Mathematical evaluation of sloped solar chimney power plant for power generation in different regions of Nepal

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Abstract

Sloped solar chimney power plant (SSCPP) could be one of the appropriate technologies for powering Nepalese communities. The main components of the plant are chimney, collector and power-generating unit. In this study, the mathematical evaluation of the SSCPP has been conducted for the estimation of the power generation in Nepalese context. For the analysis, the mathematical models have been developed from the governing equations. The parameters such as chimney height and radius, collector radius, ambient temperature and solar insolation have been taken as inputs for simulation of the overall system. The output parameters such as overall system efficiency, chimney efficiency, air velocity, power output from the turbine and electrical power from the proposed system have been evaluated. The results showed that power developed by air, turbine power and electrical power is 120, 66 and 44 kW, respectively. The developed power is estimated when the height and the radius of the chimney were 190 and 5 m, respectively. It is seen that ambient temperature and velocity of air also play an important role in the power generation. The performance influencing the power output based on turbine pressure ratio, thermal conductivity and specific heat capacity of soil and the mass flow rate have also been estimated. Besides, the solar insolation data were taken for five different regions of Nepal to find the power generation and collector efficiency.

Keywords: slope solar chimney plant; power generation; chimney height; solar insolation; turbine power; overall efficiency

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1. INTRODUCTION

The sloped solar chimney power plant (SSCPP) is regarded as one of the solar power generation technologies without solar concentration. The main components in this plant are collector, chimney and turbine. The working principle of the plant is as follows [1–3]: the SSCPP is able of converting solar energy into thermal energy by the solar collector and is converted to kinetic energy in the air. The air inside the collector is heated by the greenhouse effect. Therefore, a continuous updraft in the chimney is produced by the upward buoyancy force. The kinetic energy of the air inside the collector is utilized to operate turbine inside the chimney that drives an electrical generator to produce the electric power. The schematic diagram of the working principle SSCPP is shown in Figure 1. SCPP has been utilized in power generation, fresh water production, heating and cooling applications in buildings [4–6].

The structure of solar chimney should be robust. The concept of solar chimney was initially reported in the literature [7]. In general, a simplified mathematical model is applicable for the design and performance improvement of solar chimney systems. In order to study the effect of various environment conditions and geometric parameters on the performance of the SCPP, various 1D mathematical models were carried out. There are several authors describing the importance of SCPP but only few discussed the concept of SSCPP. Cao et al. [8] simulated the SCPP and SSCPP and analyzed the system. It was found that the SSCPP generates steadier throughout the year. Parthasarathy and Pambudi [9] studied a solar chimney air heater and the effect of glazing, fins and convection on the thermal efficiency of the heater and found that these components improved the performance of the system. Shi et al. [10] reviewed the literature regarding enhancement of the performance of a solar chimney and suggested that an
electricity is 0.83 Yuan/kWh with MARR of 8%.

The results showed that the levelized cost of economic analysis of power generation from floating SCPP with mum designs of solar chimney. Zhou

designed a solar chimney system aiming to produce power at the high latitudes of Canada. The results demonstrated that SCPPs at high latitudes may have a good thermal performance almost the same as the other parts of the country. Balijepalli et al. [14] developed a small SCPP and a test setup was constructed based on locally available materials. The reported chimney and overall plant efficiencies were 0.0187% and 0.0128%, respectively. El-Ghonemy [15] evaluated the performance of SCPP under weather conditions of the Kingdom of Saudi Arabia and developed a mathematical model for estimating the parameters such as power output, pressure drop across the turbine, chimney height, air flow temperature, velocity and the overall efficiency. The results showed that the SCPP with a chimney height and diameter of 200 and 10 m, respectively, and a collector diameter of 500 m can produce a monthly average of 118–224 kW electric power.

Aligholami et al. [16] analyzed the effect of geometrical parameters that could enhance the performance of SCPP. It was reported that by applying the slip condition on the walls to simulate hydrophobic surfaces, it would reduce shear stress on the walls, which led to roughly 11% performance enhancement. Aurybi et al. [17] proposed a new way of integrating the SCPP with an external heat source, thereby installing thermal-enhancing channels inside the collector that could operate the plant at night time. Ahmed and Hussein [18] discussed the performance of a new design of the solar chimney that includes combining the following technologies: hybrid glazed PV/solar chimney and hybrid PV/solar chimney. The total useful power produced by the hybrid PV/solar chimney is greater than the useful power produced by the other system.

The main aim of this paper is to analyze the potential for electrical power production in various regions of Nepal including the Himalayan regions. Furthermore, this study also presents an estimation and analysis regarding the influence of parameters, which includes chimney radius, chimney height, radius of collector, ambient temperature and solar insolation for the power output of SSCPPs. In addition, the overall efficiency and chimney efficiency are carried out for all regions for the future construction of SCPPs in Nepal.

2. SSCPP SYSTEM MODELING

The performance analysis and mathematical evaluation of SSCPP are based on the models developed by Schlaich [7]. The momentum and energy balance equations are used for the chimney and collector modeling. The purpose of this study is to evaluate the performance of a SSCPP. In this study, the proposed system has three main parts of the SCPP: the collector, the chimney and the power conversion unit. Governing equations were solved numerically with the boundary conditions for each component. For calculation, one of the geometric parameters of the chimney was variable and the rest were fixed. Parameters such as variable chimney height, constant chimney radius, constant collector radius and constant velocity of the air are selected. The overall efficiency and the chimney efficiency can be estimated. The performance equations of the system are considered for calculating the proposed system efficiency and power output. The working principle of the mathematical model of SSCPP is shown as flowchart in Figure 2. Several boundary conditions for chimney, collector, geographic location and turbine can be assumed. The EES code developed for the modeling has an initial guess value for the mass flow rate and other dimensions. The program then calculates the necessary parameters based on the mass flow rate. The output parameters such as power output, efficiency and overall plant efficiency of the system can be calculated.

2.1. Mathematical model of the sloped solar chimney plant

The solar chimney converts the flow of heat produced by the collector and then converts it into kinetic energy and potential energy. The air temperature difference causes the lighter air to move at the top of the chimney. The efficiency of the chimney can be expressed as [19]

\[ n_{\text{chim}} = \frac{g H_{\text{chim}}}{C_p T_0}. \]  

Here, \( n_{\text{chim}} \) is the chimney efficiency that describes the usefulness with which the quantity of heat delivered by the collector is converted into energy. \( H_{\text{chim}}, C_p, T_0, g \) represent the height of

Figure 1. Working principle of SSCPP.
Mathematical evaluation of SSCPP

2.1. Chimney model
The power contained in the air flow can be estimated by the following expression [19]:

\[ P_{\text{tot}} = \eta_{\text{chim}} \dot{Q} = \frac{g H_{\text{chim}} \rho_{\text{air}} V_{\text{chim}} A_{\text{chim}} (T_{\text{out}} - T_{\text{in}})}{T_0}. \] (2)

Here, \( P_{\text{tot}}, \dot{Q}, \rho_{\text{air}}, V_{\text{chim}}, A_{\text{chim}}, T_{\text{out}}, T_{\text{in}} \) denote the total power produced by air, heat output, density of air, velocity of chimney, area of chimney, outlet temperature and inlet temperature of the collector, respectively.

The pressure difference \((\Delta P)\) that is created due to chimney and turbine pressure can be calculated based on following equation:

\[ \Delta P = \frac{g H_{\text{chim}} \rho_{\text{air}} \Delta T}{T_0}. \] (3)

2.2. Collector model
A solar chimney collector converts available incoming solar radiation \((G)\) onto the collector surface into heat energy (output). Therefore, the collector efficiency can be expressed as a ratio of the heat output of the collector and the product of solar radiation and area of collector [19].

\[ \eta_{\text{coll}} = \frac{\dot{Q}}{A_{\text{coll}} G}. \] (4)
\[ \dot{Q} = \dot{m} C_p (T_{\text{out}} - T_{\text{in}}) \] (5)
\[ \dot{m} = \rho_{\text{air}} V_{\text{chim}} A_{\text{chim}} \] (6)

Here, \( \eta_{\text{coll}} \) denotes the efficiency of the collector that describes the effectiveness with which solar radiation is converted into heat.

\( A_{\text{coll}}, \dot{m}, G \) represent the area of collector, mass flow rate of air and solar insolation, respectively.

It is assumed that the hot air flowing inside the collector varies linearly with respect to the temperature. Therefore, for the modeling, the empirical equations are adopted for describing the properties of the air [19].

Density: \( \rho_{\text{air}} = 1.17 - 0.004(T - 300) \) (7)
Specific heat: \( C_p = [1.007 - 0.00004(T - 300)] \times 10^3 \) (8)
Thermal conductivity: \( \lambda = 0.03 + 0.00008(T - 300) \) (9)

2.3. Turbine model
The mechanical power developed by the turbine can be achieved by the rotational motion of the turbine blade installed at the base of the chimney and can be estimated by the following relationship:

\[ P_{\text{turb}} = 0.67 \eta_{\text{chim}} \eta_{\text{coll}} A_{\text{coll}} G. \] (10)

Electrical power from the solar chimney to the grid:

\[ P_{\text{ele}} = \frac{0.67 g H_{\text{chim}} \eta_{\text{coll}} \eta_{\text{turb}} A_{\text{coll}} G}{C_p T_0}. \] (11)

2.4. Overall plant efficiency
The overall plant efficiency is determined by the product of each individual component's efficiencies, which can be given by the

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following expression:

\[
\eta_\alpha = \eta_{\text{chim}} \times \eta_{\text{coll}} \times \eta_{\text{tur-gen}}.
\]  

\(\eta_{\text{tur-gen}}\) denotes the turbine and generator efficiency that have efficiencies \(\sim 80\%\) and \(95\%\), respectively [8].

3. RESULTS AND DISCUSSION

The proposed mathematical model was used to estimate the overall performance of solar chimney based on simulation. Various influencing parameters that affect the system’s performance have been discussed based on the results of developed models. The parameters such as air velocity, ambient temperature, radius of collector and chimney and solar insolation were taken for the analysis. Table 1 shows the conditions for the simulation. The temperature rise inside the collector is 11 K. Normally, the solar insolation in Nepal is around the average of 800 W/m\(^2\) in the hottest part of the country, so this boundary value can be reasonably suitable.

The simulated results are presented in Table 2. Here, the maximum output power developed from the system is 44.11 kW. The heat energy required to develop the power is 1023 kW. The overall efficiency is found to be 0.25\% when the collector efficiency is 25.4\%.

3.1. Effect of air velocity on SSCPP

Figure 3 shows the effect of air velocity on the SCPP performance. This indicates that air velocity can have an effect on the height of chimney and the chimney efficiency. For low air velocity, the height of chimney should be less, whereas if air velocity is high, the height of chimney should be increased. Similarly, the higher the velocity of the air, the higher the chimney efficiency is. It is seen that for the air velocity of 14 m/s, the maximum height of the chimney needed is 300 m and the chimney efficiency is \(\sim 1\%\). For every chimney height, the maximum power output point is selected as the indicator of the power output of the SCPP.

| Parameter                          | Value | Parameter                          | Value |
|------------------------------------|-------|------------------------------------|-------|
| Collector temperature outlet (K)   | 308   | Radius of collector (m)            | 120   |
| Collector temperature inlet (K)    | 299   | Radius of chimney (m)              | 5     |
| Ambient temperature (K)            | 288   | Chimney height (m)                 | 190   |
| Solar insolation (W/m\(^2\))       | 800   | Efficiency (turbine/generator)     | 0.8/0.95 |

3.2. Effect of ambient temperature

The effect of ambient temperature on the performance of the SSCPP is investigated in this study. The ambient temperature variation is selected as the input temperature. The range of ambient temperature is simulated from 273 to 300 K, at intervals of 5 K.
Figure 4. Effect of velocity on developed power.

Figure 5. Effect of velocity of heat output and mass flow rate.

Figure 6. Influence of ambient temperature.

Figure 7. Influence of radius of chimney.

less. The estimated power developed for each are 35, 46 and 69 kW, respectively. The higher the ambient temperature, the lower the power developed on the system is. Likewise, the overall efficiency behaved the same trend and the efficiency was found to be 0.15%.

3.3. Effect of chimney and collector radius

Figure 7 demonstrates that the larger the collector and chimney radius are, the greater the power generation will be. The theoretical power output of SSCPP is directly proportional to the square of the collector radius. Therefore, it is seen that an increase in collector radius would result in a rapid rise in the power output. It increases sharply when the sizes of the collector and the chimney are small but slowly with an increase in size. From electrical power, turbine and air power, 60, 80 and 140 kW power is produced, respectively, when the radius of the chimney is 6 m. A similar trend can be seen when the radius of collector changes. The larger the radius of the collector, the greater the power developed is, which can be seen from Figure 8.

3.4. Effect of solar insolation, pressure ratio and altitude

The simulation results on the effect of solar insolation are presented in this section. The results of the power assessment for the SSCPP are expressed for five different regions of Nepal. The climatic conditions for those five regions were estimated in [20]. The solar insolation data were used for the estimation of the collector efficiency. The sunshine duration in Nepal is around 300 days in a year [21, 22]. The performance of the system depends on the solar radiation falling on the collectors. In order to have a comparison between sloped and horizontal surfaces, the solar radiation falling on the collectors is shown in Figure 9. From the figure, it is found that the solar radiation on the horizontal surface is larger than on
the sloped surface from April and August. This is due to the longer solar radiation reception time on the horizontal surface than on the sloped surface.

The solar radiation data measured for five different locations during the months of the year are shown in Figure 10. According to Figure 10, the maximum radiation is found between March and August. The maximum solar insolation is found to have in Mahendranagar, whereas the minimum is seen in Pokhara. This is because of environmental conditions and radiation reflection from different surfaces at distinctive hours. Besides, collector efficiency is the ratio of solar energy (heat output) to the area of collector and solar insolation.

As shown in Figure 11, higher solar insolation requires low collector efficiency of the SSCPP and vice versa. The collector efficiency seems to have 45% in January, whereas it is 20–25% collector efficiency in March–August for all five locations in the country. Designing the solar chimney based on the solar isolation, one should have to determine the collector efficiency of the chimney.

It is observed from Figure 12 that power output of the plant depends on turbine pressure ratio. Higher pressure ratio yields higher power. There is a decline in power output when it reaches the optimal pressure ratio. When pressure ratio is 50 and 300, the power output is 60 and 140 kW, respectively.

The design point of the turbine is chosen based on the maximum power output from the system. In order to find the point, there must be an optimal mass flow. Higher and lower flow rates result in the drop down of pressure across turbine and the rise of temperature in the collector. During these conditions, the power output of the system is reduced dramatically. Therefore, there is a correlation among air flow rate, temperature rise in collector and potential pressure drop in turbine. Figure 13 illustrates the optimal design point for SSCPP system. At low air flow rates, the temperature rise of the air flow is high. During daytime, more heat is stored in the soil storage. This is more advantageous for the continuous supply of the power.

It is seen from Figure 14 that the power output is proportional to the specific heat capacity and thermal conductivity of the soil.
The higher the increment in the specific heat capacity of soil, the lower the value of the power output is. With an increase of specific heat capacity from 750 to 1750 J/kgK, the power generation decreases approximately from 27 to 24 kW. Similarly, when thermal conductivity increases from 0.25 to 2.25 W/mK, the power output changes with increment of ~19%.

In Figure 15, the influence of changes in the altitude on output power and altitude effectiveness is demonstrated for the solar insolation 1000 W/m². It is revealed that higher altitude results in low power output.

4. CONCLUSION

The performance of SSCPP could be one of the promising technologies for power generation in Nepal. The main aim of this study is to evaluate the performance of SSCPPs in five different regions of Nepal. The theoretical and simulation results have been carried to estimate the quantity of the produced by SSCPP. From the concept of energy balance, a mathematical model was developed for estimating the power output of SSCPP. Various influencing parameters such as air velocity, height of chimney, radius of collector and chimney, ambient temperature and solar insolation were considered for assessment of power output. The performance of a power generation in five regions of Nepal, namely Kathmandu, Pokhara, Biratnagar, Mahendranagar and Jumla, was studied. The simulation result showed that an SSCPP with 190 chimney height and 5 m chimney radius is capable of producing 44-kW electrical power. It was seen that Mahendranagar has the best capacity of electrical power generation in comparison with the other regions. The results showed that the collector efficiency should be the least for developing electrical power for high solar radiation regions. It was also shown that the SSCPP can produce more power from March to August. Furthermore, the results indicated that the electrical power generation

Figure 12. Influence of power output with turbine pressure ratio.

Figure 13. Effect of air mass flow rate on power output for various solar insolation.

Figure 14. Influence of thermal conductivity and specific heat capacity of the soil on power generation.

Figure 15. Influence of changes in the altitude on output power.
capacity increases with the increase in solar chimney height and solar collector area. The larger the collector area and the higher the chimney height, the greater the power developed. Besides, power generation is slightly influenced by changing the ambient temperature. In addition, the velocity of air plays a crucial role for higher power generation. The thermal conductivity and specific heat capacity of the soil are also directly related for a change in power output of the plant. Therefore, SSCPP could be very attractive power generation for Nepal where the majority of land is sloped due to geographic conditions and enough sunshine duration with good solar irradiance.

4. DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

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