Experimental Studies on an Inclined Collector Divergent Chimney Pilot Plant

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Abstract. Renewable energy sources become suitable options to reduce the dependency on fossil fuels or petroleum products. The International Renewable Energy Agency reports that the world will harvest 40% of energy from renewable energy sources by 2030. Conventional technologies such as solar PV technology, consumes higher capital per unit (kWh) of electricity generation cost significantly higher than the traditional sources. Hence, solar chimney power generation system can be suitable option for generating low cost energy. Solar chimneys are developed and tested by different researchers in enhancing the performance of the system. Studies on the geometric modifications of the collector, and chimney are limited. The aim of this paper is to analyse the experimental data obtained from a divergent solar chimney. Experimentation is carried under sunlight in an open atmosphere. The airflow rates in the chimneys are tested under different collector outlet height. The experimental results showed that a chimney with higher collector openings was performed well than other models. The computational analysis is also carried out using ANSYS Fluent software package which shows that the collector opening of 2.5m is recommended for higher high mass flow rate and system efficiency.

1. Introduction
A solar chimney power plant concept is widely recognized across the globe for generating green electricity. The robust design, simpler technology, and ease of operation prefer SCPP among other thermal devices. The first pilot plant was constructed at Manzarnes, Spain, in the year 1980, and worked for almost eight years. The plant was decommissioned due to structural failure. Since then, many researchers have carried out work in enhancing the power output of the SCPP. Various parameters such as the location of the plant, orientation, local wind condition, Design configurations. A simple SCPP plant consists of Tower or Chimney, Collector, and Turbine. The air under the transparent collector gets warm and rises up in the chimney because of the density difference in temperature between inside and outside. The rotational energy of the turbine is converted into electrical energy through suitable devices. The air under the transparent collector gets warm and rises through the chimney due to the buoyancy effect, which rotates the turbine. Producing green electricity is achievable with this simple technology. Hence, this study attempts to build a pilot prototype with a divergent chimney and an inclined collector. The Spanish plant has a height of 195m with a 5m radius, and a collector radius of 122m achieved a peak power output of 50KW. The chimney/tower is the critical component of SCPP as it converts the kinetic energy into mechanical energy of the air stream. The Chimney usually is cylindrical in most of the studies [1]. Okada S et al. [2] proved that divergent chimney studies are limited, but the power output of the SCPP is higher than the cylindrical chimney. The studies concerning divergent chimneys are carried out either by numerical or computational studies [3,4,5,6,7,8]. Caplar Fei cao et al. carried the experimental studies on two
collector geometries one with flat and another with inclined collector [4]. The computational studies [9] carried in the past have shown that the divergent chimneys are best suited for power generation. This paper investigated the influence of collector outlet height on the performance of the divergent solar chimney. For this purpose, the temperature in the chimney, ambient temperature, and temperature inside the collector is measured.

2. Computational Methodology
To design the pilot plant, we have taken the Manzanares plant as a reference and the specification of that plant. In general, the power output is expressed as [10]

\[ P = Q_{\text{solar}} \times \eta_{\text{chimney}} \times \eta_{\text{collector}} \times \eta_{\text{turbine}} = Q_{\text{solar}} \times \eta_{\text{plant}} \] (1)

The chimney transforms the fluid heat inside the collector into kinetic energy and potential energy. The pressure drop of the chimney is used to move up the heated air (as there exists density difference between air inside the collector and ambient) and thereby achieved the rotation of turbine. In this work the turbine is excluded and the absolute pressure difference is considered. The total pressure difference is given by

\[ P_{\text{total}} = \frac{1}{2} m \times V_{\text{chimney, max}}^2 \] (2)

Using the Boussinesq approximation [2], the maximum speed of airflow inside the chimney is

\[ V_{\text{chimney, max}}^2 = 2gh \frac{\Delta T}{T_0} \] (3)

The Efficiency of the Chimney is given as

\[ \eta_{\text{chimney}} = ghC_p \] (4)

The efficiency of the chimney increases with an increase in its height and with the temperature rise. Building a very high tower is structurally impossible; therefore, inclining the roof is viable to improve its efficiency. Computational analysis is carried out using ANSYS FLUENT V-18 on the original Spanish prototype, and the flat collector is replaced by the inclined collector. The roof inclination is achieved by adjusting collector inlet height H1, which is kept constant as 1.85 m, same as in the Spanish prototype, and the height of collector outlet H2 are 2 m, 2.5 m, and 3.5m.

3. Simulation studies
In this study, only the steady-state flow in the solar tower is simulated under following assumptions. To formulate this model the following assumptions are made:

i) The fluid is Newtonian and incompressible.
ii) The flow is steady, three-dimensional and turbulent.
iii) Axisymmetric flow field
iv) The pressure Drop in the collector region is not considered
v) No-slip condition near the wall surface.
vi) The Boussinesq approximation is assumed to be valid.

The governing equations of the present numerical model are as follow.

Continuity equation:

\[ \frac{\partial (\rho u)}{\partial x} + \frac{1}{r} \frac{\partial (r \rho v)}{\partial r} = 0 \] (5)

Momentum equations:

\[ \frac{\partial (\rho u u)}{\partial x} + \frac{1}{r} \frac{\partial (r \rho v u)}{\partial r} = \frac{\partial P}{\partial x} + \left( \rho - \rho_0 \right) g + 2 \frac{\partial}{\partial x} \left[ \left( \mu + \mu_t \right) \frac{\partial u}{\partial x} \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ (\mu + \mu_t) r \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} \right) \right] \] (6)
\[
\frac{\partial (\rho uv)}{\partial x} + \frac{1}{r} \frac{\partial (\rho vv)}{\partial r} = -\frac{\partial p}{\partial r} + \frac{2}{r} \left( \mu + \mu_t \right) \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial r} \right) + 2 \frac{1}{r} \frac{\partial}{\partial r} \left( \mu + \mu_t \right) r \frac{\partial v}{\partial r} - \frac{2(\mu+\mu_t)v}{r^2} \tag{7}
\]

Energy equation:
\[
\frac{\partial (\rho T)}{\partial x} + \frac{1}{r} \frac{\partial (\rho vT)}{\partial r} = -\frac{1}{\rho} \frac{\partial}{\partial x} \left( \mu + \mu_t \right) \frac{\partial T}{\partial x} + \frac{1}{\rho r} \frac{\partial}{\partial r} \left( \mu + \mu_t \right) r \frac{\partial T}{\partial r} \tag{8}
\]

Realizable k-ε equations:
\[
\frac{\partial (\rho k)}{\partial x} + \frac{1}{r} \frac{\partial (\rho v k)}{\partial r} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x} \right] + \frac{1}{pr} \frac{\partial}{\partial r} \left[ (\mu + \mu_t) r \frac{\partial k}{\partial r} \right] + G_k + G_b + \epsilon \tag{9}
\]
\[
\frac{\partial (\rho \varepsilon)}{\partial x} + \frac{1}{r} \frac{\partial (\rho v \varepsilon)}{\partial r} = \frac{1}{\rho} \frac{\partial}{\partial x} \left[ (\mu + \mu_t) \frac{\partial \varepsilon}{\partial x} \right] + \frac{1}{pr} \frac{\partial}{\partial r} \left[ (\mu + \mu_t) r \frac{\partial \varepsilon}{\partial r} \right] + C_1 S_{\varepsilon} + C_2 \frac{\varepsilon^2}{k+\varepsilon} \tag{10}
\]

The Boussinesq Approximation is used to model the buoyancy in the SC. The air density in the governing equations was constant during the computation while the body force is replaced by
\[(\rho-\rho_0)g = \rho_0 \beta(T-T_0)g \tag{11}\]

Where the expansion rate, \(\beta\), is \(1/T_0\).

The meshing procedure was carried out by the ICEMCFD and the structured (quadrilateral) grid was built throughout the 2D flow main. Maintaining \(y^+\) value of 1 with expansion ratio of 1.2. The length of the element edge varied from 0.08 m to 0.55 m. The near-wall region had 10-boundary layer grid for dealing with the fast changes within the near wall region. A heat source was added within a thin layer below the ground surface for modeling the heat transfer between the ground and the working air. The second-order upwind schemes are used to discrete the governing equations and solved by the SIMPLE algorithm in the commercial CFD software, ANSYS with the corresponding boundary conditions mentioned in table 1. The CFD model is validated through the temperature rises in the collector, and the updraft velocity at the tower inlet and compared with literature [11]. The Manzanares prototype experimental results indicate that, when the solar radiation is 1000 W/m², the upwind velocity at the tower base is 15 m/s and the temperature increase through the collector beneath no-load conditions reaches 20 K.

4. Discussion of Simulation Results

The velocity at the chimney base for a straight cylindrical chimney attains a value of 14 m/s, and it reaches almost 23 m/s (figure.1) when the collector outlet height is increased from 1.85 m to 2.5 m. In zero slope collectors with a straight chimney, the velocity of the flow at the collector entrance is 9.1 m/s, whereas it is doubled in the present case.

**Figure 1.** Velocity Contour collector outlet height 2.5 m

The main reason for the increase in velocity of the flow at the collector entrance is the increase of mass flow rate due to the increase of area where the air moves slowly in the inclined collector. The problem of the slow movement of air can be overcome in the present work by converging the collector
outlet. As the area converges, the airflow moves faster towards the centre. Consequently, more velocity is attained with less heating period.

![Figure 2](image1.png) **Figure 2.** Velocity Contour along the collector for different collector outlet height

![Figure 3](image2.png) **Figure 3.** Velocity Contour along the chimney for different collector outlet height

The result shows that for zero slope collectors with cylindrical chimney, the average velocity at the chimney base is 14 m/s[10], while for a semi-divergent chimney with an inclined collector of 3.5° is 30 m/s(figure.2) and for divergent chimney area ratio of 6 with semi convergent collector of 0.33° attains 29.54 m/s(figure.3). Hence, another optimized geometry for an SCPP is a divergent chimney with a semi inclined collector is suggested.

5. Experimental Studies

The Inclined Collector performs better than the conventional one. It is decided to conduct an experiment on the divergent chimney with the inclined collector. A scaling ratio of 1: 60 scale ratio is maintained (Table.1); the detailed dimension is given in table1.

**Table 1.** Specifications of the Pilot Plant.

| S.No | Parts             | Dimensions |
|------|-------------------|------------|
| 1    | Collector Diameter| 3.6m       |
| 2    | Collector Height  | 0.2m       |
| 3    | Bellmouth Diameter| 0.22m      |
| 4    | Bellmouth Height  | 0.2m       |
| 5    | Chimney Height    | 3.2m       |
| 4    | Chimney Diameter  | 0.37m      |

A 3.2 m tall SCPP built for conducting experimental study, the pilot plant consist of chimney, collector and bell mouth transition region. The bell mouth shape enhances the air to accelerate at higher rate at the chimney base region. A sheet metal plate 12mm in thickness to construct the outer
profile with 700 mm diameter and a 10 mm MS flat bar was used for inner profile of diameter of 200 mm. The chimney bell mouth was welded to the chimney using 3.2m diameter flange. Essentially the flanges were tapered to match the profile of the chimney base. The collector is spread over the frames of 40 mm x 40 mm x 1.6 mm galvanized steel square tubing. Transparent polyethylene sheet is covered over the collector frame. The chimney was made from 1.6 mm thick galvanized sheet metal. Divergent shape to the chimney was obtained by welding two different diameter sections where the smaller end fitted with flange on the bell mouth. Rubber materials are placed at the bottom to prevent flow leakages. Three thermocouples are located on the collector region at equidistance which begins at 4 cm from an inlet of a collector (figure.4). This distribution is constant in all case (Table 2).

| DAY | Collector Inlet Height | Collector Outlet Height |
|-----|------------------------|------------------------|
| 1   | 0.2m                   | 1.2m                   |
| 2   | 0.2m                   | 0.4m                   |
| 3   | 0.2m                   | 0.6m                   |

Table 2. Experimental Parameters.

Similarly, three thermocouples are located in the chimney with a 1.16m distance between each one. The experimental data were stored on a PC through a data logger. The experiment is performed on three days for three different configurations.

Figure 4. Experimental Pilot Plant

6. Experimental Results and Discussion
The Pilot plant is kept on a cement platform in an open atmosphere. Measurements are taken for a whole long day from 9 am to 3pm. The results indicate significant ground surface temperature, ambient temperature, and airflow temperature inside the chimney. Figure 5. Show temperatures against time intervals.
Figure 5. Temperature Contour on Experiment Day

The maximum temperatures were achieved at 1 p.m. collected air was heated in this region (sunrise till 1 p.m.) by greenhouse effect while the direct radiation heated the ground. The collector outlet height is modified for three values, namely 1.2 m, 0.4 m, 0.6 m. As a result of the higher opening, the collector roof inclination to the chimney base increases. Hence the solar radiation also increases. The air under the roof gets heated, which further increases the mass flow rate. The variation of temperature for three collector opening angles inside the chimney is represented in figure 6.

Figure 6. Velocity contour for different collector outlet height

The velocity at the chimney base is measured using a hot-wire anemometer. The figure 7 shows that for a higher opening angle, the velocity reaches a peak. The average temperature rises inside the collector increases as the time proceeds, and it reaches a maximum by 1 pm shown in figure 5.
In effect, higher ground surface temperatures refer that high amount of energy is available and sufficient to heat the air inside the collector, hence power output can be maximized. The simulation of a 3.5m tower using ANSYS 18 shows that the velocity reaches a peak at the chimney base, which also indicates the same with the experimental study (Figure 8).

Figure 7. Velocity variation on the experiment day

Figure 8. Comparison of Experimental and CFD Results

The power output of the divergent chimney is represented in figure 9. Comparing a divergent chimney and straight cylindrical chimney is shown; comparatively divergent chimney with inclined collector performs better than the straight cylindrical chimney.
Figure 9. Theoretical Power Output on the experiment day

7. Conclusion
According to the experimental studies, the following conclusions are drawn:

i) The collector's outlet temperature is function of the solar intensity

ii) The solar chimney power plant has an inclined collector that can achieve air heating for many hours after sunset.

iii) For collector outlet height of 2.5m peak velocity of 29.54m/s is achieved and chosen as best configuration among other two models.

iv) The results show that a higher collector angle achieves a maximum power output.

v) The bell mouth geometry enhances the flow rate ensuring less chimney pressure drop.

This study can be further extended for analysing the system performance with thermal storage systems for night time operations.

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