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Numerical Investigation of the Effect of Height Ratio, Collector Angle, and Obstacle Presence in a Solar Chimney with a Two-Level Inlet

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Abstract

Among renewable energies, solar energy stands out as one of the best sources for human use due to its easy accessibility across the globe. This study focuses on the investigation and optimization of the shape and dimensions of solar chimney power plants, which are one of the methods for converting solar energy into electricity. Recently, the use of solar chimneys with a two-story collector has become a hot topic; thus, this optimization was performed on a solar chimney power plant with a two-story collector in two phases using numerical simulations in ANSYS Fluent. The optimization was conducted in such a way that in the first phase, the flow type in the two stories of the collector, which can be either co-flow or counter-flow, was optimized along with the height ratio of the two stories. In the second phase, the angle of the roof of the collector was optimized. The results indicate that when the flow in the two stories of the collector is co-flow, the power output of the plant is significantly higher. Additionally, in this case, when the height ratio of the first story to the total is set at 80%, the maximum efficiency and power output are achieved, measuring 1.22 and 39.5 kW, respectively. Analyzing the effect of the collector roof angles reveals that when the roof of the first story is horizontal and the roof of the second story has a one-degree angle, the power output and efficiency of the plant reach their optimal state. In fact, under these conditions, the power output of the plant increases by 8%, reaching 42.6 kW.

Keywords: Solar chimney power plant, Power plant output power, Power plant efficiency, Numerical simulations

1. Introduction

The increasing demand for electricity in today's world and the decrease in fossil fuels and other non-renewable energy resources have led scholars to find alternative solutions and use renewable energies. Among the types of renewable energies, solar energy is recognized as one of the most suitable energy resources due to its easy availability in many parts of the world.

Pastohr et al. [1] conducted the first numerical studies using computational fluid dynamics on a solar chimney. They simulated the Manzanares solar chimney in a two-dimensional axisymmetric form using ANSYS Fluent software and considered solar radiation as a solid thermal storage in a small area on the Earth and did not model it directly. Ming et al. [2] considered the Earth as a porous material for the first time while studying numerically a solar chimney. Maya et al. [3] conducted a numerical analysis of the unsteady flow inside a solar chimney power plant system (using the finite volumes method). They validated their numerical solution results with experimental results and applied their model to different shapes of solar chimneys. The results of their study indicated that the height and diameter of the chimney significantly affected the performance of the solar chimney. Chergui et al. [4] studied numerically the airflow through a solar chimney. Sangui et al. [5] studied analytically and simulated numerically the performance of the Manzanares power plant and compared the results. Examining the results obtained from the two parameters of temperature and pressure, they reported that their analytical mathematical model was in very good agreement with the model simulated using the ANSYS Fluent software. Xu et al. [6] studied numerically the performance of the Manzanares solar chimney power plant using the ANSYS Fluent software. The difference between their modeling and the simulation conducted by Pastohr et al. was that they considered thermal storage as a porous material instead of considering it as a solid and they added a turbine (pressure drop) in the chimney. The results from their study indicated that the output power of the turbine was directly related to solar radiation. Using the Bernoulli equation, Hamdan [7] presented a mathematical model for solving the air flow in a solar chimney power plant and concluded that the turbine head is a parameter affecting the power output of the power plant. Fasel et al. [8] studied numerically the dimensions of a solar chimney. Ayadi et al. [9] conducted a numerical study of the impact of the collector roof inclination on the performance of a solar chimney power plant. Najm and Shaaban [10] investigated numerically a solar chimney using the ANSYS Fluent software. Abdelmohimen and Algarni [11] conducted a 3D numerical study on a solar chimney power plant of the Spanish prototype. The results showed that the average annual total energy production in six solar chimneys could be between 55 and 63 kW. Nasraoui et al. [12] numerically studied and simulated an inclined roof solar chimney. Sedighi et al. [13] investigated numerically the performance of a solar chimney power plant under the effects of turbine pressure drop, solar radiation and energy storage layer porosity. Nasraoui et al. [14] also considered the chimney inlet as a double-pass structure with inlets of equal height in another study. Das et al. [15] numerically investigated the effect of chimney divergence angle, ambient temperature, turbine efficiency, and solar flux on the performance of a solar chimney power plant. Kababsa et al. [16] numerically studied the effect of the slope of the solar chimney inlet on its performance. Singh et al. [17] changed the shape of the inlet in a solar chimney power plant and investigated its effect on the output power of the solar chimney.

Among the experimental works conducted, the following can be mentioned: Ghalamchi et al. [18] investigated the experimental performance of a laboratory-scale solar chimney.

Considering the studies carried out, the present research investigates and optimizes the shape and dimensions of the solar chimney power plant, given that the use of solar chimneys with double-pass inlets has recently received much attention. This optimization was performed numerically in two stages on a solar chimney power plant with a double-pass collector using ANSYS Fluent software. As an innovation in this project, the ratio of the first collector pass's height to the total collector height was investigated in five configurations under conditions where the flow in the two passes of the collector was consistent and inconsistent, and after obtaining the optimal state, the second stage of improving the geometry of the solar chimney was implemented. In the second stage, given that the effect of the collector roof angle in double-pass solar chimneys has not been studied so far, 9 different configurations for the collector roof angle of double-pass collectors were considered and the geometry causing the best performance was selected.

2. Governing equations

The governing equations (Mass conservation equation, Momentum conservation equation in the x direction, Momentum conservation equation in the r direction) were extracted from the research by Kababsa et al. [16]. According to the research by Najm and Shaaban [10], the total efficiency of the solar chimney power plant is calculated using equation 4 from the product of the efficiency of the three parts.

$$\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho v)}{\partial r}=0 \tag{1}$$

$$\frac{\partial(\rho uu)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho uv)}{\partial r}=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial u}{\partial x}\right]+(\rho-\rho_0)g\;\frac{1}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}\right)\right]+ \tag{2}$$

$$\frac{\partial(\rho uv)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho vv)}{\partial r}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)r\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+\frac{2}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\frac{\partial v}{\partial r}\right]-\frac{2(\mu+\mu_t)v}{r^2} \tag{3}$$

$$\eta_{tot}=\eta_c\eta_{tur}\eta_{ch} \tag{4}$$

3. Assumptions and solution method

3.1. Studied geometry

The geometry of the solar chimney used in this study was similar to that used in the research by Pastohr et al. This model, which is shown in Figures 1, includes the sections of ground, chimney, and collector. The difference was that the inlet collector involved two passes in the present study.

Given that the geometry and flow in the present study were axisymmetric, an axisymmetric design was used for simulation. To do a simulation in the present study, the given geometry was drawn using the DesignModeler, which is one of the modules of ANSYS Workbench. The geometry drawn has been presented in Figure 2.

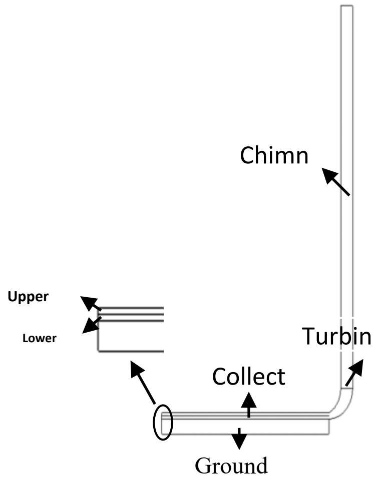

Figure 1 - Geometry drawn in DesignModeler

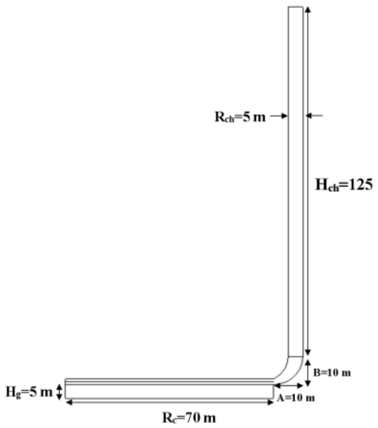

Figure 2 - Dimensions of the solar chimney geometry

3.2. Meshing

For meshing this model, ANSYS Meshing was used. To create a regular and high-quality mesh in the computational domain, the geometry was first divided or blocked in the DesignModeler. Then, the divided geometry was meshed using ANSYS Meshing. A view of one of the meshes created for a geometry in which the inlet height of the two passes of the collector was equal and the collector roof had no slope is shown in Figure 3.

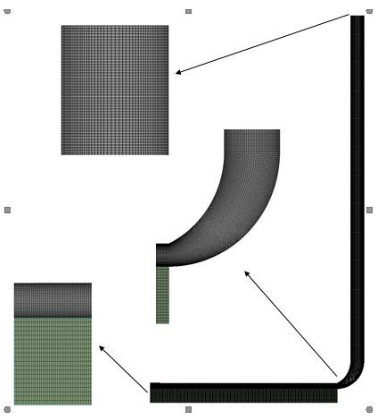

Figure 3 - Mesh generated through the software

4. Analysis of results

The simulation results are examined in three stages. In the first stage, the results from the collector type and the height ratio of the two passes in the collector are examined to obtain the optimal geometry for the next stage, which includes finding the optimal angle.

4.1. Investigating the effect of the height ratio of the two passes in the collector

After conducting the simulations in the 10 mentioned configurations, the results obtained, including the overall efficiency of the power plant and its generated power, were examined. The results have been presented in Table 1.

Table 1- Overall efficiency and output power of configurations 1 to 10

Configuration no.	Overall efficiency (%)	Output power (W)
1	21.05	37098.5
2	21.66	37922.9
3	21.75	38391.9
4	22.03	38647.8
5	22.10	39466.3
6	14.27	6889.1
7	20.34	20757.4
8	20.43	23021.7
9	21.11	22193.3
10	20.97	10763.8

According to what has been presented, it can be said that in the configurations where the collector included consistent flow, the overall efficiency of the power plant and the power generated showed a certain trend. The overall efficiency and output power in a single-pass solar chimney power plant have been presented in Table 2.

Table 2 - Overall efficiency and output power in a single-pass solar chimney power plant

Collector	Overall efficiency (%)	Output power (W)
Single-pass	21.76	31225.9

As can be seen, in the configurations where the collector included a consistent flow, the temperature of the air exiting the collector was higher than the configurations where the collector included an inconsistent flow.

However, as the mass flow rate at the exit of the collector was less than the configurations with consistent flow, the collector efficiency was lower. Therefore, using the configurations with inconsistent flow reduces the collector efficiency. Additionally, examining the turbine volumetric flow rate demonstrated that due to less collector outflow rate in the configurations with inconsistent flow compared to configurations with consistent flow and single pass, the turbine volumetric flow rate was also lower in these configurations. This caused the turbine output power in such configurations to be less than the configurations where the collector included consistent flow. The results obtained for the configurations where the flow in the two passes of the collector was consistent indicated that the main factor in increasing the output power with increasing the ratio of the first pass height to the second pass height was the increase in the turbine pressure drop. These results have been presented in Table 3.

Table 3 - Parameters extracted for configurations 1 to 10

Configuration no.	Collector outflow rate (kg/s)	Collector outlet temperature (K)	Collector efficiency (%)	turbine volumetric flow rate(m^3/s)	turbine pressure drop(Pa)
1	1161.1	320.32	60.0	947.85	48.92
2	1176.8	320.63	61.7	960.62	49.34
3	1179.2	320.67	61.2	962.57	49.87
4	1176.8	320.98	61.9	960.77	50.28
5	1171.8	320.14	63.0	956.58	51.57
6	571.7	327.98	40.7	466.69	18.45
7	964.21	323.65	58.0	787.11	32.96
8	1005.1	322.79	58.2	820.50	35.07
9	955.11	323.87	60.1	812.34	34.15
10	786.18	329.89	59.7	641.78	20.96

5. Conclusions

In this research, the performance and dimensional optimization of the efficiency and power generation in a solar chimney power plant with a two-pass collector were numerically investigated using the ANSYS Fluent software. The optimization of the power plant was carried out in three general stages. In the first stage, the type of collector, which can include consistent and inconsistent flow, was investigated along with the height ratio of the two passes of the collector. For this purpose, 5 geometries with different height ratios were considered for the consistent and inconsistent flows, and the air flow in the solar chimney power plant was studied to obtain the configurations with the highest efficiency and power generation. Then, in the second stage of the research, the effect of the roof angle of the two collector passes on the performance of the solar chimney power plant was studied. 9 different configurations were selected in which the roof of the two collector passes had an angle of zero, one, two, and three degrees, and the optimal configurations among them was recognized.

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