys increase updraft, they can also result in flow and heat losses due to increased chimney area and total frictional resistance, diminishing overall efficiency. A laboratory prototype solar chimney experiment by Guo et al. [9] confirmed the benefits of increased chimney height, leading to greater updraft velocities and improved system efficiency. However, it also pointed out that ventilation efficiency weakens as chimney height increases, owing to heat and flow losses. Furthermore, another study by Ghalamchi et al. [10] emphasized the importance of optimizing chimney height, highlighting that deviation from a specific height range negatively impacts the performance and output of solar chimneys. This height range can be calculated based on the setup scale which was 3 meters in this case.

We can observe that there is a direct relationship between chimney height and updraft velocity. However, heat loss and flow loss will also increase, leading to an optimal chimney height that is coupled with parameters such as ambient temperature and insulation. Other disadvantages associated with taller chimneys in large-scale solar chimney power plants include increased construction costs that pose an economic challenge, as the potential for more power generation must be balanced against increased expenses for construction and maintenance [11]. Moreover, taller chimneys can have more pronounced environmental impacts, affecting landscape aesthetics and local ecosystems [12]. Maintenance becomes more complex and costly due to the height, requiring specialized equipment for inspections and repairs. Additionally, the structural stability of the system is directly linked to chimney height, which may necessitate more robust construction. Consequently, when designing large-scale commercial solar chimney power plants, careful consideration should be given to estimating the upper limit for chimney height.

3.2. Chimney Diameter

The chimney diameter plays a crucial role in balancing airflow dynamics (losses, air velocity distribution, and flow patterns), thermal efficiency, and also structural considerations. Larger diameters are generally advantageous for larger-scale applications, as they have more airflow capacity and enhance updraft. However, maintaining other dimensions constant while increasing the diameter above a specific limit can lead to decreased airflow speed, recirculated flow pattern, and reduced turbine efficiency. This indicates the importance of proportional and optimized geometric design for solar chimney dimensions, especially chimney height to diameter ratio [13]. Mehla et al. [14] conducted an analysis on a solar updraft tower equipped with a collector of 1.4 m in diameter and an 80 cm tall chimney. The study involved experimental assessments of chimney diameters ranging from 8 to 12 cm. It was observed that the maximum airflow velocity was achieved with a chimney diameter of 8 cm, and the ratio of the chimney diameter to its height was established to be 0.1. Another study by Ghalamchi et al. [10] tested different chimney diameters of 10, 20, and 30 cm for a 3 m tall solar chimney power plant. Observations indicated that larger chimney diameters result in lower air temperatures and decreased air velocity. Additionally, despite a minor velocity difference between 10 cm and 20 cm diameters, the smallest diameter significantly improved efficiency. These studies address the importance of chimney diameter itself and its relation with chimney height which leads us to consider dimensionless parameters like height to diameter ratio during the design process. The fact that a lower chimney diameter results in a higher updraft velocity has been noted in other numerical studies that have not been discussed here. However, the results of these two studies confirm this observation.

3.3. Collector Inlet Height

The next significant parameter in solar chimney design, particularly in the collector part, is the collector inlet height as shown in Figure 1 . It indicates the elevation at which air or fluid enters the collector for energy conversion processes and can influence airflow patterns, pressure, and overall chimney performance. The primary advantage of smaller inlets in solar chimneys lies in their ability to increase air velocity, a key factor in improving the efficiency and power generation [13]. This increased air velocity also promotes more effective energy conversion between the collector and air, along with minimizing air temperature variation but leads to a higher pressure drop within the solar chimney [15]. Conversely, a larger height of the collector inlet may form secondary flow patterns beneath the canopy, resulting in flow and thermal losses within the collector region as highlighted in [16].

The impact of inlet height on solar chimney performance has been studied, analyzing different configurations and their effects. In one study by Rishak et al. [6] various collector heights were examined, and it was found that smaller inlet openings led to an increased air velocity, higher temperature inside the collector, and greater power generation. Kasaeian et al. [17] examined a solar chimney power plant prototype with a 10 m diameter collector and a chimney height of 12 m. They studied the effect of two different collector inlet heights (5 cm and 15 cm) on performance and observed a higher temperature rise for the 5 cm inlet configuration. In another study focused on a solar chimney in Oman [18], various inlet openings at 25%, 50%, and full inlet opening were tested; and the largest temperature difference and velocity in the chimney were observed at the 25% opening level. Golzardi et al. [16] investigated the impact of inlet heights on two collector geometries (circular and square) and concluded that reducing the inlet height significantly improved outlet velocity and energy transfer for both circular and square geometries. A pilot study [19] with a 4 m chimney and a 5 m collector diameter showed that higher collector heights negatively affected performance, with the best results achieved at the smallest collector height of 5 cm. Finally, an experiment by Abbas et al. [20] altering air gap heights from 3, 4.5, to 6 cm demonstrated that the smallest air gap yielded the highest thermal performance. Considering these experiments, it is concluded that collector inlet height has an inverse relation with temperature difference and air velocity.

3.4. Collector Diameter

A larger collector size can provide a greater surface area for solar heat absorption and potential capacity for higher temperatures at the collector. In the experimental study conducted by Jemli et al. [8], a solar tower power plant unit was analyzed using three different collector diameters (varying from 2 to 8 m) and different heights. The study concluded that in constant chimney height, the power generated by the unit increased proportionally with the collector diameter. Although larger collector diameter result in higher air velocity, there is an optimal value for this parameter, as with other dimensions, because excessively large diameters may lead to lower air temperatures at the chimney inlet due to heat dispersion. It is evident that the number of experimental studies on collector diameter size is relatively low, indicating a need for further research in this area.

3.5. Examination of Geometrical Specifications and Thermal Performance

Figure 4 illustrates the extent to which key parameters and cofactors that influence the efficiency of solar chimneys are documented and reported in the investigated experimental studies. While the majority of the literature within the scope of this study has investigated the particular impact of one or several parameters on the performance of solar chimneys, some studies aimed to validate the accuracy of the numerical/computational models through the construction of experimental pilots that are summarized in Table 1.

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Table 1. Brief review of a portion of studied literature, whereas the main focus was to utilize experimental pilot plants to validate numerical/computational models of solar chimneys. D_{co}, $H_{in,co}$, D_{ch}, H_{ch}, V_{max}, and ΔT_{max} represent collector diameter, collector inlet height, chimney diameter, chimney height, maximum velocity within the chimney, and maximum temperature difference between collector and ambient, respectively.

Reference	Year	D_{co} (m)	$H_{in,co}$ (m)	D_{ch} (m)	H_{ch} (m)	V_{max} (m/s)	ΔT_{max} $(°C)$	Location
Haaf et al. [21]	1983	244	1.85	10.16	194.6	15	20 ± 1	Manzanares, Spain
Pasumarthi and Sherif [22]	1998	9.14	0.15	0.61	7.92	2.4	30	Gainesville, USA
Gannon and von Backstrom [23]	2003	4.5	-	1.6	-	1.48	-	stellenbosch, South Africa
Gholamalizade et al. [24]	2005	1600 m^2	-	3	60	-	-	Kerman, Iran
Zhou et al. [25]	2007	10	0.8	0.3	8	2.81 ± 0.01	24.1 ± 0.5	Hust, China
Ferreira et al. [26]	2008	25	0.05	1	12.3	2.75 ± 0.165	27.2 ± 1	Belo Horizonte, Brazil
Zhou and Yang [27]	2008	10	0.05	0.3	8		24	Wuhan, China
Maia et al. [28]	2009	25	0.5	1	11	2.5 ± 0.165	30 ± 1.4	Belo Horizonte, Brazil
Akbarzadeh et al. [29]	2009	-	-	0.35	8	-	-	Victoria, Australia
Buğutekin [30]	2010	27	0.05	0.8	17.15	5	25	Adiyaman, Turkey
Al-Dabbas [31]	2011	6	-	0.29	4	7	-	Mutah, Jordan
Kasaeian et al. [17]	2011	10	0.15	0.25	12	3	23	Zanjan, Iran
Mehla et al. [14]	2011	1.4	0.05	0.12	0.8	0.5	13	Shimla, India
Zuo et al. [32]	2012	4.5	0.15	0.08	2.5	-	14 ± 0.15	Nanjing, China
Li et al. [33]	2013	-	-	0.457	12.2	1.71 ± 0.05	-	Omaha, USA
Kalash et al. [34]	2013	-	0.05	0.31	9	2.9	12.5 ± 0.15	Damascus, Syria
Aja et al. [35]	2013	-	0.075	0.15	6	6	21	Seri Iskandar, Malaysia
Sakir et al. [36]	2014	4.57	0.2	0.152	3.05	1.8	4.5	Rajshahi, Bangladesh
Okada et al. [37]	2015	0.66	0.04	0.06	0.4	0.5	30	Laboratory Condition
Guo et al. [9]	2016	1.22	0.013	0.05	1	0.43 ± 0.01	14.6	Laboratory Condition
Kinan and Sidik [38]	2016	2	0.1	0.08	1.5	1.3	-	Kuala Lumpur, Malaysia
Ohya et al. [39]	2016	0.66	0.04	0.06	0.4	0.5	30	Laboratory Condition
Bansod et al. [7]	2016	1.8	0.003	0.04	2	9872	10	Amravati, India
Ghalamchi et al. [10]	2016	3	0.06	0.25	3	1.55	20	Tehran, Iran
Hu et al. [40]	2016	25	0.05	1	11	2.5 ± 0.1	25 ± 0.1	Laboratory Condition
Mekhail et al. [41]	2017	6	0.25	0.15	6	-	-	Aswan, Egypt
Jemli et al. [8]	2017	8	-	0.3	4	-	26.3	Borj Cedria, Tunisia
Ayadi et al. [42]	2017	2.75	0.05	0.16	3	1.3	-	Sfax, Tunisia
Ridwan et al. [43]	2017	0.575	0.06	0.083	1.93	2.2	10	Riau, Indonesia
Abbood and Abbas [44]	2017	6	0.03	0.25	6	-	23.2	Kerbala, Iraq
Maia et al. [45]	2017	25	0.05	1	12.3	2.21 ± 0.132	26.5 ± 1.1	Belo Horizonte, Brazil
Hadj et al. [46]	2018	3	0.05	0.16	4	2.4	18	Ouargla, Algeria
Fadaei et al. [47]	2018	3	0.06	0.2	3	2	-	Tehran, Iran
Hussain and Al-Sulaiman [48]	2018	1.6	0.003	0.15	2	-	-	Dhahran, Saudi Arabia
Bashirnezhad et al. [49]	2018	11	0.05	0.315	12	4 ± 0.1	-	Mashhad, Iran
Nasraoui et al. [50]	2018	3.7	0.1	0.154	2.95	1.65	-	Sfax, Tunisia
Balijepalli et al. [51]	2019	3.5	0.1	0.6	6	5.5 ± 0.223	12 ± 0.751	Warangal, India
Mehla et al. [52]	2019	1.86	0.09	0.3	1.78	1.9 ± 0.038	16.4 ± 0.3	Panchkula, India
Al-Kayiem et al. [53]	2019	6	0.05	0.15	6.65	1.9 ± 0.08	17 ± 0.35	Seri Iskandar, Malaysia
Bahrainirad et al. [54]	2020	4.13	0.15	0.3	5.9	1.1	15	Tucson, Arizona
Avcı et al. [55]	2020	25.2	0.6	1	11.5	1.9 ± 0.48	-	Batman, Turkey

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Reference	Year	D_{co} (m)	$H_{in,co}$ (m)	D_{ch} (m)	H_{ch} (m)	V_{max} (m/s)	ΔT_{max} $(°C)$	Location
Mehdipour et al. [56]	2020	2.25	0.03	0.1	2.5	0.4 ± 0.12	25.5 ± 0.3	Laboratory condition
Kuscu and Eryener [57]	2020	19.54	0.02	1.13	16.5	3.5 ± 0.4	13.5 ± 0.4	Edirne, Turkey
Mokrani et al. [58]	2020	12	0.05	0.2	8	7.1 ± 0.2	40 ± 0.1	Algeria
Abbas et al. [20]	2020	2	0.03	0.074	3	2.29	-	Laboratory Condition
Mehdipour et al. [59]	2020	2.26	0.03	0.1	1.94	1.63	39.02	Laboratory Condition
Khidhir and Atrooshi [60]	2020	9	0.3	0.3	6	2.4	10.85 ± 0.54	Erbil, Iraq
Huang et al. [61]	2020	2.6	0.035	0.08	2.05	-	-	Laboratory Condition
Guzel et al. [62]	2021	6.4	0.5	0.7	8	2.2	2.4	Turkey
Rishak et al. [6]	2021	3	0.05	0.1	4.5	2.5	5	Basrah, Iraq
Belkhode et al. [63]	2021	4.5	0.6	0.15	4.8	8.321	2.386	Nagpur,India
Wang et al. [64]	2021	2.44	0.06	0.2	2	-	-	Qingdao, china
Rajamurugu [65]	2021	3.6	0.2	0.37	3.2	3.1	-	Chennai, India
Golzardi et al. [16]	2021	2.257	0.05	0.1	1.94	0.33 ± 0.01	23.6 ± 0.1	Laboratory Condition
Aliaga et al. [66]	2021	-	-	0.15	2	-	-	Laboratory Condition
Ahmed et al. [67]	2022	3.485	0.035	0.1016	3	1.8 ± 0.036	-	Kirkuk, Iraq
Maia and Silva [68]	2022	5	0.1	0.2	2.5	1.322	-	Belo Horizonte, Brazil
Mandal et al. [69]	2022	2.5	0.15	0.1	6	1.5	-	Kolaghat, india
Esmail et al. [70]	2022	28.5	1.25	1	19	1.87 ± 0.1	6.5 ± 0.065	Aswan, Egypt
Wang et al. [71]	2022	4	0.1	0.12	2.5	2.5 ± 0.1	-	Hohhot, China
Zuo et al. [72]	2022	6.25	0.3	0.3	4	2.7 ± 0.03	17 ± 0.25	Nanjing, China
Ikhlef et al. [73]	2022	5.93	0.05	0.24	4.2	2.8 ± 0.58	12	Algiers, Algeria
Adamsab et al. [18]	2022	1.7	0.07	0.023	2.14	1.4	15.2 ± 0.1	Al Musannah, Oman
Likhith Raj et al. [74]	2022	2.44	0.03 - 3	0.12	2	1.5 ± 0.045	16 ± 2.2	Chennai, india
Arefian and Hosseini Abardeh [75]	2022	8	0.2	0.6	8	1.37 ± 0.07	-	Tehran, Iran
Kang et al. [76]	2023	3	0.07	0.16	3	1.7 ± 0.1	7 ± 1	Seoul, South Korea
Hussein and Nima [77]	2023	4	0.03	0.065	3.5	1.7	-	Baghdad, Iraq
Afsari et al. [78]	2023	3.4	0.06	0.25	12	2.3	15	Tehran, Iran
Nia and Ghazikhani [19]	2023	5	0.1	0.4	4	2.1	10.6	Zanjan, Iran
Rezaei et al. [79]	2023	3.44	0.06	0.25	12	2.59 ± 0.1	22 ± 0.1	Tehran ,Iran
Bagheri and Hassanabad [80]	2023	0.886	0.075	0.09	1.26	1.49 ± 0.07	2 ± 0.05	Tehran ,Iran
Hu et al. [81]	2023	2	0.08	0.254	3	2.5 ± 0.02	-	Laboratory Condition
Nie et al. [82]	2024	2.4 m^2	0.1	0.08	1.3	1.535	10 ± 0.1	Bayannur, China
Prasad and Ahmed [83]	2024	3.2	-	0.658	8	8.29 ± 0.41	18 ± 0.09	Suva, Fiji
Elsayed et al. [84]	2024	5	-	0.25	3	2.3 ± 0.115	30 ± 0.1	Giza, Egypt
Moreno et al. [85]	2024	2	0.1	0.273	3	-	-	Sonora, Mexico
Zuo et al. [86]	2025	6.5 m^2	0.3	0.315	5.3	1.89 ± 0.2	-	Nanjing, China
Merie and Ahmed [87]	2025	5.6 m^2	-	0.1	3	1.59 ± 3	-	Kirkuk, Iraq
Al-Ghezi et al. [88]	2025	2	0.08	0.1	2	2.5 ± 0.3	-	Baghdad, Iraq
Natarajan et al. [89]	2025	2.6	0.03	0.18	4	4.49 ± 0.1	35 ± 0.1	Chennai,India

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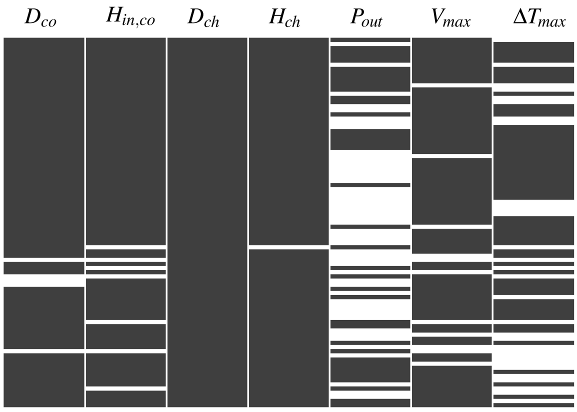

Figure 4. Missingness (white color) observed in the studied literature for geometrical dimensions and the output parameters of solar chimneys. D_{co}, $H_{in,co}$, D_{ch}, H_{ch}, P_{out}, V_{max}, and ΔT_{max} represent collector diameter, collector inlet height, chimney diameter, chimney height, power output of wind turbine, maximum velocity within the chimney, and maximum temperature difference between collector and ambient, respectively.

Figure 5 visualizes the distribution of these geometrical parameters, which include the collector's and chimney's diameter and height. As illustrated, the experimental studies, which are often utilized to validate the accuracy of the numerical and computational models, investigated a broader range of values for the collector inlet height; whereas, for the remaining parameters, these studies examined a narrower range of values, where the resulting systems are often classified as small-scale solar chimneys. It is also worth mentioning that there were few studies that experimentally assessed medium-scale systems such as Avcı et al. [55]. Haaf et al. [21] constructed the only large-scale solar chimney experimental system in Manzanares, Spain, and examined its performance in real-time [90], which is removed from this visualization to improve the quality of the graphics in the presentation of Figure 5.

Here we explore the thermal performance of the experimental solar chimneys through the evaluation of collector temperature rise and maximum velocity within the chimney. While the generated power by the wind turbine is a prominent factor in determining the efficiency of solar chimneys, as depicted in Figure 4 and described in Table 1, the majority of the literature did not report any meaningful values. Figure 6 visualizes the maximum temperature rise within the collector and maximum velocity within the chimney with respect to the collector's and chimney's dimensions, respectively. Aside from not having any thermal performance parameters, three common issues within the studied literature are discrepancies in reports of temperature rise and maximum velocities (as visualized in Figure 4, some studies did not report either temperature rise or maximum velocity or even both), inadequate information regarding the environmental conditions that resulted in the reported values, and lack of uncertainty analysis for the experimental data. Moreover, inconsistencies regarding the spatial placement for reporting these parameters could lead to misinterpretation of the data, incorrect data assessment, and a challenging comparison of data with other works.

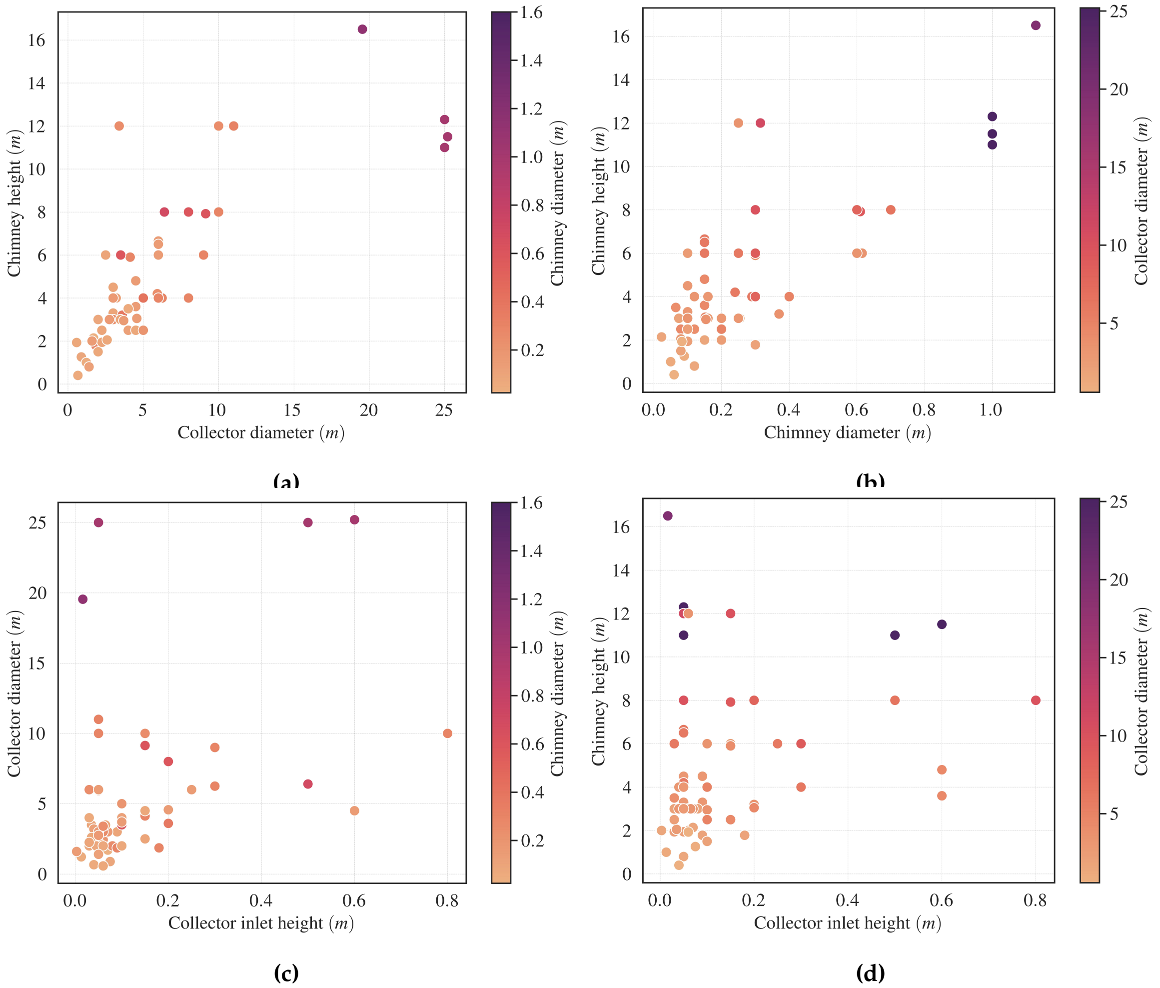

Figure 5. Plot of possible correlations between various geometrical characteristics of solar chimneys within the scope of the studied literature with experimental approaches: (a) Chimney height vs collector diameter, (b) Chimney height vs chimney diameter, (c) Collector diameter vs collector inlet height, (d) Chimney height vs collector inlet height. As shown in the above subfigures, while the experimental results provide comprehensive information for small-scale solar chimneys, they also reveal a lack of data for medium and large-scale systems.

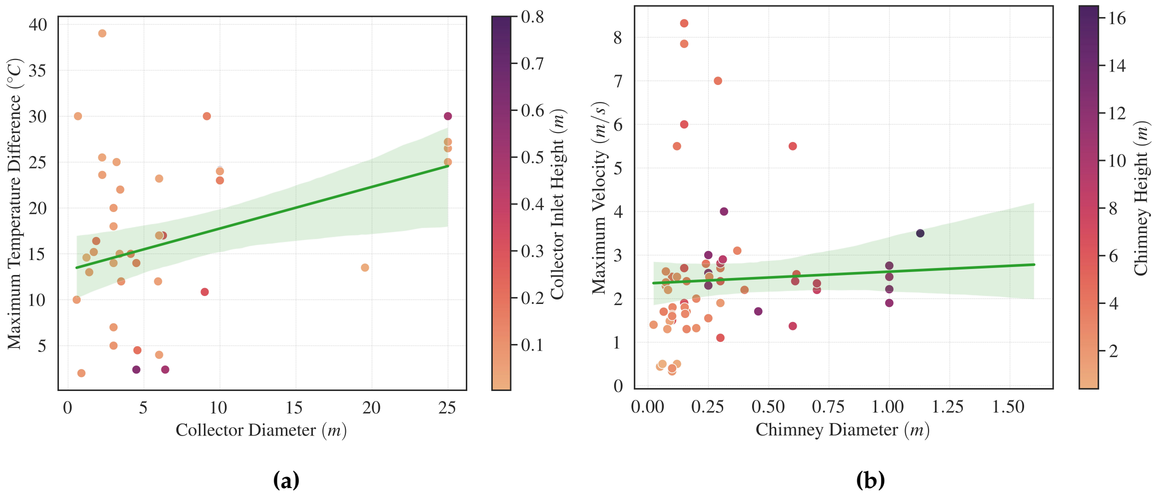

Figure 6. Exploring the potential correlation between various solar chimney geometrical specifications with respect to their thermal performance within the scope of the studied literature with experimental approaches: (a) Maximum temperature difference between collector and ambient vs collector diameter, (b) Maximum velocity within the chimney vs chimney diameter

4. Other Geometrical Assesments

Unconventional parameters related to the geometry of solar chimneys are investigated in this section. These studies examined a broader range of parameters, from the intricacies of turbine design to the exploration of collector outlet heights, vertical collectors, and divergent chimney structures. Each study plays a critical role in optimizing the efficiency of solar chimney power plants. Understanding these parameters in detail is essential for enhancing solar chimneys and tailoring their design to environmental and operational conditions.

4.1. Turbine Design

The turbine is a vital component in converting the kinetic energy of solar-heated air into electrical energy. Turbine and generator section, or what called power conversion unit in solar chimney, adds to the maintenance costs of the system. This cost is calculated during the design process based on the system scale and different model used, for instance in one study 0.18% of capital cost was considered for operation and maintenance of the power conversion unit which encompasses turbine [91]. The design and sizing of the turbine are pivotal, engineered to efficiently transfer energy without hindering the airflow, while also being designed for low maintenance, durability, and enhanced efficiency. Gannon and von Backstrom [23] conducted an experimental study to examine the performance of a solar chimney turbine. This study focused on a turbine with a single rotor, featuring a 12-bladed axial rotor with adjustable stagger angles, and utilized chimney supports as inlet guide vanes (IGVs) to introduce pre-whirl. The investigation involved using measurements from a scaled model turbine to evaluate efficiency and performance. The findings revealed high values of total-to-total efficiencies ranging between 85% and 90% and total-to-static efficiencies from 77% to 80% within the designated design parameters.

The number of studies focusing on the power conversion unit or turbine design in solar chimneys is quite low and largely confined to numerical analyses. Therefore, we recommend applying those findings in future experiments to assess how turbine optimization affects solar chimney performance under real environmental conditions.

4.2. Collector Outlet to Inlet Ratio

The ratio of the collector's outlet to inlet height can indicate variations in the cross-sectional area and consequent changes in the velocity of air passing through the collector. Rajamurugu [65] examined a solar chimney with a divergent chimney, which has a higher outlet collector size than the inlet. For an inlet size of 0.2 m, different collector outlets of 0.4, 0.6, and 1.2 m were examined. The larger collector outlet showed a greater power output and was proven to result in the maximum airflow velocity. Likhith Raj et al. [74] conducted both numerical and experimental analyses of flow inside a Solar Chimney Power Plant (SCPP) with four different collector configurations and a fixed chimney divergence angle of 2°. The experiments used a 1:1.22 chimney length to collector diameter ratio and were carried out in an open atmosphere, measuring velocity and temperature. Among the considered cases, the partially convergent collector with a 10° divergence angle exhibited the best performance based on computational and experimental results, achieving a maximum velocity of 1.5 m/s with a temperature increase of $14°C$.

4.3. Vertical Collector

Vertical collectors are specialized solar thermal collectors that are vertically oriented to efficiently capture solar energy. These collectors typically consist of vertically aligned tubes or panels designed to maximize solar exposure based on latitude and weather patterns (Figure 7a). An example of a solar chimney utilizing a vertical collector was constructed by Bagheri and Hassanabad [80]. It consisted of a vertical collector surrounding a building with a chimney on top of it (scaled at 1:50) for both ventilation and power generation simultaneously. Based on the experimental results, it was concluded that improved orientation and design of the solar collector, at the scale of the Manzanares power plant, could yield four times higher energy output due to the increased pressure difference. Additionally, energy loss decreased due to the buoyancy force and velocity both being in the vertical direction. Another reported benefit of using a vertical collector was a reduction in land usage.

4.4. Collector Geometry

Efficient heat absorption from the collector ensures maximum solar energy utilization; while high thermal conductivity promotes a uniform temperature profile across the collector surface, enhancing the system's overall performance. Additionally, the design and material of the collector significantly affect the airflow within the chimney; a well-designed collector facilitates smoother and more efficient airflow, directly impacting the plant's power generation capability [92]. While circular collectors are commonly used, alternative shapes like rectangular, square, or triangular have also been explored. Kinan and Sidik [38] found that a circular collector in a 1.5 m tall solar chimney performed approximately 6% better in various parameters compared to a square shape collector due to larger surface area for heat transfer. In another study [34], a triangular solar collector with a 35° slope was integrated with a 9 m tall chimney. Despite winter season conditions, this setup achieved an air temperature peaking at 19 °C and generated a maximum updraft velocity of 2.9 m/s in the chimney. Furthermore, Mehdipour et al. [59] conducted tests on two solar chimneys with circular and square geometries, utilizing single-inlet collector shapes under laboratory conditions and varying heat fluxes (Figure 7b). According to the results and specific design and flow conditions, the square-shaped collector outperformed the circular configuration, achieving higher airflow velocity and thermal efficiency. The study also concluded that increasing the collector area in the circular collector chimney doesn't enhance its performance, as it leads to a larger inlet cross-sectional area and increased outgoing flow from the inlet. In contrast, the square-shaped collector with a chimney installed on one side does not exhibit this issue since it minimizes the secondary flows and directs more airflow to the chimney. In another experiment, Pasumarthi and Sherif [22] made two adjustments to the collector, extending the base and introducing an intermediate absorber. These modifications led to improvements in air temperature and mass flow rate, consequently increasing the power output of the chimney. Altering the collector's geometry can have positive effects. These changes may be implemented based on climatic conditions or various applications of solar chimneys, which naturally lead to different outcomes.

(a) (b)

Figure 7. Experimental investigation of various collector designs: (a) Built prototype of solar chimney with vertical collector, reproduced with permission No. 5937170648629 [80], (b) Fabricated setups for the solar chimney (conventional geometry and the square-type collector), reproduced with permission No. 5937200412727 [59], all components of the experimental setups are visible in the respective images

4.5. Divergent Chimney

In conventional solar chimney configuration, chimneys typically take on a long, slender cylindrical shape with a constant cross-sectional area. However, several experimental studies have introduced alternative diverging chimney shapes, characterized by a larger outlet diameter than the bottom inlet. This diverging geometry enhances the system's efficiency by improving air velocity, airflow management, and convection currents. Despite their efficiency benefits, this geometry poses challenges, including increased structural complexity and manufacturing costs, which should be carefully considered for larger-scale applications.

Rajamurugu [65] demonstrated that a diverging chimney design improves the efficiency of solar chimneys, as evidenced by tests on a 3.2 m tall model. The outlet air velocity was nearly twice as high as that of a conventional cylindrical chimney. Another study by Ahmed and Patel [93] initially proposes an optimal 2-degree divergence angle for chimneys, determined through numerical simulation and then validated by experiments on a 4 m tall prototype. Additionally, studies by Okada et al. [37] and Ohya et al. [39] have investigated the performance of divergent diffuser-type chimneys with varying angles (0°, 2°, and 4°) in comparison to circular conventional design using laboratory experimentation and computational fluid dynamics (CFD) analysis on a scaled model. The results showed that the 4° angle is the optimal shape for the chimney divergent shape, and it was found to increase air velocity by approximately 1.38–1.44 times and boost power generation output to 2.6-3.0 times that of the cylindrical tower.

As can be observed, the number of studies on these geometrical parameters is quite low, leaving key questions about their effectiveness at larger scales and in different climates. For instance, in turbine design there is room to explore alternative rotor configurations that better match the airflow within the channel. The scalability of vertical collectors and various collector shapes also requires further investigation to identify the best designs for different scales and environments. Additionally, the large-scale construction and structural stability of divergent chimneys present challenges that must be addressed.

5. Enhanced Configurations

A range of innovative modifications and additions, such as metallic tubes, baffles, and guide vanes are discussed here. Each of these elements represents a strategic modification designed to optimize the capture and conversion of solar energy, as well as to improve airflow and heat transfer within the system. The subsections that follow provide detailed insights into how these enhancements, supported by experimental studies, contribute to the overall effectiveness and potential of solar chimney technology.

5.1. Metalic Tubes Inside the Collector

Utilizing metallic tubes in a solar chimney as absorbers of solar radiation enhances the system's efficiency. Suspended from the collector's canopy, these tubes heat the air inside the chimney, increasing the air temperature and creating a stronger buoyancy force. The experimental setup of this chimney is depicted in Figure 8. This results in increased upward airflow, leading to higher system efficiencies. Rezaei et al. [79] investigated the effect of placing an array of 120 metallic tubes, covering 10% of the collector canopy's surface. This setup increased the temperature at the chimney inlet by about 5°C, resulting in an 8% rise in collector efficiency compared to cases without tubes.

5.2. Baffles

One of the improvements in the configuration of solar chimneys, specifically concerning the collector part, involves the use of baffles. Baffles regulate the speed of incoming air and evenly distribute it across the collector area, preventing the air from bypassing the collector without being adequately heated. They enhance heat transfer by increasing the surface area for heat exchange, leading to a more uniform temperature distribution and effective heat absorption. However, it is important to note that these baffles can create flow resistance and a consequent pressure drop, which can diminish the natural draft and reduce overall efficiency if not properly designed. Wang et al. [71] conducted an experimental study focusing on the impact of baffles within the collector of a solar chimney. The research examined six distinct baffle designs to determine their influence on

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(a) (b)

Figure 8. Insertion of hanging metallic tubes in the collector: (a) Side-view of hung metallic tubes from the canopy of the collector [79], (b) Overall view of the experimental solar chimney setup, reproduced with permission No. 5937201014767 [79]

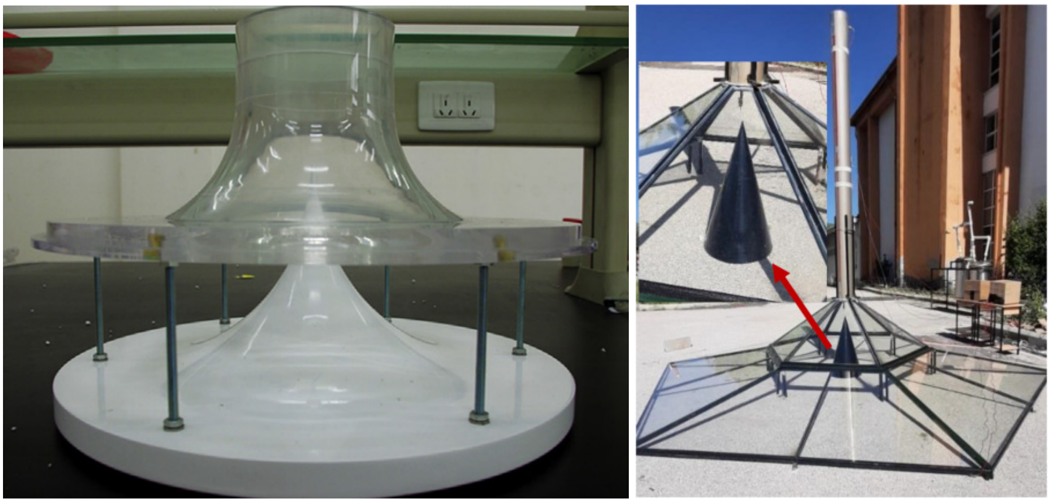
system performance. Findings revealed that half-size, straight baffles were particularly effective, outperforming other types in terms of enhancing both temperature and air velocity. The study also noted a positive correlation between the number of baffles and performance improvement, albeit with a concurrent rise in construction costs. Furthermore, it was established that the optimal number of baffles is dependent on the intensity of solar radiation, indicating a need for adaptable design strategies. To mitigate the impact of external crosswinds, the study by Wang et al. [64] suggests installing a set of transparent baffles at the inlet of the collector. The study includes both experimental tests and numerical simulations to assess solar chimney models with different numbers of baffles. Three configurations were analyzed: an SCPP with no baffles, one baffle, and two baffles. The results demonstrated that using one baffle increases the chimney inlet temperature and velocity by 0.92% and 11.83%, respectively, compared to the configuration with no baffles. Furthermore, employing two baffles leads to improvements of 3.92% in temperature and 18.70% in velocity, along with a collector efficiency boost of 58.52%

5.3. Guide Vanes

Guide vanes or walls, when added to the collector-to-chimney transition area in solar chimney systems, serve as crucial components for efficiently directing horizontal air flow upwards into the chimney. These structures are instrumental in improving flow control, significantly mitigating turbulence, and consequently boosting the system's overall efficiency. Beyond their aerodynamic functions, guide vanes can also act as structural supports for turbines [40]. Several studies have emphasized the positive impact of guide vanes on the performance of solar chimney power plants. Ikhlef et al. [73] conducted an experimental study on a SCPP with a guide vane in Isparta, Turkey (Figure 9b). The results revealed that addition of the guide vane to the device improved performance by reducing turbulence in the collector, increasing efficiency by 21%. Furthermore, it was observed that wind speed outside the collector had a negligible effect on energy production. Das and Chandramohan [94] focused on enhancing the performance of a solar updraft tower plant by utilizing guide vanes inside the canopy. Significant improvements were observed in flow and performance parameters in the case with guide vane compared to the baseline case. The maximum average velocity at the chimney base and theoretical power potential increased by 9.4% and 10.7%, respectively. Additionally, The overall efficiency of the solar updraft tower system was enhanced by 46.7% during study period by using guide vanes. The study concluded that guide vanes positively affected the system's performance, but further research is needed to optimize the guide vanes for even better results. In their study, Hu et al. [40] introduced a guide wall configuration at the center of the collector to assist air flow from the collector to the chimney, which is shown in Figure 9a. The performance of this modified chimney was experimentally evaluated against a baseline case, encompassing various chimney geometries.

Additionally, numerical simulations were conducted to assess the effects of different guide wall heights. These simulations revealed that the potential maximum power output, which was mainly governed by the driving force, increased with increasing the guide wall height. Notably, the power output of the SCPP experienced an approximate 40% enhancement in a cylindrical-chimney system and around 9.0% in a divergent chimney system, compared to the configurations without a guide wall.

All discussed configurations each have been shown experimentally to enhance solar chimney performance. Metallic tubes suspended under the collector canopy raise inlet temperatures and buoyancy forces, yielding up to an 8 % increase in collector efficiency. Baffles improve heat transfer uniformity and air-flow distribution, with optimal designs delivering up to 18.7 % higher inlet velocity and significant efficiency gains. Guide vanes streamline the transition from horizontal to vertical flow, reducing turbulence and lifting overall system efficiency by around 46.7 % in certain setups. Despite these promising results, the underlying parameter space remains sparsely explored. In particular, there is still room for research in optimizing baffles, guide vanes and metallic tubes, examining variations in geometry, spacing, orientation, and material properties. Likewise, dynamic performance under fluctuating solar radiation and crosswinds needs further study, as does the scalability of these enhancements to large-scale chimneys.



(a) (b)

Figure 9. Utilization of guide vane in the collecor: (a) Collector-to-chimney transition section with a white solid guide wall subset, reproduced with permission No. 5937210060622 [40], (b) Diffuser of the solar chimney prototype, reproduced with permission No. 5937210444412 [73]

6. Material Selection

In order to achieve the highest efficiency, one should choose materials that enhance the absorption of solar energy, reduce heat loss, and improve the conversion of thermal energy into electricity. Moreover, these materials must be long-lasting and environmentally sustainable to support extended operational lifetime. Minimum heat loss is crucial for all components, while maximum transmissivity, absorptivity, and minimum weight are necessary for the collector roof cover, collector bottom, and turbine blade, respectively. Experiments related to component materials in recent years mostly involve collector materials.

Belkhode et al. [63] carried out an experimental study to analyze the performance of various collector cover materials in a solar updraft tower. The research revealed that increasing the chimney height from 3.6 m to 4.8 m resulted in higher power output, with 37.92%, 36.13%, 16.78%, and 32.18% improvement for glass, acrylic, crystalline, and polycarbonate sheets as roof collector materials, respectively. Glass emerged as the most reliable roof collector material, showing a 5% to 15% increase in power output potential compared to the other materials. Another experiment was focused on the absorber material [10]. Aluminum and iron were chosen as the absorber. Aluminum absorber outperformed iron absorber in terms of heat transfer due to a higher thermal conductivity . Al-Ghezi et al. [88] tested sand, pebble, and a mixture of sand and pebble as the absorber material. The Pebble resulted in the highest efficiency compared to the others due to higher conductivity, specific heat, and surface area. In other experiments, where it was not focused on the component materials, collector roof covers were mostly made of plastic, glass, acrylic sheet, or Perspex [13]. It should be noted that testing different materials for being used as the chimney has not yet been done experimentally in one research.

Selecting appropriate component materials is critical to the performance and sustainability of solar chimneys. Glass has proven to be a superior collector cover material due to its high transmissivity and durability, despite being heavier and more expensive than alternatives like acrylic or polycarbonate. Aluminum as an absorber offers significant advantages in heat transfer efficiency, making it preferable over iron in experimental setups. However, there is a notable gap in experimental research regarding chimney materials, which presents an opportunity for further studies. Future research should explore innovative materials for chimney construction to optimize thermal and mechanical performance while ensuring cost-effectiveness and environmental sustainability. This direction could significantly enhance the efficiency and applicability of solar chimney systems.

7. Optical Properties

The transmissivity of collector roof cover can influence the incoming energy of a solar chimney. Material selection plays a significant role in increasing transmissivity. It is also essential to clean the collector roof cover surface periodically, as dust and dirt can decrease the transmissivity of the surface.

An experiment examined dust and moisture effects on collector roof cover transmissivity, focusing on water vapor condensation. A 10-day experiment found that morning condensation of humid air on the collector roof cover notably reduced the absorption of solar radiation, impacting both collector and solar chimney efficiency (Figure 10). Wet canopies resulted in 9% to 10% less solar radiation absorption. Condensation took 2 to 3 hours to evaporate, lowering the wet canopy's air temperature by 3 to 5°C [53].

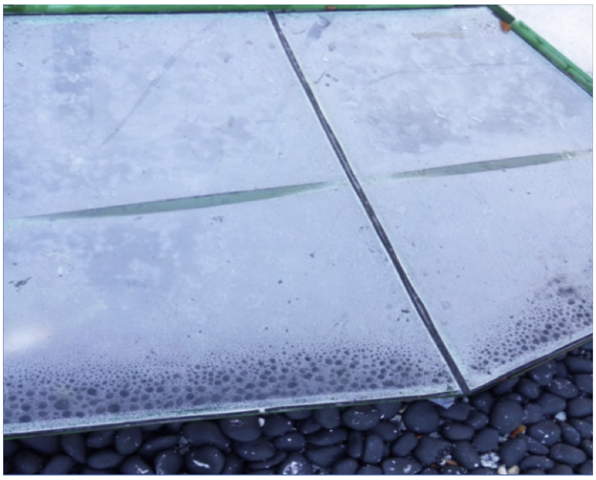


Figure 10. Water vapor condensation film on the collector cover, reproduced with permission No. 5937210610125 [53]

One way to increase the absorption of solar radiation by the collector is to use an external reflector. This method has received much attention in recent years. Hussain and Al-Sulaiman [48] explored the effectiveness of incorporating reflectors into a solar chimney power plant design and compared its performance to a conventional one. Conducting a detailed thermodynamic analysis, they found that the reflector-enhanced design increased energy efficiency by 22.61% and power output by 133%. The study utilized both analytical and empirical models, noting a modest 8% variance between them. The reflector-enhanced solar chimney achieved an average power output of 230 kW and an energetic efficiency of 0.641%. The findings indicated that while the floor component had the highest potential for exergy improvement, the incorporation of reflectors significantly boosted the overall efficiency and power output of the system.

Khidhir and Atrooshi [60] used tracking reflectors to enhance solar radiation in the lower part of the chimney. The reflectors were installed far from the collector and reflected solar radiation to the lower part of the chimney inside the collector. DC motors were used to change the direction of the mirrors during the experiment. This design was used to increase the temperature difference inside the collector. By using this method, an increase in airflow velocity by up to 25% was achieved, where the air density was reduced by approximately 2%.

Condensation on the canopy can significantly reduce solar radiation transmittance, delaying energy conversion and reducing system efficiency during early operational hours. Incorporating reflectors effectively enhances solar radiation capture, improving temperature gradients and airflow dynamics, thereby increasing the overall efficiency of solar chimney power plants. These experiments have focused on the effect of humid air condensation on transmissivity and the application of reflectors. Other parameters that can be considered for future experiments may involve the optimum thickness of different materials and their hydrophobicity. The application of iron-free glasses or Fresnel lens as the collector roof cover material to increase transmissivity can be considered as well.

8. Energy Storage to Mitigate Intermittency

Solar chimneys cannot provide a consistent power output; and their effectiveness can be reduced during cloudy days or at night, necessitating the integration with energy storage. Energy storage allows for the capture and storage of excess energy generated during the day, which can then be used to generate power, increasing the overall efficiency and reliability of the system. Researchers have examined the effect of energy storage on the output of solar chimneys by testing different materials as the collector absorber. Mehla et al. [52] employed four different materials as heat absorbers in the collector of the chimney; where black PVF plastic polythene, gray sand, small stone pieces, and small water packets were individually placed in the collector. The collector outflow was monitored during the experiment; and collector efficiency, exergy, and overall efficiency were calculated for each scenario. The highest temperature difference and the aforementioned efficiencies were achieved when using small stone pieces. The study concluded that increasing the temperature difference between the collector outflow and the ambient environment enhances collector efficiency and exergy, but it results in a decrease in the average chimney efficiency.

Ikhlef et al. [73] conducted an experimental study on a small-scale SCPP with a thermal storage system. The prototype, consisting of a chimney tower and an air collector, was tested with various thermal energy storage (TES) to assess their impact on the SCPP's performance. Among the TES options, crushed gravel demonstrated the best efficiency compared to asphalt, sand, and sand plus water, reaching 89.73%. Figure 11 illustrates the use of crushed gravel at the bottom of the collector.

Afsari et al. [95] used soil as the thermal storage material at the bottom of the collector. This choice did not significantly impact the overall efficiency. While an air velocity of 0.2 m/s was recorded at night hours, a slightly lower air velocity was observed during the day compared to the conventional collector. Additionally, the temperature difference increased by only 0.5°C. Abbood and Abbas [44] worked on thermal storage materials for the collector. Three different materials were tested: sand, a combination of pebbles and sand, and black pebbles, all of which served as the collector absorber. Black pebbles resulted in the highest airflow temperature inside the chimney, while the combination of pebbles and sand exhibited the highest surface temperature and temperature difference between collector and the ambient. It was found that black pebbles had the highest thermal storage quality among these three materials. It is evident from the results of the articles that changing the absorber material to store energy in the collector will not affect only one output. One material may increase the temperature difference, while another may result in an increase in airflow velocity by reducing friction. This issue should be considered in the design process. The use of phase change materials (PCMs) for

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Figure 11. Use of crushed gravel inside the collector, reproduced with permission No. 5937210444412 [73]

energy storage, in addition to other materials, has also received recent attention. Utilizing PCMs has both positive and negative effects. Energy storage and the operating hours of the solar chimney will be enhanced. Nevertheless, some issues, such as a limited operating temperature range and complexities in design and heat transfer, could have negative effects if not properly implemented.

Bashirnezhad et al. [49] conducted experimental research on a solar chimney power plant utilizing phase change materials like water and paraffin as thermal storage. The study revealed that incorporating water and paraffin improved productivity period by 9% and 20% and power output by 6.2% and 22%, respectively. Specifically, the model using paraffin generated the highest electrical output of 11.5 kWh/day. Furthermore, the paraffin system demonstrated increased efficiency and offered more operational stability. Fadaei et al. [47] also used paraffin wax as a phase change material with the purpose of heat storage inside the collector. Results showed an increase in both air velocity and temperature.

Reviewing these experiments, it can be concluded that the proper integration of PCMs enhances energy storage and, consequently, the performance of solar chimneys. Considering different materials, crushed gravel is the best heat storage material due to its high collector efficiency (89.73%), and paraffin wax is the best PCM due to its high heat storage potential and heat release during phase changes. Additionally, this approach offers advantages such as cost savings and improved economic feasibility of the system. However, it can bring complexities and tradeoffs in terms of airflow, peak performance timing, and material selection. Further research is required in this field, given the vast array of available PCMs. There is room for experimental studies to gather more data on the suitability of different PCMs for energy storage in solar chimneys to ensure consistent power generation. The optimization of PCM properties in solar chimneys, including thickness, melting point, thermal conductivity, and other parameters, must also be further studied.

9. Environmental Conditions

In the previous sections, we have explored several categories of experimental studies, which encompass studies focused on the variation of the geometrical specifications to the enhanced configurations and integration of energy storage into the conventional design. In this section, we shift our focus to the notable influence of environmental conditions on system performance. This section examines how factors such as wind speed, solar radiation intensity, and ambient temperature play crucial roles in shaping the efficiency and output of solar chimneys.

9.1. Effect of Wind On the Performance of Solar Chimney

Generally speaking, ambient wind has both positive and negative effects on the driving force and efficiency. The driving force is caused by the density difference, which results from the convective heat released from the collector cover and the absorber. These heat sources can be limited by ambient wind in two ways. First, ambient wind can cause convective heat loss by passing through the collector cover, thereby reducing the surface temperature. Additionally, when entering the collector area from the collector inlet, the wind can displace the hot air inside, diminishing the buoyancy driving force. The collector inlet height plays a significant role in minimizing this effect. The lower the collector inlet height, the less negative impact ambient wind will have. Ambient wind can also have positive effects. When passing through the top of the chimney, it creates negative pressure at the chimney outlet, increasing the updraft velocity inside the chimney. This effect is more pronounced when the chimney outlet aligns with the direction of the wind flow rather than being perpendicular to it. The effect of wind speed on updraft velocity was investigated by Esmail et al. [70]. Their study revealed that wind speed at the top of the chimney can significantly increase updraft velocity. In the absence of solar radiation, a wind speed of 6 m/s or higher can produce an updraft velocity equal to that produced under high solar radiation. In contrast, wind speeds lower than 2.1 m/s will result in a downward airflow. Moreover, during the daytime, high wind speeds increase heat loss from the collector, reducing the buoyancy effect. Another study investigated how ambient wind speed and direction influence the performance of a south-facing inclined solar chimney power plant model [35]. The research revealed that wind speed significantly affects convective heat loss through the system's cover and walls to the surroundings. Additionally, this case study found that the system performs best when the wind blows from the south to the north. At the same time, performance is negatively affected when the wind blows from any other direction. The research suggested that using inlet guide vanes as windbreakers at traditional solar chimney power plant collector inlets can mitigate wind-related losses and improve overall system performance.

While ambient wind poses challenges such as increased convective heat loss and potential displacement of hot air within the collector, it also presents opportunities to enhance system performance by increasing outlet air velocity. Studies have shown that strategic design choices, such as optimizing the collector inlet height and incorporating windbreakers or inlet guide vanes, can mitigate the negative effects while leveraging the positive impact of wind at the chimney outlet. These findings underscore the importance of tailoring solar chimney designs to regional wind patterns and environmental conditions, thereby improving efficiency and ensuring robust performance under varying climatic scenarios.

9.2. Effect of Solar Radiation Intensity

Solar irradiation serves as the primary energy input for the solar chimney. The effectiveness of a solar chimney is tied to the intensity and interval of solar irradiance, influencing the system's temperature difference, airflow velocity, and energy output. Therefore, the selection of the installation site for a solar chimney power plant holds great importance, requiring ample solar radiation for the technology to be both economically feasible and operationally effective. A solar simulator was constructed for testing a solar chimney in laboratory conditions by Guo et al. [9]. Variable solar radiation intensity was examined, and its impact on efficiency and updraft velocity was measured. Higher solar radiation intensity led to higher efficiency. It was emphasized that the relationship between solar radiation intensity and updraft velocity and efficiency is not linear. Another experiment by Ahmed and Patel [93] revealed a direct relationship between solar radiation intensity and absorber temperature, velocity, and output power. Higher solar radiation intensity enhances the performance of a solar chimney power plant, resulting in a greater temperature difference, a stronger updraft in the chimney. However, the relationship between solar radiation intensity and collector efficiency is non-linear. As solar radiation intensity increases, the rate of improvement in collector efficiency decreases.

9.3. Effect of Ambient Temperature

The environment significantly influences the system's efficiency. Parameters such as solar radiation intensity, wind speed, air humidity, air pressure, location, pollution, climate, and seasonal changes each exert varying influences on efficiency, impacting different aspects of the system. In the case of ambient temperature, an experiment conducted by Jemli et al. [8] revealed that solar radiation had a more pronounced effect on output power compared to ambient temperature. Furthermore, an experimental test conducted by Kasaeian et al. [17] uncovered an air inversion phenomenon in the chimney during the morning hours, attributed to low ambient temperatures. This phenomenon dissipated as ambient temperatures rose after the morning hours, resulting in a steady-state airflow within the chimney. In general, ambient temperature affects the solar chimney performance and power generation, and it is also proportional to the temperature distribution inside the chimney.

10. Innovative Structures

Some researchers have focused on innovative structural modifications that can be applied to solar chimneys. These modifications often involve rethinking the design and, in some cases, considering the removal of certain components to enhance the overall efficiency and effectiveness of the system. For instance, the concept of using a heat exchanger within the chimney, as an emplacement for employing a collector, was initially proposed by Aliaga et al. [66]. This innovative approach was designed to harness external reflectors positioned at a distance from the chimney to redirect solar radiation onto the heat exchanger located inside the chimney. Their experiment involved a 2-meter-high channel equipped with heaters serving as the heat exchanger. It was reported that the modified chimney achieved a higher energy density compared to conventional solar chimneys. This approach is suitable for areas with spatial constraints. Two other approaches have also been reported, which are suitable for windy environments. Arefian and Hosseini [75] introduced a floating solar chimney comprising a hollow vertical tube as the chimney and a conventional collector. As downwash flows and vortices inside the chimney can reduce the updraft flow in the system when ambient crosswind is present, this type of chimney was designed to tilt in response to ambient crosswinds for improved performance. The experiment conducted under ambient conditions revealed that floating solar chimneys can perform effectively when exposed to ambient crosswinds, even with a lower height than conventional solar chimneys. Additionally, it was noted that the chimney has an optimal tilt angle that varies with different wind speeds. In another experiment, controlling solar chimney power output was demonstrated through airflow management, allowing different operating conditions to reach their maximum power points. Results indicated that employing an airflow controller can enhance power output by up to 50% in solar chimney systems [57].

11. Combined Solar Mechanisms With Solar Chimney

Hybrid solar chimneys merge a conventional solar chimney with supplementary mechanisms, typically for functions such as power generation, cooling, drying, or water desalination. They provide opportunities for eco-friendly energy generation and a range of applications, but they are accompanied by notable obstacles involving cost, land requirements, and climate dependence.

11.1. Desalination

Hybrid solar chimneys with desalination mechanisms offer a sustainable way to generate electricity and provide fresh water, making them potentially valuable in arid regions with abundant sunlight and limited freshwater resources. A small-scale experimental setup combining a solar chimney with seawater desalination was constructed and evaluated under ambient conditions by Zuo et al. [32]. The results demonstrated that the integrated system can efficiently produce both power and freshwater with distilled water being generated mostly during periods without solar radiation. Compared to a standalone solar chimney power generation system, the integrated system offered significantly improved solar energy utilization efficiency. Zuo et al. [72] also presented an experimental pilot for a solar chimney power plant combined with distillation for water-electricity cogeneration. Experimental research under ambient conditions revealed the interaction between parameters such as seawater temperature, airflow temperature, temperature difference, freshwater yield, and generated power. Key findings include an optimal arrangement of solar stills, a high-water yield period, and the influence of temperature on freshwater production. The study showed that the daily water yield of solar stills decreases as it moves from the heat collector inlet to the chimney and recommends arranging the solar stills in the area from the collector inlet to one-third the radius of the collector. Hu et al. [81] presented a novel solar desalination system. The system utilized a solar collection chamber with thermal insulation glasses and an integrated metal-sheet chimney to draw ambient air, condense moisture, and facilitate evaporation. Laboratory tests revealed that up to 84% of the supplied energy was utilized for water evaporation, demonstrating effective moisture removal through the chimney-effect-induced airflow. Several conclusions were drawn, including the importance of fully humidifying the airflow for efficient condensation, the impact of chimney height on water production, and the need for improved heat transfer on the chimney surfaces. Moreno et al. [85] explored water desalination in arid climates using a compact solar chimney. The study combined experimental and numerical methods to assess the feasibility of integrating desalination mechanisms with solar chimneys. Experimental results indicated that the system achieved a freshwater production rate of 2.1 liters per hour under peak solar radiation conditions. Key findings highlighted the efficiency of heat absorption by the solar chimney and its impact on desalination rates, emphasizing the role of compact designs for small-scale applications in arid regions. The study demonstrated that the hybrid system can significantly optimize energy usage for both power generation and desalination. Similarly, Elsayed et al. [84] investigated a solar chimney integrated with a bladeless wind turbine and explored its potential for sustainable energy harvesting. Though primarily focused on energy generation, the study also discussed absorber materials, including shredded rubber, which enhanced thermal efficiency. Experimental results showed that shredded rubber absorbers improved thermal performance by up to 38.9% compared to concrete absorbers. This improved heat transfer capability could support desalination processes when combined with appropriate mechanisms. The integration of bladeless turbines with solar chimneys introduces novel ways to enhance hybrid systems for water and energy applications. These types of hybrid solar chimneys, with the desalination mechanisms mentioned here, have the potential to be transformative in addressing water scarcity challenges in arid regions. Their advantages include low operational costs, sustainability, and dual functionality in producing both energy and fresh water. However, challenges such as initial investment costs, scalability, and the need for consistent solar radiation limit their current practical implementation. Further research is necessary to address these limitations, optimize their efficiency, and develop cost-effective deployment strategies.

11.2. Photovoltaics

The purpose of integrating solar chimneys with photovoltaic (PV) modules is to utilize the collector area to produce more electric power. PV modules can be placed on top or at the bottom of the collector for extra power generation. The advantage of doing this is to increase the efficiency of PV modules. As the airflow passes inside the collector, it works as a working fluid for cooling the top or bottom surfaces of PV modules by convection, depending on where the PV modules are installed. By reducing the surface temperature, the efficiency of PV modules will increase. This will also help the airflow get warmer, which increases airflow velocity inside the chimney. Experiments in recent years have mostly focused on the emplacement of PV modules. Hassan et al. [96] placed solar cells in the collector of a solar chimney to investigate the behavior and electrical efficiency of the solar cells. Their results showed that more electrical power is produced during the morning hours due to the lower temperature of the solar cells. Additionally, because of the higher airflow velocity at the collector inlet, solar cells near the collector inlet remained at a lower temperature compared to cells located in the center of the collector. Huang et al. [61] used PV modules separately inside and on the top of the collector. By replacing approximately 50% of the collector surface with PV modules, the airflow rate decreased by only 14%. However, a considerable amount of electricity was produced. This experiment

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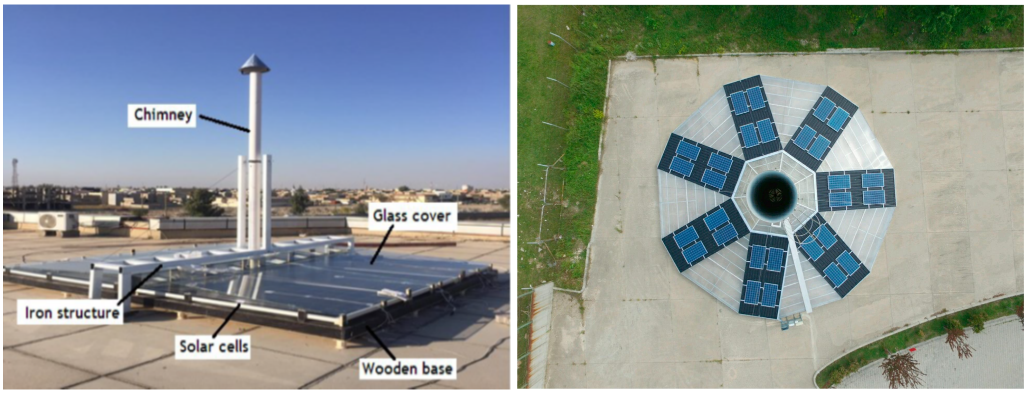
was then used to validate a large-scale simulation, which showed that if the entire collector surface is covered with solar panels, the flow rate decreased by approximately 40%. Still, the total electric power output would significantly increase. Another experiment by Eryener and Kuscu [97] showed that covering 42% of the collector roof with PV modules results in an average 2% increase in solar chimney efficiency.

Based on the reviewed experiments, it can be concluded that utilizing PV modules inside the collector to generate more power is feasible. While it does reduce the airflow to some extent, the overall power output increases while decreasing surface area. The effect and output of PV modules vary depending on their position inside the collector, whether they are located on top or at the bottom of the collector and their proximity to the collector inlet or chimney. Figure 12 shows examples of using photovoltaic panels in the solar chimney. The use of transparent solar cells for the collector roof cover is a recommended approach for future research.



(a) **(b)**

Figure 12. Utilization of photovoltaic panels in solar chimneys: (a) Utilizing solar panels inside the collector [96], (b) Utilizing solar panels on the collector, with visible components such as the central chimney, surrounding glass collector area, and symmetrically arranged rectangular solar panels on each collector segment, reproduced with permission No. 5937220512580 [97]

11.3. Solar Dryer

Another way to utilize the field occupied by the collector is to use it as a solar dryer for agricultural products. This can help reduce energy costs for the drying process. A limited number of experiments have been conducted for this purpose in recent years. One of these experiments was conducted using a prototype located in Brazil. It involved the continuous monitoring of critical parameters such as air velocity, temperature, and humidity. The prototype generated a hot airflow with an average temperature rise of 13°C compared to ambient air, enabling a drying capacity of approximately 440 kg and a reduction in relative humidity from about 63% to 53% [26]. In another experiment, Maia et al. [45] investigated the potential of the collector for use as a solar dryer. Exergy was calculated both with and without a load, which was the drying process of bananas. An increase of 7% in exergy was reported in the case with a load. Researchers have suggested that the central part of the collector be used for drying purposes due to higher air velocity and temperature. Moreover, due to heat losses through the ground and the plastic cover, thermal insulation under the ground and using covers with higher solar radiation transmittance and lower infrared transmittance was recommended to enhance solar dryer efficiency. Many experiments are required to collect sufficient data for the potential use of the collector as a solar dryer. The viability of the collector area with various agricultural products and the influence of product-induced humidity are parameters recommended for further study.

11.4. Other Systems

Various innovations and mechanisms have been employed to enhance the efficiency of solar chimneys. These systems have been designed to increase air temperature or velocity inside the collector and chimney. Due to the diversity of these designs, they are separately investigated in

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this section. Al-Kayiem et al. [98] examined thermal enhancing channels inside the collector. These channels acted as a barrier when facing ambient wind and, consequently, mitigated the adverse impact of ambient wind. Through this optimization, the velocity and airflow temperature inside the chimney increased by 6.87% and 6.3%, respectively. In another study, geothermally treated water was used as an additional heat source. A spiral pipe carrying geothermally treated water was placed within the collector. The study conducted experiments to measure temperature profiles across the collector, the chimney's entry temperature, and air velocity. These tests included scenarios of night-time water heating and daytime solar irradiance heating and two directions of water circulation. The experiments revealed that nighttime heating with water raised the temperature of the collector center to 37.1°C and air velocity to 5.1 m/s. Combining solar irradiance with water further elevated the temperature of the collector center to 80°C and air velocity to 7.1 m/s [58]. Li et al. [33] explored an innovative passive air conditioning system that combines earth-to-air heat exchangers (EAHEs) with solar collector-enhanced solar chimneys. The system harnessed both geothermal and solar power, resulting in significant energy savings for buildings and a reduction in peak electricity demand during the summer. Experiments were conducted during the summer in a test facility to assess the system's performance. The coupled system's maximum cooling capacity was reported to be 2.5 kW. Ghalamchi et al. [99] conducted experimental research to investigate the impact of electrohydrodynamic (EHD) systems with different electrode layouts on a solar chimney pilot setup. The experiment revealed that integrating an EHD system significantly enhances the chimney's performance, especially when employing a parallel electrode layout with six electrodes spaced 3 cm apart. This configuration resulted in an increase in outlet air temperature of up to 14°C, a decrease in outlet absorber temperature by 7°C, and an overall performance improvement of approximately 28%. However, the study identified limitations in the radial and symmetric layouts due to constraints related to electrical current and ineffective heat transfer mechanisms. Jemli et al. [8] conducted an extensive study on the performance of a Solar Tower Power Plant with a natural convection effect for electricity generation. The research examined factors such as climatic conditions, chimney height, and collector diameter to evaluate their impact on electricity production. By utilizing a convergent nozzle, hot air velocity got high enough to drive a wind turbine, converting kinetic energy into electricity. The results indicated that for an 8 m diameter chimney with a 2 m height in 45°C temperature, the average electrical power output was 0.3 W/m^2.

Before concluding, it is helpful to summarize the main parameters and their corresponding effects on solar chimney performance. Table 2 provides an overview of these factors, illustrating how each parameter can either enhance or hinder the system's efficiency.

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Table 2. Key parameters and their effects on solar chimney performance.

Parameter	Effect	Comment
Chimney height ↑ [6], [7] [8], [9], [10]	updraft velocity ↑, heat loss ↑, flow loss ↑, construction cost ↑	There is an upper limit due to stability and function.
Chimney diameter ↓ [10], [13], [14]	updraft velocity ↑	There is a lower limit due to stability and turbine structure.
Collector inlet height ↓ [6],[13],[15], [16], [17], [18], [19]	temperature difference ↑, updraft velocity ↑	Larger inlet height results in secondary flow pattern with heat and flow loss.
Collector diameter ↑ [8]	updraft velocity ↑	Has an upper limit due to heat dispersion.
Collector outlet to inlet ratio ↑ [65], [74]	updraft velocity ↑	Different optimal values were reported.
Collector geometry [80], [92], [22], [34], [38], [59]	Different results based on structure and environmental conditions	No specific shape was reported as the most efficient.
Divergent chimney [65], [93], [37], [39]	updraft velocity ↑	All reports are in agreement.
Baffles [64], [71]	temperature rise ↑, updraft velocity ↑	It results in more uniform temperature distribution and also regulates the incoming air velocity.
Guide vanes [40], [73]	overall efficiency ↑, power output ↑	Their most significant effect is mitigating turbulance.
Utilizing reflectors [48], [60], [53]	temperature difference ↑, updraft velocity ↑	Reflectors increase the temperature gradient by enhancing the radiation intesity.
Energy storage [52], [73], [44],[49], [47], [95]	temperature difference ↑, efficiency ↑	They are suitable for continues power production at night hours.
Wind [35], [70]	Increases updraft velocity at high speeds; if low, can cause downward flow in the chimney. Also induces convective heat loss through the collector cover.	Wind direction is a key factor to be utilized for enhancing updraft velocity inside the chimney.
Ambient temperature [8], [17]	Can cause air inversion if low	It generally can control the temperature distribution inside the chimney.

12. Conclusions and Future Work

This paper has presented a comprehensive review of experimental investigations into solar chimneys for power generation, categorizing and analyzing the influencing parameters examined to date. We have also discussed innovative designs and combined mechanisms aimed at enhancing solar chimney performance, alongside an analysis of component dimensional relationships. While this review has strived to encompass all experimentally investigated parameters in recent years, a clear disparity exists between the number of experimental studies and numerical analyses in the field. This imbalance underscores several critical knowledge gaps that future research should address to advance the practical implementation of solar chimney technology.

- Moving forward, we recommend a significant shift towards experimental investigations that address the limitations of current research. Firstly, while small-scale solar chimney performance has been extensively studied, there is a pressing need for experimental data from **medium- and large-scale prototypes** to validate scaling effects and assess real-world energy generation potential. Understanding the performance characteristics and potential challenges associated with larger systems is crucial for their eventual deployment.

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- The **material selection in experimental studies** has predominantly focused on the solar collector. To gain a more holistic understanding of system performance, future experiments should place greater emphasis on the **material properties of the chimney itself**, investigating their impact on airflow and overall efficiency.
- The **incident angle of solar radiation**, a known significant factor for solar collectors, has often been overlooked in experimental studies of solar chimneys. Future work should prioritize detailed investigations into the transient behavior of solar chimneys under varying incident angles throughout the day, providing crucial insights for optimizing collector design and system operation.
- Given the geographical dependence of solar energy systems, exploring the **impact of collector orientation** is vital. Specifically, for the northern hemisphere, experimental studies investigating the performance of south-facing collectors, including novel designs like half-circular configurations, warrant further attention.
- Considering the ultimate goal of electricity generation, there is a significant lack of experimental studies integrating **turbines** within solar chimney setups. Future research must focus on the practical challenges and performance characteristics of solar chimneys coupled with turbine systems to better evaluate their power generation capabilities.
- Exploring **alternative collector designs**, such as vertical collectors combined with concentrators, represents a promising avenue for performance enhancement that has received limited experimental attention. Future studies should investigate the feasibility and effectiveness of such configurations.
- The integration of **energy storage** remains a critical area for development. Future experimental work should focus on testing a wider range of materials for thermal energy storage within solar chimneys, alongside optimizing parameters like material thickness and placement to improve system efficiency and dispatchability.
- Recognizing the growing global challenge of freshwater scarcity, further experimental investigation into **solar-driven desalination chimneys** is essential. Research should focus on optimizing the integration of desalination [100] units with solar chimneys to enhance the economic viability and efficiency of this sustainable solution.
- The influence of **atmospheric optical properties** such as sky clearness and air pollution on solar radiation collection deserves more detailed experimental analysis. Additionally, exploring the use of advanced materials like iron-free glasses and Fresnel lenses for the collector cover to increase transmissivity warrants experimental investigation. Furthermore, the impact of **environmental parameters** such as relative humidity and air density on solar chimney performance should be more thoroughly examined through controlled experiments.

By addressing these identified knowledge gaps through rigorous experimental investigation, the field of solar chimney technology can move closer to realizing its potential as a viable renewable energy solution.

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Nomenclature

CFD	Computational Fluid Dynamics
EAHE	Earth to Air Heat Exchanger
EHD	Electrohydrodynamic
IGV	Inlet Guide Vane
PCM	Phase change Material
PV	Photovoltaic
SCPP	Solar Chimney Power Plant
TES	Thermal Energy Storage
$H_c h$	Height of the chimney (m)
g	Gravitational acceleration (m/s^2)
$\Delta p_t ur$	Turbine pressure drop (Pa)
$\dot{V}$	Volumetric flow rate of air (m^3/s)
$\eta_t ur - gen$	Efficiency of the turbine-generator system (dimensionless)
ρ	Air density (kg/m^3)
$v_c h$	Velocity of air at the chimney inlet (m/s)
c_p	Specific heat capacity of air (J/kg·K)
ΔT	Temperature difference between the collector inlet and outlet (K)
G	Solar radiation intensity (W/m^2)
A	Area (m^2)
T_a	Ambient temperature (K)

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