Experimental and Numerical Investigation of Solar Chimney Prototype

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***Abstract*— In the global energy system, fossil fuels have a leading position despite their effect on the environment. As a result, the demand for renewable energy has increased. Solar chimney power plants (SCPPs) attracted the attention of scientists in recent years. This paper observes a solar chimney power system. It creates an induced air flow to drive a turbine and generate electricity. To evaluate its performance, experimental and numerical models are developed for a prototype plant with a collector's area of 16 m² and a chimney diameter and height of 0.15 and 3 m, respectively. It has a metrological site (Alexandria, Egypt 31°18'43.0"N 30°04'00.4"E), and the experiment was conducted during the summertime. This research aims at obtaining electric generated power based on variables such as air velocity, mass flow rate and pressure difference. From the experimental setup of this small chimney, a power production of up to 0.011W was generated. This research numerically obtained the contours of density, pressure, temperature, and velocity parameters. A comparison between the experimental and numerical methods is introduced showing a good agreement has been achieved. This paper is utilized to forecast the output power of similar-type solar power plants.**

Keywords*— *Solar Chimney; CFD; Experimental Analysis; Numerical Analysis

I. Introduction

Energy has a significant and constructive factor in the global change. Fossil fuels can have drawbacks, too, as they are the primary cause of air pollution and the release of greenhouse gasses like carbon dioxide (CO2). Thus, the need to decarbonize, lessen our dependency on fossil fuels, and switch to lower-carbon energy sources must be balanced with the role of energy in social and economic growth [1]. The higher output of new wind and solar projects finished the previous year helped to boost the demand for renewable energy by almost 1.5% year over year in 2020. Renewable energy sources are typically prioritized in the grid and are not obligated to modify their output to meet demand, which isolates them from the effects of decreased electricity demand [2]. The increased use of solar energy has attracted the attention of scientists to establish the solar chimney (SC) technology in recent years. Several studies have been carried out in this timeframe. The experimental studies are primarily based on small-scale structures, both experimentally and theoretically. Kasaeian et al. [3] offered a detailed analysis that included experimental research, theoretical and simulation work. Their work involved reference-based solar chimney types. They stated way of a looking at the various sections. Solar Chimney is a renewable energy power plant designed for the applications of low temperature solar heat for producing electricity. The design resembles a very large greenhouse-like a structure of roofed collector covering a tall chimney tower central base, where sunlight heats the air. The resulting convection causes the chimney effect to contribute to the hot air updraft in the tower. This airflow drives a wind turbine to generate electricity [4].

Many researchers carried out experiments with electrical heating to simulate irradiation of sun and confirmed various arrangements, together with CFD simulations and experimental data validations and two analytical models [5]. The addition of two insertions increased the mass flow rate by 30%, with CFD simulations showing that using 15 insertions resulted in a 57% increase in flow rate, though further insertions were not beneficial due to increased friction. Cao et al. [6] used transient 3D-validated numerical simulations to evaluate a solar chimney performance ventilator. They discovered that optimizing the tilt angle significantly improved the ventilation performance, while the air mass flow rate increased by 144%, achieving a higher energy savings. El Hadji et al. [7] investigated the impact of adding three reflectors (boosters) to a solar chimney collector. The addition of reflectors increased solar radiation absorption, which raised the collector temperature and significantly boosted airflow velocity. Fine et al. [8] introduced a novel flow network analysis method for tall buildings solar chimneys. Ikhlef et al. [9] designed, built, and tested an experimental thermal storage system of SCPP prototype. The crushed gravel basement proved to be the most effective thermal storage system, achieving a collector efficiency of 89.73%. Zuo et al. [10] presented SCPP with membrane distillation (SCPPMD). The system showed peak power generation around 4 p.m., with peak water yield occurring two hours later. Zuo et al. [11] evaluated the SCPPMD system's techno-economic characteristics using a heat and mass transfer model, performance analysis, and a cash flow-based economic evaluation model. Zhang et al. [12] investigated the airflow characteristics of wall solar chimneys. Increasing chimney height within range of 3.0 to 5.0 m improved the capacity of ventilation by 90%, and raising the inlet location to mid-wall height enhanced the ventilation by 57.28%. Tariq et al. [13] established a digital twin model of SCPP. AI-based MLP-ANN method outperformed the regression model in accuracy and optimization results showed an improvement in air changes by 71% to 87%. Gong et al. [14] introduced a staggered split absorber design for solar chimneys. Their proposed staggered split absorber design significantly improved outlet flow uniformity, increasing the ventilation rate by 57%. Bouchair [15] found that altitude has a modest effect on performance when assuming constant ambient temperatures. Zhang et al. [16] found that the cavity gap would gradually rise from 0.2 m for single-story structures to 1.5 m for seven-story structures to achieve optimal ventilation, improving it by 45.6%. Jafari and Kalantar [17] developed a sustainable solution combining a windcatcher. Water Spray System (WSS) led to a temperature reduction of 6 to 12°C and 80% rise in relative humidity (RH) on floor number three. Zuo et al. [18] declared that modeling SCPPs performance accurately is essential to enhance energy absorption and system efficiency. Fallah and Valipour [19] showed that the steady-state flow conditions are solar radiation levels above 600 W/m², with a supreme air velocity value of 2.73 m/s under 800 W/m². Bai et al. [20] experimentally assessed the SCEAHE system's performance by monitoring the indoor air temperatures, and airflow rates. Aziz and Elsayed [21] used numerical simulations to evaluate over 40 configurations of the solar chimney system, focusing on the design parameters. Long et al. [22] developed a coupled system dynamic model and validated it to simulate the performance over biannual and annual periods. Rashidi et al. [23] studied using Phase Change Materials (PCMs) inside solar energy systems, focusing on their use in SCPP. Wang et al. [24] combined numerical and empirical analyses to examine the impacts of design factors. Their study found that cavity gap negatively affects heating performance, while solar radiation positively influences both cooling and heating modes. Rajput and Bartaria [25] experimentally evaluated solar chimneys performance in improving ventilation plus temperature distribution. Solar chimney improved ventilation by up to 20% during summer. Pandey et al. [26] upgraded solar chimney model by mixing waste heat recovery system. The incorporation of the waste heat recovery system improved solar chimney performance, achieving a supreme efficiency of 5%. Mebarki et al. [27] established a 3D axisymmetric CFD scheme to SCPPs. Both energy output and system efficiency decreased with a reduction in scale factor, with daily energy production ranging from 191.93 kWh/day to 51.12 kWh/day depending on the scale factor. Saad et al. [28] presented numerical simulations to examine the effect of increasing the collector area on flow behavior besides power output. The power output increased from 26.1 kW to 47.4 kW when collector angle was increased from 120° to 360°. Hussam et al. [29] developed a hybrid system combining PV panels and an inclined solar chimney. That hybrid system achieved an efficiency values from 9% to 11%, expressively higher than traditional SCPP efficiency, and enhanced output power by 18% related to stand-alone PV panels. Nateghi and Jahangir [30] compared three modes while simulating a numerical model of a house using EnergyPlus,. In the Hot-Humid climate, PMV improved from 0.75 to 0.67 in summer, and in the Cold Semi-Arid climate, PMV improved from 1.24 to 1.16 in summer, with the greatest improvement in the cooling mode for Cold Semi-Arid conditions.

II. EXPERIMENTAL ANALYSIS

In this paper, an experimental test rig is utilized to evaluate the power of SCPP, Fig. 1. It consists of chimney, collector, turbine, and measuring instruments. The transparent collector covers a considerable area and it is slightly inclined to the highest point in the middle. Air flow runs from the inlet ambient air to the collector. Air is heated by the sun and it tries to rise. The chimney allows hot air to escape. As a result, it flows through the chimney, moving the chimney entrance turbine, generating electricity. Table 1 shows all assumptions data of the present SCPP prototype. The chimney is made of PVC pipe. The collector is made of a wood structure supporting a transparent plastic cover. The chimney entrance takes air kinetic energy then conducts it to the generator, efficiently converting the fluid power to shaft power and controlling the flow and output power by adjustment of the blade angles [31].

Fig. 1. Experimental setup of SCPP prototype.

TABLE I. SUMMARY OF ASSUMPTIONS

Parameter	Amount
Height of chimney (H_{ch})	3 m
Diameter of chimney (D_{ch})	0.15 m
Collector length (L_{coll})	4.5 m
Distance from ground to the collector	0.1**:** 0.2 m
Solar irradiance (G)	500 W/m^2 for Alexandria
Ambient temperature (T_{amb})	295 k
Ground roughness (ε)	0.8
Air density (ρ)	1.1968 kg/m^3 at temp.= 295K
Specific heat of air (C_p)	1005 J/kg.K

2.1 Measurements and instruments

- Air temperature inside and outside SCPP are measured using thermometer (range: -50 to 110℃ and accuracy: ±1℃).
- Air velocity is measured at the entrance of the tower using velocity Anemometer (range: 0.00045 to 44.7m/s and accuracy: ±3%).
- Electric power from the generator is measured using Digital Multimeter (range: -0.2 to 2V and accuracy: ±0.8%).

2.2 Numerical Analysis

Simulations of air flow inside SCPP prototype were conducted using Ansys FLUENT. The numerical domain is a quarter of SCPP with the same features as the experimental SCPP, Fig. 2. The collector has a square shape; 4.5m width, 0.1m height at the outer boundary and 0.2m height at the center, the chimney is 3m height.

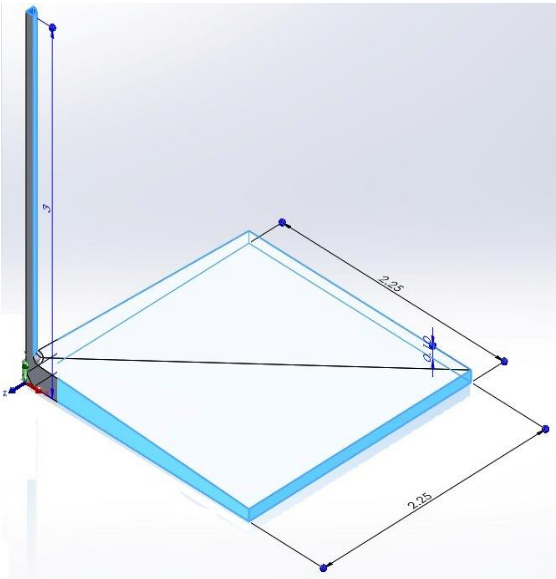


Fig. 4. Solar chimney quarter domain with dimension in m

Fig. 3 shows the Boundary conditions (BCs). Outer collector BC was defined as a pressure inlet. The air flows from this boundary and exits from the chimney. Pressure outlet BC was assigned at the upper surface of the chimney boundary. Other boundaries were considered to be symmetrical. Mesh independency analysis was conducted to verify accuracy of results. To give a high level of accuracy with minimum consumed time, 5.3×10^5 elements were used, Fig. 4. Triangle mesh was used of $2e^{-2}$ element size.

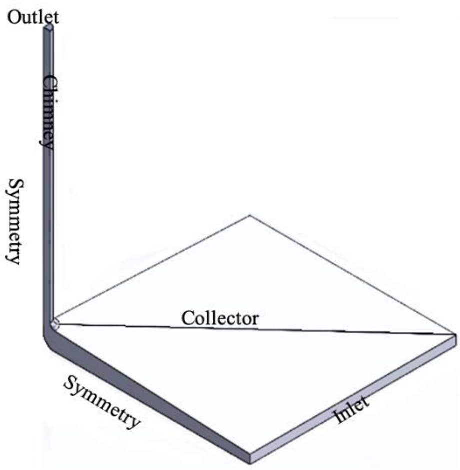


Fig. 3. Solar chimney Boundary condition.

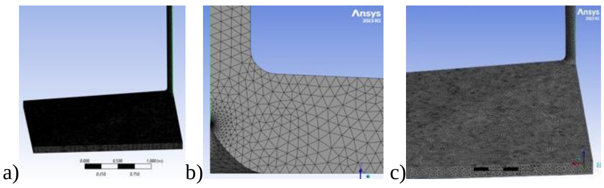


Fig. 4. Mesh a) full Asymmetric domain b) zoom in collector chimney connection c) zoom in collector mesh.

Previous studies showed that the k-ε RNG model can catch and predict the flow progress [32]. Radiation is set to ON using Discrete Ordinates (DO) with Solar Ray Tracing model. Direct solar irradiation is configured as Solar calculator, in which, the longitude and latitude of Alexandria were adjusted at one o'clock in the afternoon. Collector and chimney walls' materials are considered as glass and concrete, respectively. Heat flux equals 1373 W/m^2. Second order discretization was used for all solution variables. The regime of the system was transient with time step equals $2x10^{-4}$.

III. Results and Discussion

3.1 Experimental Results

The prototype was constructed in summer, which helped in heating up the air quickly and effectively. Also, the selection of the collector material was effective, especially in improving the greenhouse effect inside the prototype. The experimental results were examined at test day 3/7/2022 from 10 am to 3 pm. Fig. 5 illustrates the relationship between generator output power and the day hours. Electrical power was noted along the test day. The supreme power was verified just before 2 pm. Output power generation from the present SCPP is within (0.001W to 0.011W) throughout the experiment period.

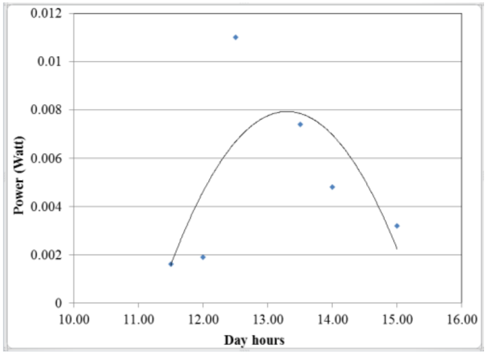


Fig. 5. Relationship between the generator output power and day hours

From the previous results, the average power will be 0.006W. Daily energy will be equal to 0.03 (Watt hours) Wh. The estimated output power over the year 10.95 Wh.

Fig. 6 shows the relation between chimney outlet air velocity along day hours. Air velocity started from 1.0814 to 1.8699 m/s. It had a maximum value of 1.8699 m/s just before 2 pm. Compared to the power output graph, it seems that both curves topped at the same time. The velocity kept slightly decreasing till the end of the time period.

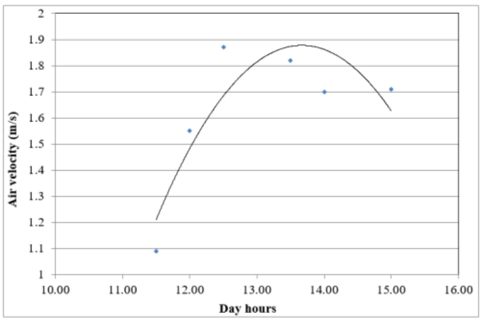


Fig. 6. Relation between air velocity at chimney outlet and day hours.

Fig. 7 depicts the same attitude for the mass flow rate delivered to the chimney when compared with output power and air velocity. It increased from 0.022 kg/s to a peak of about 0.036 kg/s just before 2 pm then decreased slightly.

Fig. 8 states the relation between pressure difference along the day hours. Air velocity started from 0.66 to 1.9 m/s. It has a maximum value of 1.9 m/s just before 2 pm. Then the pressure decreased till the end of the time period.

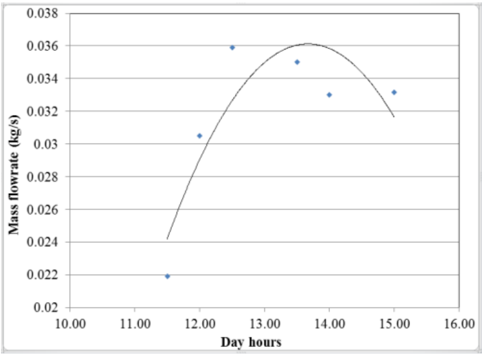


Fig. 7. Relation between Mass flow rate and day hours.

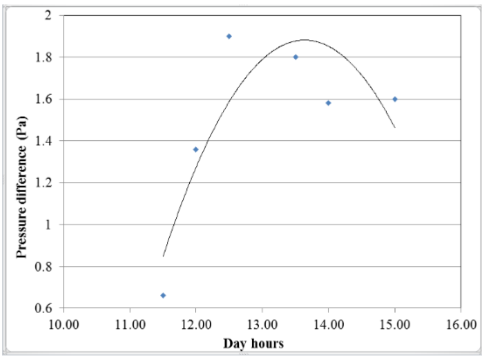


Fig. 8. Relation between Pressure Difference and day hours.

The measured ambient temperature through the experiment was in the range from 28℃ to 32℃. As a result, the enthalpy of air increased, which helped improving all the other parameters (air velocity, mass flowrate, and pressure difference) depending on temperature difference. All of the parameters peaked at the same time just around before 2 pm. Due to the outer wind, certain variations occurred. When the outside wind blows in reverse direction of hot air flow, production drops. When the wind moves in similar direction or has a component blowing in the same direction. In most of the curves, the output and other homogenous characteristics did not fall as sharp as before mid-day. As a result, with the vertical axis of 12 PM, the curves were not symmetrical or close to symmetrical. This occurred as a result of the collector's greenhouse effect. When the sun began to descend from its highest point, the ambient temperature began to drop. However, the heat contained inside the collector, on the other hand, kept it warm.

3.2 Numerical Results

Fig. 9 states density contours of the asymmetric domain. Inlet and the outlet air density was 1.2 kg/m^3. Inside the chimney, the density reached a value of 0.57 kg/m^3 because of the heat generated inside the chimney.

Fig. 10 shows pressure contours of the asymmetric domain. Inlet and outlet pressures are considered atmospheric. At the junction between collector and chimney, pressure becomes vacuum. Air moves from collector's inlet to chimney's outlet.

Fig. 11 shows temperature contours of the asymmetric domain. The inlet and outlet temperature is ambient. Inside the chimney, the temperature has a maximum value because the gained heat from the solar energy through the collector and the chimney.

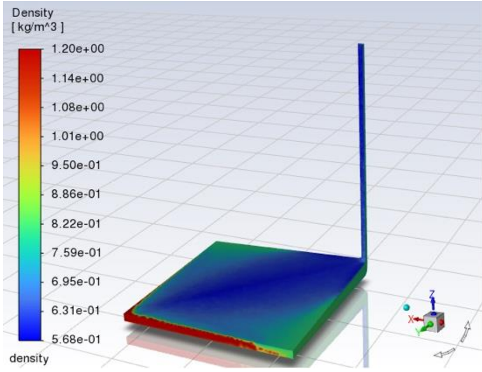


Fig. 9. Density contours of the Asymmetric domain.

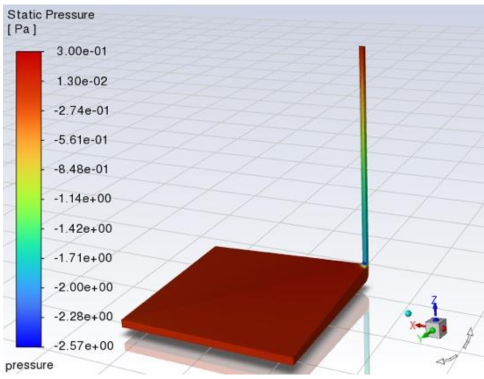


Fig. 10. Static pressure contours of the Asymmetric domain.

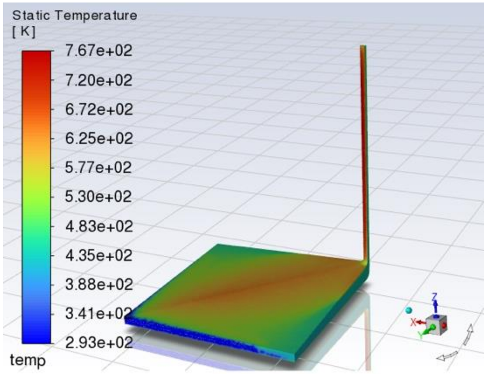
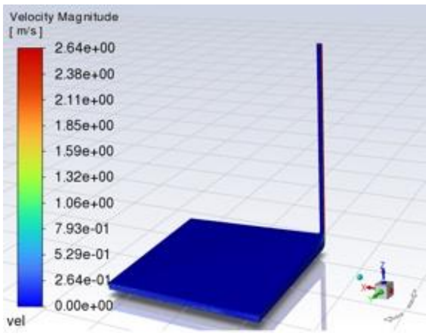


Fig. 11. Static temperature contours of the Asymmetric domain.

Figs. 12 and 13 show velocity contours and vectors, respectively, of the asymmetric domain.



a)

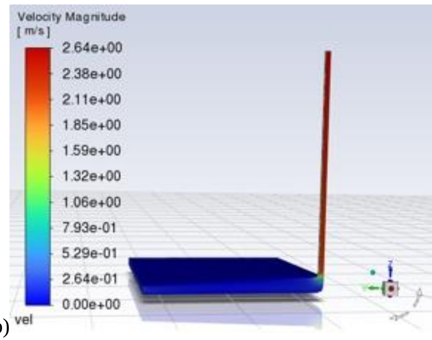
b) 

Fig. 12. Velocity contours of the Asymmetric domain a) isometric plane b) side view.

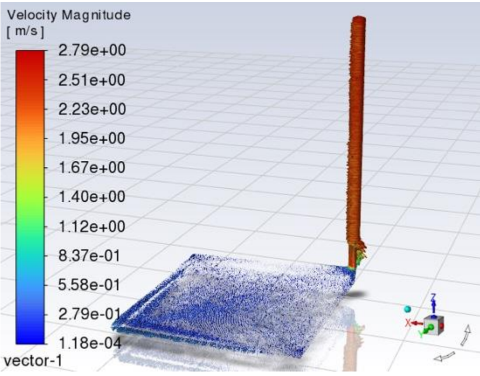


Fig. 13. Velocity vectors of the Asymmetric domain.

3.3 Numerical verification with experimental results

Fig. 14 represents velocity profile at the chimney outlet across the diameter line. From the figure, the average velocity can be calculated to be 1.76 m/s at 1:00 pm.

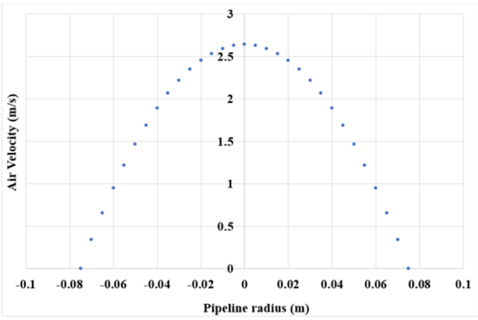


Fig. 14. Velocity profile at the chimney outlet across the diameter line

Fig. 15 represents air velocity numerical and experimental results comparison at the chimney output.

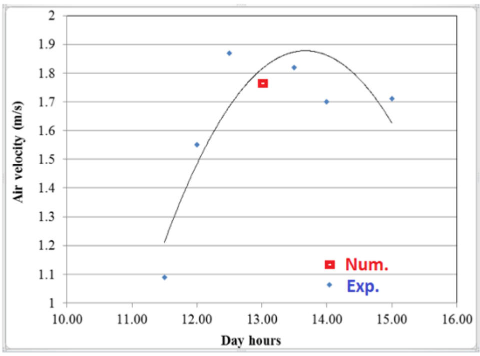


Fig. 15. Air average velocity Numerical and Experimental studies comparison at chimney output and day hours.

IV. Conclusion

In the current paper, experimental and numerical studies of SCPP prototype are presented. It has 16 m² solar collector, 0.15m diameter, and 3m chimney height in July of 2024 in Alexandria, Egypt. From the previous results (power, air velocity, mass flowrate, temperature, density and pressure difference), it can be concluded that:

- All the maximum experimental results values appear just before 2 pm. The sun's intensity decreases after mid-day, but the residual heat inside the solar chimney lasts longer and then begins to decrease.
- All experimental results have the same increasing, peak and decreasing trend.
- For the asymmetric numerical domain, the pressure appears to have a vacuum at the chimney entrance. This is why air is sucked into the solar chimney.
- Air flows in SCPP according to air density change resulted from the increase in temperature. The less dense air moves forward towards the collector's center and then up to the chimney.
- A matching has been achieved when comparing between the velocity numerical and experimental results.

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