# Development of a Hybrid Solar Chimney for Small- Scale Power Generation, PV Cooling, and Passive Ventilation

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**Abstract:** Due to the Philippines' strategic location near the equator, the country can maximize the application of different renewable energy, specifically solar energy. This study focuses on developing a small-scale model of a hybrid power generation system consisting of a solar chimney-turbine set up and PV solar system. The air passing thru the collector to the solar chimney shall both be performing passive ventilation of a residential building and cooling of the PV panel. Tests on an experimental setup and simulation in ANSYS Fluent are conducted to evaluate the system's performance and assess its potential as an alternative energy solution. Data collection involves measuring air velocity, temperature, and solar irradiance at various points within the system. The solar panel was tested under two configurations, standalone and incorporated in the hybrid system. The results show that the hybrid system effectively harnesses solar energy, with the PV panel maintaining lower temperatures compared to the standalone setup. Furthermore, the simulations and experimental data exhibit a reasonable agreement, indicating the accuracy of the simulation model.

**Key Words:** CFD; chimney draft; passive ventilation; PVC cooling; solar chimney

## 1. INTRODUCTION

The global increase in energy consumption, along with the urgent need to reduce greenhouse gas emissions, has led many countries to turn to renewable energy sources. In the Philippines, where reliance on fossil fuels remains high, the development of new power plants, particularly in the renewable sector, has been stagnant, leading to an inadequate power supply (Department of Energy, 2022). Solar energy has gained popularity as a renewable energy source, and its utilization in residential homes has been driven by its accessibility and scalability. Photovoltaic (PV) systems, which directly convert solar energy into electricity, have become increasingly prevalent (Smets et al., 2016). However, PV panels have limitations in terms of efficiency and temperature sensitivity (Thong et al., 2016). The market for solar energy has seen significant growth, particularly in Europe, but countries like the Philippines face barriers such as cost and political factors that impede their full investment in solar power. Wind energy, on the other hand, harnesses wind turbines to convert wind power into electricity, but its variability poses challenges. Solar chimney power plant (SCPP) systems combine solar and wind energy by utilizing airflow to generate power. They have undergone various designs and configurations, including hybridization with PV panels for improved efficiency and power generation (Cuce et al., 2022). Additionally, solar chimneys can also provide ventilation, offering a natural cooling solution in hot climates (Suhendri et al., 2022). This research highlights the need for a hybridized configuration that addresses the limitations of solar updraft tower (SUT) technology, offering increased energy conversion efficiency at a lower cost.

Further research is needed to sustain the development of solar chimneys and their potential contribution to meeting global electricity demand and transitioning to sustainable energy practices. Solar chimneys offer promising technology for solar power generation, but some limitations need to be addressed to enable widespread use. The focus of solar power research has primarily been on increasing the efficiency of solar panels. However, it is crucial to explore and study different methods of enhancing the efficiency of solar power generation, electricity generation, and natural ventilation within solar chimney systems. This study provides valuable insights into the viability of small-scale hybrid solar chimneys, serving as a foundation for the design of solar chimney power plants and future research in evaluating their performance.

## 2. METHODOLOGY

### *2.1 Experimental Setup*

The study focuses on developing a small-scale model of a hybrid power generation system consisting of a solar chimney-turbine set up and PV solar system. The air passing thru the collector to the solar chimney is simulated to be induced from a residential building, as such, provides passive ventilation. In the hybrid system, the PV panel is placed within the collector, thus, the air can also serve as cooling medium to the PV panel.

The experimental setup for the hybrid solar chimney system was adapted from Hussam et al. (2022). It consists of several components, including a heat collector/case, PV panel, nozzle, wind chimney, and turbine (the turbine was considered theoretically, not experimentally). The collector's opening and air inlet had dimensions of 54 cm in length and 5.35 cm in width, with an overall collector length of 121.5 cm. Galvanized iron was used to construct the collector, nozzle, and chimney. To minimize thermal losses, the bottom, and sides of the collector, as well as the chimney and nozzle, were insulated with glass wool. The top panel of the collector was made of glass with an emissivity of ε=0.95. The PV panel, with dimensions of 55 x 121.5 x 4.2 cm and emissivity of ε=0.9, was used. The collector was connected to a convergent nozzle to increase the airflow velocity inside the chimney. The chimney itself was 2 m in height and 15.24 cm (6 inches) in diameter. Near the base of the chimney, a theoretical turbine was considered. The setup allows for easy attachment and detachment of the PV panel, and the angle of the collector can be adjusted from 0 degrees (flat) to 45 degrees in 15-degree increments, with the primary angle set at 15 degrees.

Fig. 1. Experimental set-up

The testing of the set-up took place in Marikina City, Philippines, with an elevation of approximately 15 meters above sea level and coordinates of about 14.64600° N, 121.10369° E. Data was collected during June 2023, from 7 am to 6 pm, considering both sunny and cloudy conditions. The setup was located on the third-floor rooftop of a residential area in an open space, with the collector facing south at a 15-degree angle from the horizontal. Data collection involved measuring air velocity at three points in the hybrid system: the collector inlet, base, and chimney outlet, using an anemometer with probes inserted into these locations. Temperature measurements were taken at various points within the hybrid system using six thermocouples. These thermocouples were placed at the collector opening, halfway through the collector, halfway inside the collector (on the PV panel surface), halfway through the collector glass, at the collector outlet near the nozzle, and the chimney outlet. Solar irradiance was measured using a solar power meter, and voltage and current sensors were connected to the PV panel to measure its electrical characteristics. The data collection procedure was repeated for three days. After collecting data from the hybrid system, the PV panel will be detached to allow direct sunlight exposure. Measurements of temperature, solar radiation, voltage, and current will continue at 30-minute intervals for three days.

## *2.2 Simulation*

The boundary conditions of the system consist of the chimney, nozzle, and collector surfaces treated as standard opaque walls with properties of a steel sheet. The collector opening serves as the inlet with a velocity boundary condition of 2 m/s and an inlet temperature of 35°C. The chimney outlet has a static pressure boundary condition to represent atmospheric pressure. The glass cover has a semi-transparent wall boundary condition to allow solar radiation to pass through, while the PV panel is set as an opaque wall with silicon material properties. Heat transfer coefficients of 7.84 W/m$^2$ and 11.88 W/m$^2$ are defined for the PV panel and glass cover, respectively, which can be computed in Eqn. 1 and Eqn. 2 which were derived from the works of Duffie and Beckman (2013), Cuce et al. (2022), and Kumar and Mullick (2010). The flow conditions are simulated using the standard k-ε model, while solar radiation is simulated using the Discrete Ordinates model with sun direction and illumination parameters determined using ANSYS' solar calculator. The simulation parameters for the standalone PV panel setup are similar, with the PV panel tilted at 15 degrees and subjected to a velocity of 1.5 m/s and a temperature of 35°C. Both setups utilize the standard k-ε model for flow simulation and the Discrete Ordinates model for solar radiation simulation. The results of the simulation are shown in Figure 1 and Figure 2.

$$h_{pv} = k\,Nu/L \qquad \text{(Eq. 1)}$$

where:

$h_{pv}$ = convection heat transfer coefficient at surface of PV panel, W/m$^2$-K

$k$ = thermal conductivity of the air, W/m-K

$Nu$ = Nusselt number

$L$ = length of collector

$$h_{gc} = 8.55 + 2.56V_w \quad \text{for } V_w < 5 \text{ m/s} \qquad \text{(Eq. 2)}$$

where:

$h_{gc}$ = convection heat transfer coefficient at surface of glass cover, W/m$^2$-K

$V_w$ = wind velocity in the collector, m/s

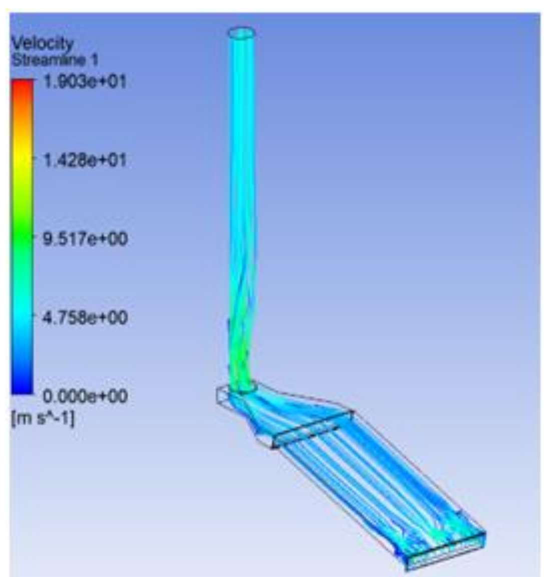


*Fig. 2. Simulation Setup for the Hybrid System*

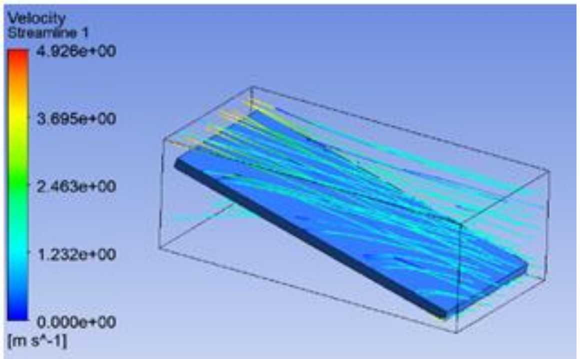


*Fig 3. Simulation Setup for PV Panel Standalone System Setup*

## 3. RESULTS AND DISCUSSION

### *3.1 Experimental Results*

Fig. 4 shows a recorded maximum temperature increase of 6.1°C at a solar radiation of 1110 W/m$^2$. The highest temperature values were observed around midday when solar radiation was highest. The temperature difference between ambient air and air at the chimney inlet increased with higher solar radiation readings, indicating effective heating of the air by the collector.

The velocity of air at the chimney inlet varied throughout the day, as shown in Fig. 5. Velocities ranged from 3.8-4.15 m/s, except for higher solar radiation levels (>1000 W/m2) resulting in velocities of 5 m/s and above, and lower solar radiation levels (<100 W/m2) resulting in velocities of 3.6 m/s and below. The effect of collector heating on the chimney inlet velocity is most evident at solar radiation values above 1000 W/m$^2$.

Both the standalone and hybrid setups showed an increase in PV panel temperature with solar radiation, as depicted in Fig. 6. The highest temperatures recorded were 64.6°C for the PV panel alone and 56.9°C for the hybrid setup, observed at a solar radiation of 1180 W/m$^2$. The graph also compares the PV panel temperatures between the standalone and hybrid setups, revealing that the PV panel in the standalone setup had higher temperatures than the hybrid configuration. On average, the PV panel in the hybrid setup was 4.57°C cooler, indicating effective temperature reduction in the hybrid setup.

Fig. 7 indicates a decrease in PV panel efficiency at high solar radiation levels. The lowest efficiencies were recorded at 1100 W/m$^2$, with 4.17% for the PV panel alone and 6.21% for the hybrid setup. This decrease is attributed to the temperature increase caused by solar radiation. The figure also compares the efficiencies of the PV panels in both setups, showing that the hybrid setup had a higher average efficiency of 7.93% compared to the PV panel alone setup with an average of 6.71%. The cooling effect experienced by the PV panel in the hybrid system contributes to its higher efficiency. The turbine efficiency is negligible compared to the PV panel efficiency, with only around 0.01%.

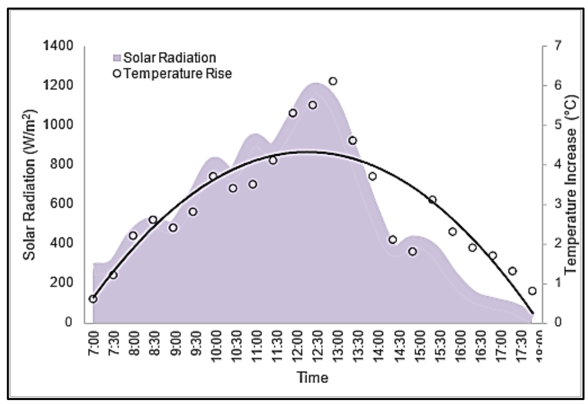


Fig. 4. Temperature increase between ambient air and chimney inlet throughout the day with varying solar radiation.

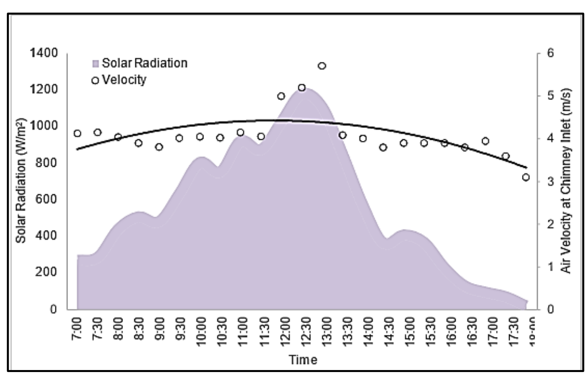


Fig. 5. Velocity of the air at the chimney inlet throughout the day with varying solar radiation.

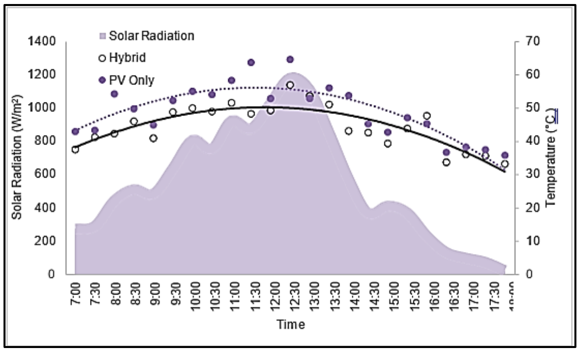


Fig. 6. Temperature of the PV panel in the standalone setup and PV panel in the hybrid setup throughout the day with varying solar radiation.

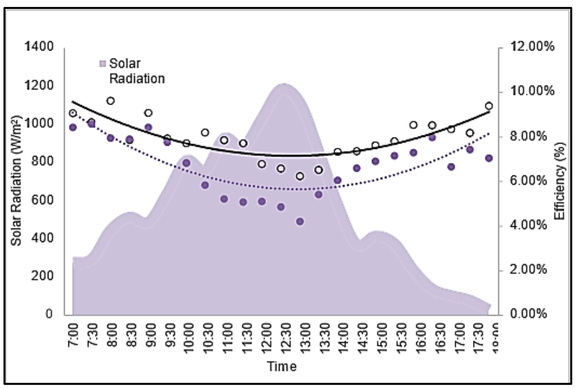


Fig. 7. Efficiency of the PV panel in the standalone setup and the hybrid setup throughout the day with varying solar radiation.

### *3.2 Simulation*

The accuracy of the ANSYS simulation was assessed by comparing the results with the experimental data. Both the simulation and experimental setups were designed to be as similar as possible, using the same data parameters. Data collected from 7am to 6 pm at one-hour intervals were used for the comparison. A percent difference analysis was conducted to measure the disparity between the simulation and experimental datasets. The velocity and temperature contours are presented in Figures 8 and 9.

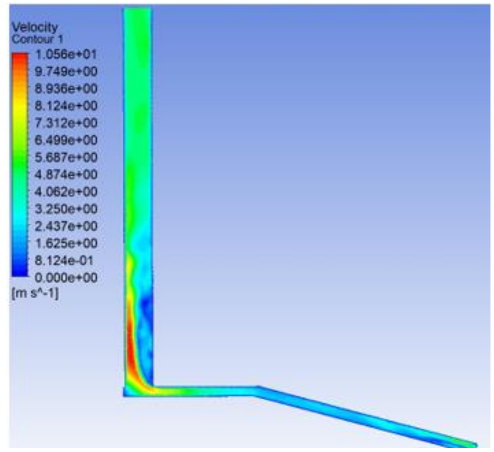


Figure 8. Velocity Contours at the Hybrid System's Symmetry

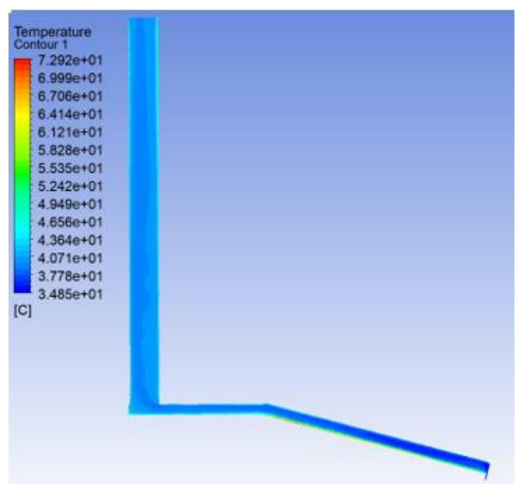


Figure 9. Temperature Contours at the Hybrid System's Symmetry

The velocity within the hybrid system gradually increases from the collector to the nozzle and chimney inlet, with the maximum velocities observed at the turbine region above the chimney inlet, reaching up to 10.56 m/s. This increase in velocity is accompanied by increased turbulence, likely resulting from the contraction of the flow area at the nozzle. As the air flows upward, it stabilizes in the chimney, maintaining an approximate speed of 6.5 m/s. Similarly, the temperature within the collector gradually rises due to the heat generated by the glass and PV panel. The PV panel surface reaches the highest temperature in the system, causing the air near its surface to heat up. This is evident from the temperature gradient near the outlet of the collector, indicating the heating of the air. The air within the collector ranges from 34.85 to 39°C, while the average temperature at the chimney inlet is 41.98°C.

The average percentage differences for the PV panel temperature in the standalone setup, the hybrid setup, and the temperature rise and velocity at the chimney inlet in the hybrid setup were found to be 11.93%, 10.03%, 22.17%, and 18.8% respectively. The percentage difference values indicate a relatively close agreement between the simulation and experimental data for the PV panel temperatures. Although there were still some differences between the two datasets, these disparities remained within an acceptable range. However, the average percentage differences for the temperature rise and chimney inlet velocity were considerably high, indicating greater discrepancies between the simulation and experimental data. The specific reasons for these inaccuracies could not be definitively determined, as multiple factors could have contributed to the discrepancies. Possible factors may include measurement errors, equipment limitations, meshing issues in the simulation, or other uncertainties that were not accounted for.

### *3.3 Ventilation*

Table 1 provides information on the volume of space that can be effectively ventilated at specific air change rates, considering the expected air velocity from a house or building ventilation. The air change rates considered in the table are 0.35, 0.70, and 1 air change per hour. The volume of space is measured in cubic meters, indicating the size of the area that can be adequately ventilated. ASHRAE recommends a minimum of 0.35 air changes per hour and at least 15 cfm per person for residential homes to ensure proper indoor air quality. For the minimum recommended air change rate of 0.35 air changes per hour, the maximum volume of space that can be effectively ventilated is approximately 442.28 m3, which is a considerable amount of space for a single room.

*Table 1. Comparative volume of space that can be used for specific air change rates*

| Air Velocity, m/s | Q, cfm | Volume of Space, **m³** | | |
|---|---|---|---|---|
| | | ACH (.35) | ACH (0.70) | ACH (1) |
| 0.24 | 22.088 | 107.22 | 53.61 | 37.53 |
| 0.28 | 25.769 | 125.09 | 62.54 | 43.78 |
| 0.33 | 30.370 | 147.43 | 73.71 | 51.60 |
| 0.36 | 33.131 | 160.83 | 80.41 | 56.29 |
| 0.48 | 44.175 | 214.44 | 107.22 | 75.05 |
| 0.52 | 47.856 | 232.31 | 116.15 | 81.31 |
| 0.54 | 49.697 | 241.24 | 120.62 | 84.43 |
| 0.65 | 59.820 | 290.38 | 145.19 | 101.63 |
| 0.69 | 63.502 | 308.25 | 154.13 | 107.89 |
| 0.71 | 65.342 | 317.19 | 158.59 | 111.02 |
| 0.77 | 70.864 | 343.99 | 172.00 | 120.40 |
| 0.79 | 72.705 | 352.93 | 176.46 | 123.53 |
| 0.84 | 77.306 | 375.27 | 187.63 | 131.34 |
| 0.99 | 91.111 | 442.28 | 221.14 | 154.80 |

Similarly, at an air change rate of 1 air change per hour, the maximum volume of space that can be ventilated is 154.80 m3. Even at the lowest volumetric flow rate considered, which is 22.088 cfm, the volume of space ranges from 37.53 to 107.22 m3. This indicates that the computed volumes of space are well within the range of average bedroom sizes, which typically range from 15 to 25 square meters. The corresponding volume range of approximately 36 to 75 m3 aligns with the computed volumes, further emphasizing the suitability of the ventilation system for residential applications.

## 4. CONCLUSIONS

In this study, a small-scale model of a hybrid solar chimney for residential use was evaluated for its performance at different configurations. The model incorporated PV panels within the solar chimney to generate power, cool the panels, and provide passive ventilation. The researchers constructed an experimental setup to replicate the system and collect experimental data. ANSYS Fluent software was also used to simulate the airflow and heat transfer characteristics of the hybrid solar chimney and standalone PV panel.

Throughout three days, measurements were taken from the experimental setup from 7 am to 6 pm. The air velocity was measured, and temperatures were measured at six different locations within the system. Solar irradiance and PV panel current and voltage were also measured. The highest temperature increase that was recorded was 6.1 °C, which occurred at midday with a solar radiation of 1110 W/m2. The velocity of air at the chimney inlet remained relatively constant, except for higher solar radiation values that resulted in increased velocities. The hybrid setup showed lower PV panel temperatures compared to the standalone setup, indicating its cooling effect. The hybrid configuration demonstrated higher average efficiency of 7.93% than the standalone setup of 6.71%, but the turbine power output remained relatively low compared to the PV panel power output.

Results from the ANSYS simulation revealed valuable insights into airflow and thermal behavior. The velocity contours showed airflow buildup at the collector, acceleration at the nozzle and chimney inlet, and highest velocities at the turbine region. Temperature contours illustrated the gradual rise of temperatures within the collector and PV panel surface. Like the experimental setup, the hybrid system achieved lower average temperatures of 55.41°C compared to the standalone setup with 65.67°C, indicating effective heat dissipation and efficient utilization of solar thermal energy.

Meanwhile, the provided volumes of space demonstrate that the ventilation system can effectively ventilate a significant area, encompassing a wide range of room sizes, and aligning with the recommendations for maintaining proper indoor air quality in residential homes.

The results provided vital evidence of the effectiveness of the hybrid solar chimney system in terms of airflow, heat transfer, power generation, PV panel cooling, and ventilation. The system demonstrated functionality and performance, confirming the achievement of the defined objectives.

## 5. ACKNOWLEDGMENTS

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