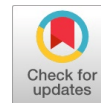




Experimental Investigation of a Domestic Solar Chimney with Variable Collector Inclination for Passive Building Ventilation



Birju R. Yagnik, Bharat M. Ramani

Abstract: Various passive means of increasing the air movement in interior spaces have received significant attention due to the continuous effort made by the building industry in decreasing the amount of energy consumed due to the conventional means of mechanical ventilation and cooling systems. Several passive ventilation systems are available; however, the solar chimney system has become an efficient alternative since it uses solar energy to produce a convection effect and hence natural ventilation. This work involves the design and analysis of a residential solar chimney under the climate of Jamnagar, Gujarat, India. For experimental development of the unit, the hexagonal solar collector is attached to the central tapered chimney. To evaluate the effect of collector orientation on the heat transfer process, inclined collector operation was performed at angles of inclination equal to 10°, 20°, and 30°, with the same geometrical characteristics. The air temperatures at the specified points were measured with calibrated K-type thermocouples. Theoretical analysis based on energy balance, buoyancy flows, and natural convection equations was also used to evaluate temperature distributions and airflow generation. Based on analytical predictions, air temperature will increase as heat is gained from the sun and collected through the collector. Under typical summer conditions, the outlet air temperature will be higher than the ambient air temperature by about 9–10°C. In the configurations tested, the inclined collector with a slope of 10° showed the highest heat gain and efficiency because it captured solar radiation more efficiently. The analysis also shows that the system can sustain natural ventilation without the use of fans. In general, the findings show that a mini solar chimney can be a viable and energy-efficient alternative for ventilating homes in areas with high amounts of solar insolation. The approach adopted, methodology used, and predictions made in this study will form the basis for future experiments, simulations, and geometry optimization to improve the efficiency of mini solar chimneys.

Keywords: Solar Chimney, Passive Ventilation, Natural Convection, Solar Air Collector, Collector Inclination, Renewable Energy, Thermal Performance, Buoyancy-Driven Airflow, Domestic Buildings, Heat Transfer.

Nomenclature:

MOO: Multi-Objective Optimization
CFD: Computational Fluid Dynamics
SSCPP: Sloped Solar Chimney Power Plant
HSCPPs: Hybrid Solar Chimney Power Plants
MS: Mild Steel
SCPPCD: Solar Chimney Power Plant and a Desalination System

Symbol	Description	Unit
A_c	Collector area	m^2
A_{ch}	Chimney cross-sectional area	m^2
C_d	Discharge coefficient	–
C_p	Specific heat of air	$J\ kg^{-1}\ K^{-1}$
D_i	Chimney inlet diameter	m
D_o	Chimney outlet diameter	m
g	Gravitational acceleration	$m\ s^{-2}$
Gr	Grashof number	–
H	Chimney height	m
H	Convective heat-transfer coefficient	$W\ m^{-2}\ K^{-1}$
I	Solar irradiance	$W\ m^{-2}$
I_e	Effective solar irradiance	$W\ m^{-2}$
k	Thermal conductivity	$W\ m^{-1}\ K^{-1}$
M	Mass flow rate	$kg\ s^{-1}$
Nu	Nusselt number	–
P	Pressure	Pa
Pr	Prandtl number	–
Q_u	Useful heat gain	W
Ra	Rayleigh number	–
Re	Reynolds number	–
RH	Relative humidity	%
T_a	Ambient temperature	$^{\circ}C$
T_i	Inlet temperature	$^{\circ}C$
T_o	Outlet temperature	$^{\circ}C$
V	Air velocity	$m\ s^{-1}$
V_w	Wind speed	$m\ s^{-1}$
ΔP	Stack pressure difference	Pa
ΔT	Temperature rise	$^{\circ}C$

I. INTRODUCTION

The demand for energy-efficient buildings has led to the development of ventilation techniques that can make buildings comfortable while reducing the use of mechanical cooling systems. As ventilation and air conditioning make up a major percentage of the energy consumption of buildings, especially in tropical regions, this has become a crucial field

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of study. The solar chimney has been regarded as one of the most promising techniques of passive ventilation due to the use of solar energy to develop buoyant flow without using any electricity. Solar radiation heats the air in the collector, decreasing its density and leading to buoyant flow in the chimney. As a result, fresh air from the environment will constantly enter the building, improving natural ventilation. Due to the simplicity of design and maintenance, the solar chimney has been used in different buildings.

The performance of the solar chimney depends on several parameters, such as the collector geometry, chimney dimensions, absorber properties, glazing, insulation, and collector inclination. In this regard, although the effect of collector inclination has been less investigated experimentally in the context of small-scale prototype systems, it has a considerable impact on solar energy collection as well as airflow generation. Furthermore, earlier studies have mainly concentrated on simulation work or large-scale systems.

To overcome this limitation, the current study proposes a domestic solar chimney that employs a regular hexagonal solar air collector coupled with a central tapered chimney. The collector angle was varied to 10°, 20°, and 30° for comparative purposes in relation to thermal behaviour at similar structural parameters. A theoretical approach, which involves energy balance and buoyancy effects, was used for the design, considering summer climatic data of Jamnagar, Gujarat, India. K-Type thermocouple temperatures were recorded for performance evaluation.

II. LITERATURE REVIEW AND RESEARCH GAP

Prasad et al. [1] suggest the power generation capacity of a solar chimney is solely based on thermal parameters. Thus, they have done a controlled weather study. In that, they experimented with collector angle, chimney height and collector area. They found that the major obstruction to power generation is the secondary airflow, which causes a 9% loss in power generation. Also, they found that changing the collector angle from 0 degrees to 14 degrees improved the heat transfer coefficient by 41.6%. This shows the importance of collector inclination.

The investigation by Mehdipour, R et al. [2] has highlighted that collector area also plays a vital role in the chimney output. They found that weather parameters change constantly in real-life experiments, and thus taking the average values of solar irradiance, wind velocity, and temperature may help to get the result behaviour. They calculated the average parameters across various locations, and the results show very minor changes within the domain. This results in the chimney performance varying largely with continental change and not with somewhat similar weather locations.

Adenigba et al. [3] used a Computational Fluid Dynamics (CFD) tool for their evaluation of a 3D model inspired by the Manzanares Plant, Spain. They investigated the numerical values of pressure, temperature, and airflow distribution by using 1000 to 1400 W/m². The results show that 1000 W/m² is enough to get the desirable outcomes, and in addition to that, they also found that increasing the solar irradiance doesn't significantly affect the output parameters.

Murena et al. [4] used a 5 m-high solar chimney with a 4.5 m square collector over a period of 7 months and obtained temperature and pressure readings. This suggests that a simpler solar chimney design and collector shape may also provide sufficient results for domestic usage. They also cross-verified the results with their CFD analysis.

Cisse et al. [5] proposed the idea that optimal design of a solar chimney with a horizontal absorber will help increase the efficiency of natural ventilation in building structures. Optimal values of chimney outlet diameter and chimney height were found to be the most effective design variables impacting airflow using three-dimensional CFD analysis coupled with the MOGA approach. Furthermore, it was demonstrated that a horizontal absorber is beneficial not only from the viewpoint of ventilation but also in terms of decreasing the solar heat gain through shading of the roof surface.

The Authors Mohamad et al. [6] indicate that the geometrical design of solar chimneys is crucial for the thermal and fluid dynamic behaviour of such structures. In the study, using the 2D CFD model, the researchers examined the impact of the collector slope, chimney divergence angle, solar irradiation, air temperature, and geometrical design on the airflow and power generation capacity. It was revealed that a negative collector slope contributes to thermodynamic performance and increases air velocity by 125%, whereas a divergent chimney improves airflow behaviour. Also, enlarging the collector diameter and chimney height is associated with increased air velocity and power production.

According to Lorestani et al. [7], a sloped solar chimney power plant (SSCPP) is capable of matching the performance of a normal solar chimney, but with lower chimney height and construction cost. The authors used a three-dimensional CFD simulation to investigate the influence of solar irradiation and turbine pressure drop on flow velocity, heat transfer, and generated power. The findings indicated that the no-load case yielded a maximum flow velocity of about 17 m/s when the solar irradiation was 1000 W/m², and optimum operation yielded a power generation of 50 kW at a turbine pressure drop of 120 Pa.

As indicated in Ye et al. [8], the addition of a deflector to the two-channel solar chimney results in enhanced natural ventilation and thermal efficiency. Through simulations based on computational fluid dynamics and backed up by experiments, the researchers determined the optimum configuration, with an angle of deflection of 35° and a length-to-diameter ratio of 0.3. At a solar irradiation of 800 W/m², the optimised solar chimney recorded an increase of 8.2% in ventilation rate (0.185 kg/s) and 7.4% in thermal efficiency (41.2%) compared to the conventional one. This has resulted in an overall reduction in building energy usage by 13.6%.

According to Zuo L. et al. [9], a combination of a solar chimney power plant and a desalination system (SCPPCD) can produce electricity and freshwater at once in real outdoor conditions. From the experimental findings, it was discovered that the maximum freshwater production took place within one-third of the collector radius from the





collector inlet. The temperature of the air flow in the chimney increased by 17 degrees Celsius. It stayed higher than 5 degrees Celsius during nighttime in comparison to the ambient temperatures, thus ensuring uninterrupted operation of the system. The maximum produced electric power was equal to 0.71 mW.

According to Attig Bahar et al. [10], Computational Fluid Dynamics (CFD) can be used effectively to investigate the performance of solar chimney power plants under various climatic conditions. Based on results from the Manzanares prototype, the researchers conducted a feasibility study of solar chimney systems in ten locations in Tunisia. It was found that the annual energy produced by the plant was within the range of 109 to 140 MWh, and the maximum energy production took place in the southern regions of Tozeur and Remada owing to higher amounts of sunlight and solar radiation received in these regions.

Hassan [11] states that including an adsorption chiller with a solar chimney power plant, along with recovering heat from the condenser, greatly improves the system's efficiency. Through a dynamic mathematical modelling process, the researchers found that when the condenser tubes are installed at the inlet of the collectors, the heat of condensation can preheat the air going in and hence increase the updraft of the chimney and the power production by the turbine. The new design showed a 5.95% increase in power production and about a 6% increase in the efficiency of energy conversion from solar into electricity compared to the traditional solar chimney.

As per Mandal et al. [12], the role of multi-objective optimization (MOO) is critical for improving the design and performance of hybrid solar chimney power plants (HSCPPs). In their comprehensive analysis of 185 research papers, it was revealed that integrating evolutionary optimisation techniques with AI and machine learning could yield system efficiency 25 times better than traditional optimisation methods. According to the analysis, MOO is effective in optimizing not only the power output but also economic and environmental parameters of the systems.

According to Cuce et al. [13], solar chimney power plants (SCPPs) have proven to be one of the most promising renewable energy technologies, producing power through natural convection, which is possible even for continuous generation when SCPPs are combined with thermal energy storage. The researchers conducted a comprehensive review of SCPPs to describe the design, mechanism of operation, and efficiency of the system. As described in the paper, the efficiency of SCPPs depends mostly on the collector, chimney, and turbine design. It was found that collector efficiency can reach 40-60% in conventional SCPPs; however, using the improved collector design (polycarbonate glazing), it can reach 60-80%. Other aspects that improve SCPPs' performance include chimney height, collector geometry, and hybrid energy storage systems, which positively influence airflow, temperature difference, and power production.

Solar chimney power plants (SCPPs), as stated by Biswas et al. [14], are considered sustainable and environmentally friendly sources of power production technology; however,

their utilisation is still rare owing to poor efficiency and a lack of experimental confirmation of their performance. The researchers examined the history of evolution, working principle, prototype structure, and improvement strategies used in SCPPs, noting that almost 80% of the available literature is purely theoretical and only 20% consists of experimental research. The research shows that the performance of SCPPs depends considerably on collector design, chimney dimensions, absorber material, and hybrid systems. However, despite the use of some design improvements and hybridization strategies aimed at better air flow and power output, the technology has not been commercialized because of lack of experimental studies on a larger scale.

Kassaei et al. [15] suggest that experimentation is very important in enhancing the performance and applicability of solar chimney systems. The authors performed a systematic review of experimental studies on the effects of collector/chimney dimensions; materials used for construction; novel design features; environmental factors; and hybrid systems on system performance. The study notes that parameters like chimney height, collector diameter, collector inlet height, and chimney shape have a significant effect on airflow, temperature increase, and power production. The study also notes that experiments have been done on small-scale models of the system, while mid- and large-scale experimental studies have not been adequately carried out.

According to Ebadi et al. [16], despite being a sustainable technology for the production of renewable electricity, the implementation of solar chimney power plants (SCPPs) is limited because of inefficiency, high cost, and large space requirement. A comprehensive review of advancements over the past two decades found that geometrical optimisation, collector improvements, efficient turbines, and hybrid systems coupled with thermal energy storage, desalination, geothermal, photovoltaic, and hydrogen energy are the best ways to improve the efficiency of such systems. It is noted that thermal energy storage can help achieve a consistent operation during day-night time periods. In addition, the use of concentrated solar reflectors appears to be a good idea which has been explored to a lesser extent so far.

As per the findings of Cui et al. [17], it is stated that the performance analysis of the ventilation system with a combination of a solar chimney can be achieved effectively through theoretical scaling and validated numerically. The study identified two natural convection modes with respect to the variation in the Rayleigh number with either the presence of a thermal boundary layer or the absence of a thermal boundary layer. The developed scaling theory model has predicted the thermal boundary layer thickness, air velocity, and air mass flow rates successfully under various conditions.

III. EXPERIMENTAL SETUP, PROTOTYPE DESIGN AND EXPERIMENTAL METHODOLOGY

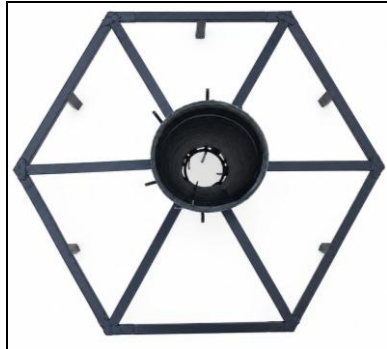
The solar chimney model shown in [Figure 1](#) and [Figure 2](#) represents the actual experimental model used.



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[Fig.1: Front View of Domestic Solar Chimney]



[Fig.2: Top View of Domestic Solar Chimney]

The developed solar chimney model comprises three main parts: a solar air collector, a divergent-shaped chimney, and a central frame. Solar radiation passes through a transparent plastic sheet, heating the enclosed air. This creates a pressure difference, and the warm air moves upward through the chimney while surrounding air enters through the collector perimeter, enabling natural ventilation.

The solar chimney was designed to achieve an adjustable collector mechanism that allows inclination angles of 10° , 20° , and 30° , so that we can get various results from its geometry.

The developed solar chimney consists of a regular hexagonal-shaped collector with an effective area of 1.461 m^2 and a 2.0 m high divergent-shaped chimney. The collector has a side length of 0.75 m and an inclined length of 0.68 m , while the chimney diameter gradually increases from 0.12 m at the inlet to 0.24 m at the outlet, achieving the divergence we need.

The selected materials were a mild steel (MS) frame, an MS sheet chimney, and a plastic cover to maximise solar heat absorption. Stainless steel fasteners and K-type thermocouples (which are widely used for temperature measurements) were employed for corrosion resistance and temperature measurement, respectively.

The experimental setup was equipped to monitor the temperature at various places alongside the model. For that purpose, a K-type thermocouple was attached at various locations in the solar chimney model. Measurements were recorded at regular 1-hour intervals throughout the experiment.

The performance analysis was carried out using representative clear-sky but slightly windy side weather conditions for Jamnagar, Gujarat, India on the day of 22 June 2026. The adopted average conditions included an ambient temperature of 34°C , solar irradiance of 910 W/m^2 , wind

speed of 5.8 m/s , relative humidity of 36% , and atmospheric pressure of 1004 hPa . These values are taken directly from the IMD weather website as a reference.

The solar chimney was tested at collector inclination angles of 10° , 20° , and 30° . For each case, after reaching steady conditions, temperatures from six K-type thermocouples were recorded during peak solar radiation. The same procedure was repeated for all configurations to compare their thermal performance.

The K-type thermocouple uncertainties ($\pm 1.5^\circ\text{C}$) and variations in solar irradiance under actual outdoor conditions are taken into consideration.

The results are as follows: The estimated effective solar irradiance decreased from 896 W/m^2 to 788 W/m^2 when the collector inclination angle increased from 10° to 30° , but the temperature rise ranged from 22.9°C to 26.1°C as the collector inclination angle increased.

The measured temperature rise was 10.4°C , 9.9°C , and 9.2°C for collector inclinations of 10° , 20° , and 30° , respectively. The chimney outlet temperatures were 44.4°C , 43.9°C , and 43.2°C , as measured by installed K-type thermocouples.

The measured temperature profile indicates a gradual increase in air temperature from the collector inlet to the chimney outlet for all collector inclinations. This pattern is consistent across all collector inclination cases. The highest outlet temperature was found for the 10° collector. In contrast, the 30° configuration showed the lowest temperature rise, demonstrating the influence of collector inclination on the solar chimney model's temperature measurements.

IV. DISCUSSION

The thermal performance of the proposed solar chimney is significantly influenced by collector angle, solar radiation, and collector geometry. Solar heating causes a temperature rise in the air inside the collector, which creates buoyancy and helps move air through the chimney. The design was studied for collector angles of 10° , 20° , and 30° for the climate conditions of Jamnagar, Gujarat. The outlet air temperature obtained is from 43.2°C to 44.4°C , providing a temperature rise of about $9\text{--}10^\circ\text{C}$.

The expected temperature profile indicates an increasing trend of air temperature from the inlet of the collector to the outlet of the chimney. Most of the heating takes place in the collector, where the absorber plate absorbs the solar energy, while an increment in temperature is witnessed in the chimney. This indicates that the collector is the heat-transfer zone.

Even though a bigger increase in temperature is expected, in reality the efficiency depends on factors such as wind convection, radiated heat loss, conductive heat loss through construction, poor glazing, and air loss. In this way, the increase in temperature is limited to $9\text{--}10^\circ\text{C}$, which corresponds with the experimental data of the three configurations considered, the 10° collector tilt had the maximum effective solar irradiation, absorbed heat, outlet temperature, and efficiency





value. The slight reduction in heat absorption and airflow performance at 20° and 30° collector tilts suggests that the 10° configuration is the optimal thermal performance configuration for the designed solar chimney.

V. CONCLUSION

Experimental and theoretical findings show that the performance of the solar chimney within the country depends significantly on collector tilt, solar irradiance, and collector shape. Energy received by the collector increases air temperature, creating buoyancy that drives natural airflow in the chimney. The model was studied for the tilt angles of 10°, 20°, and 30° at typical weather conditions for Jamnagar, Gujarat. It is expected to get the outlet air temperature range between 43.2 and 44.4 degrees, which equals a 9- 10 °C increase compared to the ambient air temperature.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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