Design, Construction and Performance Test of a Small Solar Chimney Power Plant

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This paper presents theoretical and practical experience of making a small and less expensive prototype plant which can be built on rooftops of residential buildings. The plant covering approximately 16.4 sq. meter area has a polythene cover as the collector instead of glass for reducing the cost. The base is tar covered concrete. The tower is made of PVC and approximately 3.05 meters high. Data were taken within November and December 2013.

Experimental results show that the average power output varies from 3 to 20 watts and the efficiency was maximum 0.11%. The output and efficiency of the plant was relatively low because of the lacking of solar intensity as the data were taken in winter and because it was a smaller solar chimney plant. But the prototype has a low initial cost and absolutely no operating cost. Thus using of less costly components enables making of a small economical plant.

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I. INTRODUCTION

The future of this earth and mankind substantially depends on our ability to meet our increasing power demand with renewable and environment friendly power sources. This is a burning question to the human race that how we can transfer our dependency on the fossil fuel into renewable environment friendly sources. In this circumstance we can chose over many types of renewable sources. Among these extracting from solar energy is the most prospective. A wide range of existing power technologies can make use of the solar energy reaching earth. Basically, all those ways can be divided into two basic categories: transformed for use elsewhere or utilized directly- direct and involving more than one transformation to reach a usable form- indirect. The solar chimney power plant is the part of solar thermal group of indirect solar conversion technologies.

a) Functional Principle

A solar chimney power generator has three major components:

- A circular solar collector (Greenhouse)
- A tall cylinder in the center of the solar collector (Solar Chimney)
- A set of air turbines geared to electric generators around the bottom of the solar chimney.

A typical solar chimney plant is shown in Fig. 1. As shown in figure, a large area is covered by the transparent collector which is slightly sloped being highest at middle. The air heated by sun is trapped, trying to go up. Hot air finds only way up through the chimney. So it flows through the chimney driving the turbines situated at the chimney entrance thus generates power.

Figure 1: Simple diagram showing the functional principle of solar chimney plants

Figure 2: Simple diagram showing the parameters for theory
b) Theory

The theory and mathematical expressions for this paper is described below with the aid of Fig.2.

The output power of the plant depends upon various parameters presented simply by the following equation.

\[ P_{\text{out}} = Q_{\text{solar}} \cdot \eta_{\text{coll}} \cdot \eta_{\text{tower}} \cdot \eta_{\text{turbine}} = Q_{\text{solar}} \cdot \eta_{\text{plant}} \quad (1) \]

If the temperature rise in the collector is \( (T_i - T_o) \) then it can be easily expressed as:

\[ \eta_{\text{coll}} \cdot I \cdot A_{\text{coll}} = \dot{m} \cdot C_p \cdot (T_i - T_o) \quad (2) \]

The input energy from sun, \( Q_{\text{solar}} \) can be express as:

\[ Q_{\text{solar}} = I \cdot A_{\text{coll}} = I \cdot (\pi/4) \cdot D_c^2 \quad (3) \]

The tower (chimney) converts the heat-flow produced by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). Thus the density difference of the air caused by the temperature rise in the collector works as driving force. The lighter column of air in the tower is connected with the surrounding atmosphere at the base (inside the collector) and at the top of the tower, and thus acquires lift. A pressure difference \( \Delta p_{\text{tot}} \) is produced between tower base (collector outlet) and the ambient [1]:

\[ \Delta p_{\text{tot}} = g \int_0^H (\rho(t) - \rho) \, dH \quad (4) \]

This is simplified to,

\[ \Delta p_{\text{tot}} = g \rho(t) \cdot H_t \quad (5) \]

The static pressure difference drops at the turbine the dynamic component describes the kinetic energy of the airflow. With the total pressure difference and the volume flow of the air \( \Delta p_s = 0 \) the power \( P_{\text{out}} \) contained in the flow is now [2]:

\[ P_{\text{out}} = \Delta p_{\text{tot}} \cdot v_i \cdot A_{\text{coll}} \quad (6) \]

Mass flow rate, \( \dot{m} = \rho_i \cdot A_i \cdot v_i = \rho \cdot (\pi/4) \cdot D_t^2 \cdot v_i \quad (7) \]

Thus without the turbine installed, the total power available to the turbine can be obtained from equation (6).

And also the velocity at the entrance is found by [3],

\[ v_i = \sqrt{2gH_t(T_i - T_o)/T_o} \quad (8) \]

- Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{\text{solar}} )</td>
<td>Solar power input to the plant (W)</td>
</tr>
<tr>
<td>( \eta_{\text{coll}} )</td>
<td>Collector efficiency</td>
</tr>
<tr>
<td>( \eta_{\text{tower}} )</td>
<td>Tower efficiency</td>
</tr>
<tr>
<td>( \eta_{\text{turbine}} )</td>
<td>Turbine efficiency</td>
</tr>
<tr>
<td>( \eta_{\text{plant}} )</td>
<td>Plant efficiency</td>
</tr>
<tr>
<td>( I )</td>
<td>Solar intensity (earth surface) (W/m²)</td>
</tr>
<tr>
<td>( \Delta p_{\text{tot}} )</td>
<td>Total pressure difference (N/m²)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>Gravitational acceleration (9.8 m/s²)</td>
</tr>
<tr>
<td>( T_o )</td>
<td>Ambient/outside temperature (°C)</td>
</tr>
<tr>
<td>( T_i )</td>
<td>Temperature at tower entrance (°C)</td>
</tr>
<tr>
<td>( \rho_o )</td>
<td>Outside air density (kg/m³)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Air density at tower entrance (kg/m³)</td>
</tr>
<tr>
<td>( H_t )</td>
<td>Height of the tower (m)</td>
</tr>
<tr>
<td>( v_i )</td>
<td>Air velocity at tower entrance (m/s)</td>
</tr>
<tr>
<td>( D_c )</td>
<td>Diameter of the collector (m)</td>
</tr>
<tr>
<td>( A_{\text{coll}} )</td>
<td>Area of the collector (m²)</td>
</tr>
<tr>
<td>( D_t )</td>
<td>Diameter of the chimney (m)</td>
</tr>
<tr>
<td>( A_t )</td>
<td>Area of the chimney (m²)</td>
</tr>
</tbody>
</table>

\[ \rho_i \cdot A_i = \rho \cdot (\pi/4) \cdot D_t^2 = 16.4 \text{ m}^2 \]

\[ C_p = 1005 \text{ J/kg} \]

\[ A_t = 0.018 \text{ m}^2 \]

\[ \rho_i \] was assumed as the density of air changes very little with the temperature.

\[ \rho_o \] = air density at 303 K = 1.165 kg/m³

c) Design

The design of the prototype plant is described as follows:

Firstly the rooftop of the Shahid President Ziaur Rahman Hall, RUET, Rajshahi, Bangladesh was selected as the place for making the prototype considering the availability of sunlight and conveniency of building the plant.

The collector diameter \( D_c \) was selected as 4.57 m (15 ft) considering availability of space on the selected rooftop.

The ratio of collector diameter to the tower diameter is called the diameter ratio (DR). The 50 kW plant in Manzanares has DR= 20. For our plant DR=30 (approximately) was selected considering availability of tower material in the local market. Thus the tower diameter \( D_t \) was selected as \( (30\times4.57) \text{ m} = 0.152 \text{ m} (6 \text{ in}) \).

The height of the tower \( H_t \) is proportional to the efficiency of the tower. The higher the chimney is the better is the output. \( H_t = 3.05 \text{ m} \) was selected considering availability in the local market and ease of installation and support.

The collector inclined angle \( \beta \) was selected 25°, as large as possible considering conveniency of work. The larger the angle \( \beta \) higher velocity of air is obtained [4].

Solar intensity \( I \) for a normal day was assumed 1160 W/m² and temperature \( T_o = 303 \text{K} \) for designing. The \( \eta_{\text{coll}} = 0.005 \) was assumed. Then from equation (2),

\[ \eta_{\text{coll}} \cdot I \cdot A_{\text{coll}} = \dot{m} \cdot C_p \cdot (T_i - T_o) = \rho_i \cdot A_i \cdot v_i \cdot C_p \cdot (T_i - T_o) = \rho \cdot (\pi/4) \cdot D_t^2 \cdot v_i \cdot C_p \cdot (T_i - T_o) \quad ([\text{using equation} (7) \text{ and } (8)]) \]

\[ \text{Or,} \quad (T_i - T_o) = 4.69 \text{ K} \quad (9) \]

Here,

\[ A_{\text{coll}} = \pi/4 \cdot D_c^2 = 16.4 \text{ m}^2 \]

\[ C_p = 1005 \text{ J/kg} \]

\[ A_t = 0.018 \text{ m}^2 \]

\[ \rho_i \] was assumed as the density of air changes very little with the temperature.

\[ \rho_o \] = air density at 303 K = 1.165 kg/m³
Then from equation (9) we found,
\[ T_i = T_o + 4.69 \text{ K} = 307.69 \text{ K} \]
And actual \( \rho_i \) corresponding to \( T_i \) found-
\[ \rho_i = 1.148 \text{ kg/m}^3 \] (which is close to the assumed value, so the assumption was excepted).

From equation (8),
\[ v_i = 1.0 \text{ m/s (approximately)} \]
\[ \Delta p_{tot} = 0.52 \text{ Pa} \] [using equation (5)]
\[ \dot{m} = 0.021 \text{ kg/s} \] [using equation (7)]
\[ P_{out} = 8.63 \text{ W} \] [using equation (6)]

Thus the plant was designed for a temperature rise of 4.6 K, \( v_t \) of 1.0 m/s, mass flow rate of 0.021 kg/s and a pressure rise of 0.52 Pa with a design output of 8.63 W.

d) **Technical data of the prototype**

The different parameters of the prototype plant as designed are given in Table 1 and the photographic view is given in Fig 3.

**Table 1:** Technical data of the designed solar chimney power plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower height</td>
<td>3.05 m</td>
</tr>
<tr>
<td>Tower radius</td>
<td>0.076 m</td>
</tr>
<tr>
<td>Collector radius</td>
<td>2.28 m</td>
</tr>
<tr>
<td>Min roof height (at centre)</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Max roof height (at centre)</td>
<td>1.68 m</td>
</tr>
<tr>
<td>Collector slope angle</td>
<td>25°</td>
</tr>
<tr>
<td>Typical ( \Delta T )</td>
<td>4.5 K</td>
</tr>
<tr>
<td>Average output</td>
<td>12 watt</td>
</tr>
<tr>
<td>Tower material</td>
<td>PVC</td>
</tr>
<tr>
<td>Collector Material</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>Plant frame and support material</td>
<td>Wood</td>
</tr>
</tbody>
</table>

**II. Experimental Procedure**

The experimental procedure is described below:

a) The outside temperature \( T_o \) was measured by thermometer.
b) The temperature \( T_i \) was taken measured at the same time by thermometer.
c) The air velocity at the entrance of the tower \( v_i \) was then taken by using the anemometer. The densities \( \rho_i \) and \( \rho_o \) were taken corresponding to the temperatures \( T_i \) and \( T_o \) respectively by using.
d) The steps 1 to 4 were repeated after every half an hour throughout the time period the day.
e) Thus data were taken for 6 experimental days and with necessary calculations the result was found.

**III. Results and Discussion**

The analysis is based on the simple mathematical model expressed in theory. The result is described with some curves found in a typical day in the section below:
Fig. 4 shows that the power output was increasing with the time of the day at first from 3.75 watts at 9 am and then dropped suddenly. Then at 12:30 pm it peaked to 20.1 watts. At these times a vigorous variability was seen in the curve. Overall it can be said that the output increased with time until mid day and then fell.

Fig. 5 shows that the velocity of air was fluctuating between 1 and 2 m/s throughout the whole day. At first it started from 1.1 m/s and changed slightly. It topped to 1.8 m/s at 12:30 pm and dropped then. Comparing to the power output graph its seen that both the curves topped at the same time. Then at last the velocity kept slightly increasing to the end of the time period.

Figure-5 shows that the curve of the mass flow rate shows volatility throughout the day. It started from 0.024 kg/s to the peak at almost 0.04 kg/s at 12:30 pm while the power output and the velocity both topped. Also each of the parameters dropped at 11 am because of the sudden pressure drop and each of these parameters kept almost unchanged at the end.
Fig. 7 shows that the curve of the pressure difference shows a number of ups and downs at the midday with a peak of approximately 0.85 Pa. It started from just below 0.2 Pa to the top increasing gradually. Then kept making sudden changes to the end of the day.

Fig. 8 shows that the efficiency of the plant made gradual increment from approximately 0.02 % till reaching 27.5°C. Then after a sudden drop efficiency peaked to 0.11 % which is the same point where the power, velocity and other curves peaked at 29.5°C. Then it kept decreasing to the end.

**Figure 7:** Pressure difference Vs. Time of the day curve

**Figure 8:** Efficiency Vs. Outside temperature curve of 20/12/13
Fig. 9 shows that the output power did not vary so significantly with days, though kept slightly changing between approximately 9 to 14 watts. This difference occurred because the radiation of sun was not same every day thus the output varied.

The results presented by the curves were reasonably approaching to the expectations though there had been some deviations due to many things. First of all it is obviously seen that the power output along with the parameters which are homogeneous to the power such as velocity at entrance, pressure difference, mass flow rate approaches their peak almost always at mid day approximately as expected because at that time sun radiation becomes maximum due to it’s position.

Some deviations occurred due to outside wind. When outside wind flows in such a direction that opposes the hot air flow the output suddenly falls. Also the wind can be a help when it flows in the same direction or it has a component in the same direction. That’s why certain volatilities were found in some curves with sudden rising and sharp falls. After the mid day the output and other homogeneous parameters did not fell as sharp in most of the curves. Thus the curves were not symmetrical or close to symmetrical with the vertical axis of 12 pm. This happened due to the green house effect of the collector. When the sun started to fall from the maximum position the outside temperature started to fall. But the heat trapped inside the collector kept it warm. Also the use of black concrete i.e. concrete covered with tar as base, worked as a heat storage and provided to make a better green house effect.

IV. Conclusion

✓ The design power output of the prototype was 8.63 watts while the average power outputs found practically ranged between 9 watts to 14 watts and the maximum output at any instance was about 21 watts. Thus the actual output powers were significantly more than the designed output.

✓ The design mass flow rate was 0.02 kg/s and the actual values found ranged between 0.022 kg/s and 0.045 kg/s i.e. always more than the designed flow rate.

✓ The design $v_t$ was 1.0 m/s while the actual value varied from 1.0 m/s to around 2 m/s i.e. always more than the $v_t$.

✓ The design pressure difference was 0.52 Pa but the actual value varied from 0.1 Pa to around 0.9 Pa. Thus the actual pressure difference was not always higher than the design value rather it changed through a wide range having an average almost equal to the design value.

✓ The prototype was constructed successfully as targeted. Though the prototype we have built is too small to operate at night and has low efficiency, the project result shows that a real large model can be a huge source of green power. If significant investment is done with adequate importance the solar chimney technology can be the most important pillar of energy source.

V. Acknowledgements

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