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# Computational studies on the effect of geometric parameters on the performance of a solar chimney power plant

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ABSTRACT

A solar chimney power plant (SCPP) is a renewable-energy power plant that transforms solar energy into electricity. The SCPP consists of three essential elements – solar air collector, chimney tower, and wind turbine(s). The present work is aimed at optimizing the geometry of the major components of the SCPP using a computational fluid dynamics (CFD) software ANSYS-CFX to study and improve the flow characteristics inside the SCPP. The overall chimney height and the collector diameter of the SCPP were kept constant at 10 m and 8 m respectively. The collector inlet opening was varied from 0.05 m to 0.2 m. The collector outlet diameter was also varied from 0.6 m to 1 m. These modified collectors were tested with chimneys of different divergence angles (0°–3°) and also different chimney inlet openings of 0.6 m to 1 m. The diameter of the chimney was also varied from 0.25 m to 0.3 m. Based on the CFX computational results, the best configuration was achieved using the chimney with a divergence angle of 2° and chimney diameter of 0.25 m together with the collector opening of 0.05 m and collector outlet diameter of 1 m. The temperature inside the collector is higher for the lower opening resulting in a higher flow rate and power.



## 1. Introduction

The increases in oil prices and energy demand combined with recent environmental constraints have rapidly increased the global demand for renewable energy. Solar energy is one of the most promising solutions, especially considering its technological advancements and its growth in the recent years. One of the options that will help meet these demands is the solar chimney power plant (SCPP). The SCPP is a proposed type of renewable-energy power plant that transforms solar energy into electricity.

The SCPP is a low temperature power plant consisting of three essential elements – the collector, the chimney, and the wind turbine(s) [1,2]. The chimney is a long cylindrical structure normally placed in the center of a greenhouse collector which is made out of transparent glass or plastic film [3–6]. The height of the collector increases towards the center where the chimney is placed to guide the hot air up the chimney. Turbine(s) are normally placed at the base of the chimney for power generation. The solar radiation enters the collector and gets absorbed by the ground which heats up the air above it. The hot buoyant air rises up towards the chimney base where a turbine is placed. Suction from the chimney draws in more hot air and the cooler air from outside the collector enters the chimney to replace the hot air through natural convection. Power can be generated round the clock by placing water filled bags under the collector roof and this provides an added advantage of this plant over other solar technologies [6].

The first SCPP prototype was proposed by Schlaich and was built in 1982 in Manzanares, Spain [3,7]. Research works were conducted on the plant and it proved that the SCPP concept is technically viable for power generation [8]. There are normally three methods to study the performance characteristics of a solar chimney power plant: analytical method, numerical method and the method based on similarity theory [9].

The very first theoretical model was developed by Mullet [10] who derived the overall efficiency of the SCPP. According to his model, the overall efficiency of the plant is very low and concludes that the SCPP can be used for large scale power generation. Due to this fact, very few experimental models of SCPP were built and tested and more theoretical and mathematical models have been developed to predict the SCPP performance.

Several analytical investigations have been conducted by Refs. [2,3,5,7,11–16] to predict the performance of a SCPP. Koonsrisuk and Chitsomboon [17] compared theoretical models produced by Refs. [7,12–14,16] to study the accuracy of these theoretical models for the prediction of SCPP performance by studying various plant geometrical parameters and the insolation. They even conducted computational fluid dynamics (CFD) studies to compare the results with these theoretical models. According to the results obtained in their study, it can be said that the theoretical models

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**Nomenclature**

| | |
|---|---|
| $A$ | flow area, m$^2$ |
| $h_{total}$ | total enthalpy, kJ/kg |
| $p$ | pressure, Pa |
| $P_{available}$ | available power, W |
| SCPP | solar chimney power plant |
| $S_E$ | source term in the energy equation, W/m$^3$ |
| $S_M$ | source term in the momentum equation, N/m$^3$ |
| $T$ | absolute temperature, K |
| $u$ | velocity |
| $V$ | air flow velocity, m/s |

*Greek Symbols*

| | |
|---|---|
| $\lambda$ | thermal conductivity, W/mK |
| $\rho$ | density of air, kg/m$^3$ |

*Subscripts*

| | |
|---|---|
| $i$ | component $i$ |
| $j$ | component $j$ |

produced by [13,16] compared very well with the CFD results and thus are recommended for the prediction of SCPP performance.

Of late, the use of CFD in studying the flow and the performance of SCPP has increased. This is due to the accurate results and flow visualization offered by CFD software. The first known attempt made to simulate the flow in a SCPP using CFD was conducted by Bernardes et al. [18] in which they performed numerical analysis on the natural convection in a radial solar heater to predict the thermo-hydrodynamic behavior of the device by studying different junction shapes at the collector base.

Kirstein and Backstrom [19] performed numerical analysis to study the flow through a SCPP collector-chimney transition section using commercial CFD software, ANSYS-CFX. CFX was used to verify the experimental data of a scaled model SCPP. Due to the very good agreement between the experimental and numerical results, CFD software can be used to predict the performance of a full sized SCPP.

Further studies using CFD were conducted by Tingzhen et al. [3] and Sangi et al. [20]. Tingzhen et al. [3] performed numerical simulation on the Manzanares SCPP coupled with a three-bladed turbine to validate their CFD code. The CFD code showed good agreement with the experimental data and a MW-grade SCPP was designed and numerically tested with a five bladed turbine to provide a reference for the design of large scale SCPP systems. Sangi et al. [20] developed a mathematical model of a SCPP based on the Navier–Stokes, continuity and energy equations. They also performed numerical simulations using a commercial CFD software FLUENT for the Manzanares SCPP. Both the mathematical model and the numerical analysis were compared to the experimental data and showed a good quantitative agreement.

Koonsrisuk and Chitsomboon [21] studied the effect of tower area change on a SCPP using CFX. From their studies, it can be concluded that divergent tower helps increase the mass flow rate and kinetic energy compared to a constant area tower and the maximum kinetic energy occurs at the tower base. For a convergent tower, the velocity increases at the tower top but the mass flow rate decreases thus causing the kinetic energy to be similar to that of a constant area tower.

A recent study using CFD was conducted by Ming et al. on the influence of ambient crosswind on the performance of a SCPP [22]. According to their study, ambient crosswind has a positive and a negative effect on the performance of a SCPP. When the ambient crosswind is weak, the flow field is deteriorated and the output power reduces. When the ambient crosswind is strong enough, the mass flow rate increases, thus the output power also increases. This increases in mass flow rate results from a wind suction effect on top of the chimney caused by the high velocity wind (Bernoulli principle). Further numerical analysis was conducted by Ming et al. [23] to overcome the negative effect of strong ambient crosswind by employing a blockage a few meters away from the collector inlet opening. According to their study, negative effects resulting from strong ambient crosswinds have been greatly overcome by a large extent with the help of these blockages.

The present work investigates the influence of various geometrical parameters on a fixed solar chimney height and collector diameter to improve the performance of SCPP. Geometric parameters such as collector inlet opening, collector outlet diameter, collector outlet height, chimney inlet opening and chimney divergence angles were varied and tested with different configurations to study and improve the air flow characteristics inside a SCPP.

## 2. Methodology

ANSYS-CFX Version 14 was used for simulation purpose in this research project. ANSYS-CFX Version 14 uses unsteady Navier–Stokes equation in their conservation form to solve set of equations. The instantaneous equation of mass (continuity), momentum, and energy conservation are presented below [17]:

$$\text{Mass conservation}: \frac{\partial y}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\text{Momentum conservation}: \frac{\partial y}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + S_M \tag{2}$$

$$\text{Energy conservation}: \frac{\partial y}{\partial x_j}(\rho u_i h_{total}) = -\frac{\partial p}{\partial x_i} + \left(\lambda \frac{\partial T}{\partial x_i}\right) + u_i S_M + S_E \tag{3}$$

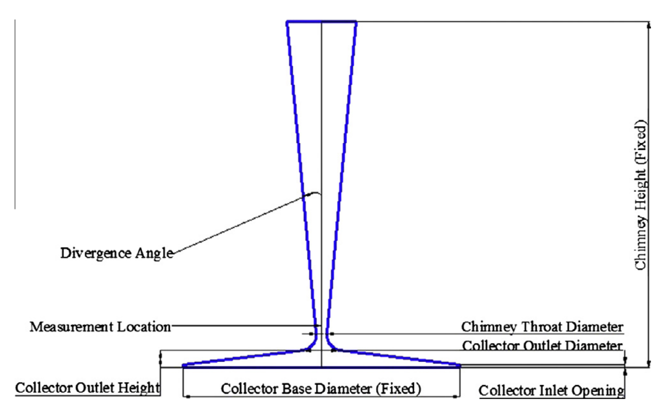


**Fig. 1.** Diagram of the SCPP with the various parameters that are studied.