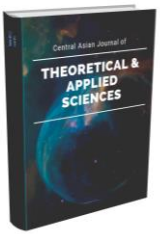

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Article

A CFD Study of The Effect of Chimney Diameter on a Solar Chimney Power Plant (SCPP) Output

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Abstract: The solar chimney power plant (SCPP) is a promising renewable energy system that leverages solar thermal energy to generate electricity with low operational costs and minimal environmental impact. This study investigates the impact of chimney diameter on the overall power output of an SCPP using computational fluid dynamics (CFD). The objective is to determine the optimal diameter ratio to maximize energy generation efficiency and airflow dynamics. A 2D steady-state CFD simulation was performed using ANSYS Fluent, applying the k-omega turbulence model and Boussinesq approximation. The system was modeled with a fixed collector diameter of 40 m and a chimney height of 30 m, while chimney diameters corresponding to ratios of 0.03, 0.05, and 0.1 were analyzed. Simulations were conducted under typical Baghdad summer conditions. Results indicate that a smaller diameter ratio increases air velocity and turbulence kinetic energy, thus enhancing power output. The optimal turbine location was identified at the chimney base near the collector junction, where maximum airflow velocity was observed. Excessive diameter (0.1 ratio) caused flow dispersion and decreased efficiency. The findings suggest that chimney diameter significantly influences SCPP performance, and optimizing this parameter can contribute to more efficient solar energy harvesting in arid regions. The novelty of this work lies in its CFD-based quantitative assessment of diameter ratio effects, offering insights into geometrical optimization of SCPP systems.

Keywords: solar chimney, convection, thermal radiation, renewable, ANSYS Fluent, SCPP

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1. Introduction

There is an environmental growing need for acceptable renewable energy sources due to the depletion of fossil fuel supplies and the rise in global pollution. Growing demand for power has spurred a lot of research interest in a variety of engineering applications. This offers a long-term solution to the issue of energy security. Among all kinds of renewable energy sources, solar energy delivers a significant amount. One of the solar systems is the solar chimney power plant. The solar chimney power plant is defined as a renewable energy source that outperforms other solar power plants in terms of continuous generation, cheap operating costs, and straightforward technology, see Figure 1.

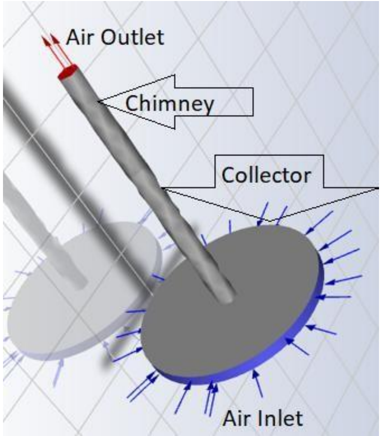

Figure 1. Solar chimney power plant system.

The solar chimney power plant consists of a solar collector, a chimney in the middle of the collection, turbine generators at the chimney's base, and a heat storage layer. Some heat energy is stored in the heat layer of storage, whereas the other heat energy is transferred to the heat's airflow. surface of the storage layer by convection. by convection on the storage layer's surface. The warm air flow accelerates along the solar collector to the chimney's base, drives the turbine generators to generate electricity, and finally leaves the system from the top of the chimney. At same time, a constant air current is produced because of the outside air enters the system through the edge of the solar collector. The system continuously produces electricity because the heat storage layer releases its heat energy during nights or cloudy days.

Several scientists were tried to investigate the solar chimney power plant deeply. For example; Ming et al [1] performed numerical simulations on solar chimney power plant systems with turbines. The system is separated into three regions: collector, chimney, and turbine, with corresponding mathematical models for heat transfer and flow. While, Zhou et al [2] analyzed the ideal chimney height for a solar chimney power plant's maximum power output and the maximum chimney height for convection. They found that the maximum height for convection and the optimal height for maximum power production both rise as the collector radius increases. Maximum height rises with lapse rate and collector radius, according to sensitivity analysis.

Koonsrisuk and Chitsomboon [3] were considered multiple validated measurements and iteration procedures to simulate the solar collector, the chimney, and the turbine. Also, Stojkovski [4] is used a computational fluid dynamics (CFD) to analyze the technical features of a solar chimney power plant, and optimizing its geometry and thermo-fluid aspects. The discrete ordinates (DO) model was selected for thermal radiation analysis. While, Ghalamchi et al [5] adjusted three parameters : collector slope, chimney diameter, and collector entry gap. A FLUENT software was able to assess the performance of the solar chimney power plant. Again, Ghalamchi et al [6] developed and built a solar chimney prototype power plant. The temperature distribution and air velocity were tested and analyzed. The output data were gathered and demonstrates that a reduction in inlet size has effect on the pressure regeneration required to start separation.

Also, Dhahri et al [7] offered a quantitative study on a solar chimney power unit with steady state and Navier-Stokes and energy equations in cylindrical coordinates using the k-ε turbulent model, in FLUENT software. The simulations were made based on a prototype in Spanish. The effects of the main collector and solar irradiation on the air mass flow rate and the distributions of fluid and ground temperatures were also presented and analyzed by them. However, Yetimgeta and Mulugeta [8] had comprised a mathematical model comprised of Navier-Stokes, continuity, and energy equation for complete numerical modeling of a solar chimney power plant. One simulation was executed using steady state parameters, while the other utilized transient parameters, all considering climate conditions of Dire Dawa. To explain, the 2D ax-symmetric model of the plant, as well as its temperature, velocity, and static pressure distributions corresponding to each geometry configuration, were computed using the CFD program FLUENT.

Also, Husain et al [9] Used fluent software to solve the continuity, Navier-Stokes, energy, and radiation transfer equations pertaining to solar chimney power generation. The alterations to the collector diameter and chimney height have a noticeable effect on collection system performance. Again, Zhou et al [10] compared and analyzed different modes of solar radiation on the collector and simulation methods. They verified that the two-parallel-plate model for radiation heat transport within the collector is appropriate by proving that the two-dimensional model approach is in agreement with the three-dimensional method described in literature and corroborated by experimental data. Moreover, Mekhail et al [11] utilized a tiny replica of a chimney. Its performance is predicted using a mathematical model based on the thermodynamic analysis of the flow inside the SCPP. There is a good agreement between the theoretical performance, which is derived from the mathematical model, and the experimental one. They demonstrate that a theoretical power of almost 600 hundred times that of the smaller model can be generated by the larger one.

Toghraie et al [12] also applied the k-e turbulence model, continuity, momentum, and energy equations in the 3D finite volume method inside a solar chimney power plant, the numerical effects of geometrical parameters on a solar chimney were examined. Collector radius, collector height, chimney height, chimney radius, and heat flux should all be considered. Investigations were conducted on how variations in these parameters affected output power, efficiency, temperature, velocity, and pressure distributions. They showed that a negative correlation with collector height but a positive correlation with chimney height and collector radius for output power and solar chimney efficiency. Furthermore, it was discovered that the chimney radius parameter has an optimal range with the highest output power and efficiency values.

Also, using the ANSYS Fluent software [13], a numerical simulation of a solar chimney power plant model was carried out by solving the pertinent equations using the conventional k-epsilon turbulence model and the discrete coordinates (DO) radiation model. They concentrated on the temperature increase in the collector, air velocity at the chimney base, and pressure drop inside the chimney. Furthermore, Zhou et al [14] investigated the thermodynamic characteristics of airflow in SCPP and power production efficiency as a function of design parameter values using a series of numerical simulations using the CFD approach and the $k-\varepsilon$ turbulence model. By decreasing airflow pressure and increasing airflow velocity and temperature close to the chimney base, they discovered that increasing these parameters will increase power generation efficiency.

ANSYS Fluent CFD software is used again [15] in a quantitatively study the performance of the solar chimney power plant. They found that the solar chimney power plant with thermal storage as water could decrease the variance in power production caused by variations in solar radiation. Additionally, when the intensity of solar radiation increases, the system's velocity also increases dramatically. When gravel is used as thermal storage, the energy storage layer's average surface temperature rises noticeably. Yousif et al [16] approved that increasing the collector radius and chimney height improves the system's efficiency and power output. The chimney tower radius has the greatest effect on performance, and Performance-wise, the ideal values for collector height and tilt are determined. However, Cuce et al [17] assessed comprehensively and succinctly the design elements as well as the theoretical, numerical, experimental, and performance results. They also mentioned great details about the limitations of solar chimney power plants and the different between optimization techniques.

Akhil et al [18] examined how the solar chimney power plant's driving potential is affected by the area ratio of the chimney and collector using ANSYS Fluent. Indeed, Al-Ali et al [19] focused on reviewing the articles examining the performance of the main components of solar chimney power plants. The most important approaches to improve the performance of the system is by using various methods, including integrating the system with thermal storage materials and phase changes materials (PCMs) as well as integrating it with other technologies and in addition. Also, Al-Ali et al [20] indicates that a MATLAB/Simulink model that assesses the SCPPs' engineering and physical specifications, pressure loss, power output, and other features. They discovered that, within a specific range, ambient temperature had a bigger effect on energy output than solar radiation. Otherwise, the biggest influence comes from solar radiation. What's more, Al-Ali et al [21] assessed the performance of a solar chimney power plant system using a numerical simulation, where the impacts of different parameters on the relative static pressure, driving force, power production, and efficiency were further examined. An experimental model and the upwind velocity in the solar chimney were compared in order to validate of their work.

It is noticeable that the most of the previous scientists works were based on the ANSYS Fluent for well known reasons, therefore this study will adopted it to investigate the targeted parameters.

2. Materials and Methods

CFD modeling and simulation

The chimney height is considered constant of 30 m and the collector radius is constant also of 20 m as shown in Figure (2). Three different diameter ratios of 0.03, 0.05 and 0.1 are investigated to find the effect of changing the chimney diameter on the power generation. For this purpose, three different meshes is generated. Additionally, the optimum turbine location is approved in this study.

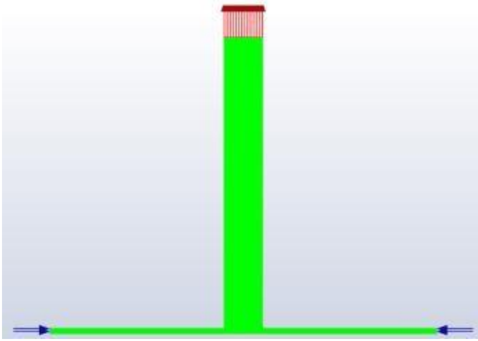

Figure 2. The 2D modeling of solar chimney.

Moreover, the governing equations for mass, momentum and energy are solved using a commercial CFD code. The computation is performed using the assumption of steady 2-D flow. The pressure-based and absolute velocity solver have been used. The turbulence is taken into consideration with the k-omega realizable model. The Boussinesq approximation is considered. Also, all properties are assumed to be constant except for density in the momentum equation.

The boundary condition is selected based on Baghdad city for a normal summer day. To explain: the inlet air boundary condition of initial values are 0.5m/s velocity, 40°C temperature and 1 atm. The outlet air initial pressure is 1 atm and 40°C. The walls of chimney is considered as stationary walls with no slip for the following: the chimney one of a constant temperature of 40°C and neglected thickness. The constant sun radiation is supplied on the collector at 40°C, and the fixed temperature of 15°C for the soil one.

Moreover, the controlled equations for the chimney and collector can be written as following:

The continuity equation is given by:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

The momentum equations:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u u)}{\partial x}+\frac{\partial(\rho u v)}{\partial y}=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad \ldots\ldots\ldots \text{(2)}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho u v)}{\partial x}+\frac{\partial(\rho v v)}{\partial y}=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad \ldots\ldots\ldots \text{(3)}$$

The energy equation is:

$$\frac{\partial(\rho cT)}{\partial t} + \frac{\partial(\rho cuT)}{\partial x} + \frac{\partial(\rho cvT)}{\partial y} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad \text{……………….. (4)}$$

The k-omega equation is:

$$\frac{\partial k}{\partial t} + U\frac{\partial w}{\partial x} = P_k - \beta^{\square} kw + \frac{\partial}{\partial x}\left[(v + \sigma_k v_T)\frac{\partial k}{dx}\right] \quad \text{………..… (5)}$$

The SCPP output power can be represented using the turbulence kinetic energy if all kinds of losses such as turbine loss are neglected.

3. Results and Discussion

In this paper, the effect of diameter ratio (chimney diameter/collector diameter) on the output power of SCPP is investigated. Figure (3) shows the effect of diameter ratio on the total pressure drop across the system. The results of this study show that increasing the diameter ratio has a minor influence on the total presser drop. This is because of all study cases have the same height of chimney.

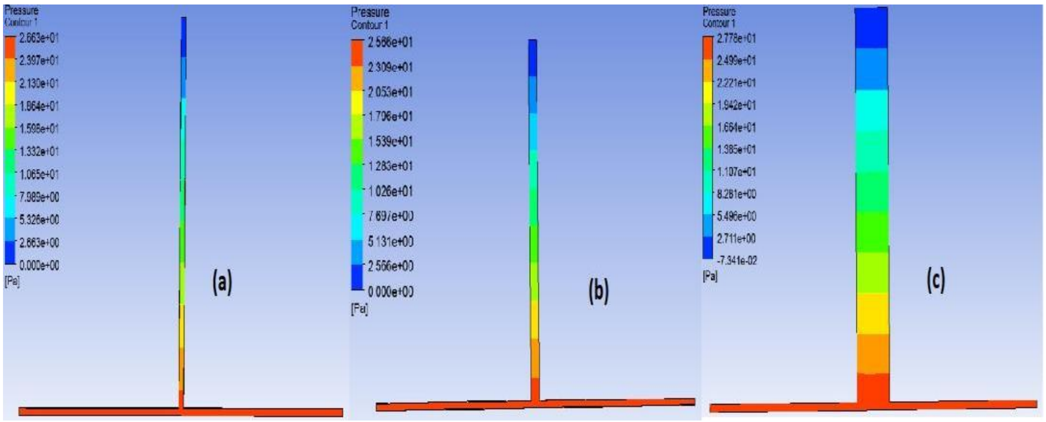

Figure 3. Pressure contours of SCPP for different diameter ratios (a) 0.03 (b) 0.05 (c) 0.1

Figure (4) of the velocity contours for the 0.03 and 0.05 cases approved that increasing the chimney diameter reduces the air velocity passing across the system from 1.38m/sec to 1.05m/sec. The air velocity increment leads to gain more output SCPP due to increasing the turbine rotational speed. In addition, these two counters approved that the suitable place of the turbine is located at the chimney end nearby the collector. However, the 0.1 diameter ratio counter shows that this ratio is completely unsuitable because it is causing a flow dispersing and a variation in the location of the maximum velocity.

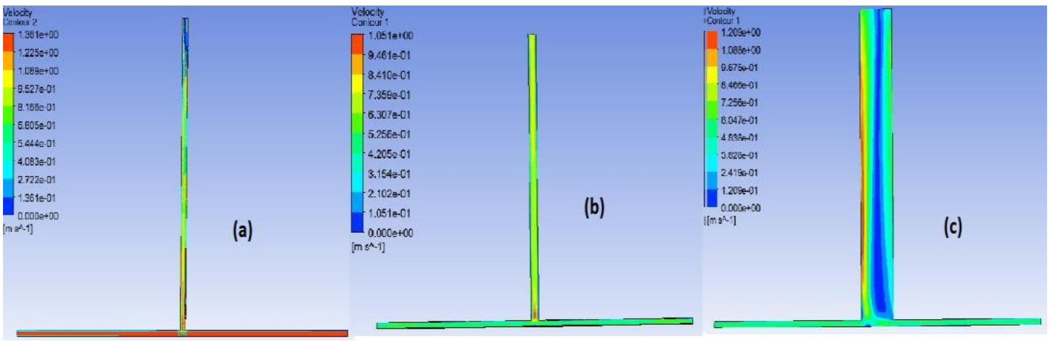

Figure 4. Velocity contours of SCPP for different diameter ratios (a) 0.03 (b) 0.05 (c) 0.1

The turbulence kinetic energy counters are shown in Figure (5). This energy decreases with diameter ratio increment. Because this kind of energy depends on air velocity.

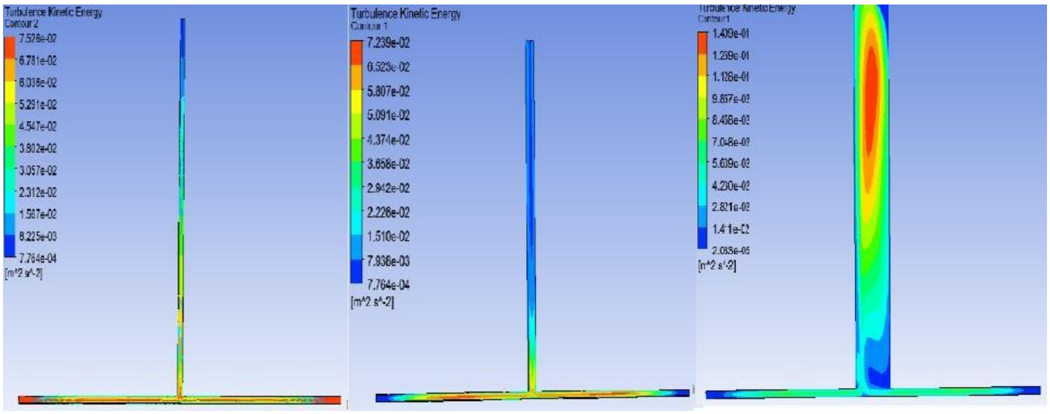

Figure 5. Turbulence Kinetic energy contours of SCPP for different diameter ratios (a) 0.03 (b) 0.05 (c) 0.1

4. Conclusion

Numerical computations ANSYS Fluent has been performed on the commercially available finite volume code. The effect of diameter ratio on output power of SCPP is investigated. The velocity of the air increases, as diameter ratio decreases inside the SCPP. Additionally, the power output of the SCPP increases. This study approved that the best location of the turbine is located at the end of chimney from the collector side.

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