Analysis of a solar chimney power plant in the Arabian Gulf region

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ABSTRACT

A simplified thermodynamics analytical model for steady airflow inside a solar chimney is performed. A simplified Bernoulli equation combined with fluid statics and ideal gas equation was implemented and solved using EES solver to predict the performance of the solar chimney power plant. The analytical model matched the experimental data and numerical study available in the literature. The developed analytical model was used to evaluate the effect of geometric parameters on the solar plant power generation. The analysis showed that chimney height and turbine pressure head are the most important physical variables for the solar chimney design. The study showed that second-law efficiency has a non-monotonic relation with turbine pressure head. The model shows that second-law efficiency and power harvested increase with the increase of chimney height and/or diameter. The developed model is used to analyze the feasibility of solar chimney power plants for the UAE climate which possesses typical characteristics of the Gulf climate. The solar characteristics of the UAE are shown along with characteristic meteorological data. A solar chimney power plant with a chimney height of 500 m and a collector roof diameter of 1000 m would produce at least 8 MW of power. The amount of power produced during the summer would be higher where the demand in the Gulf area is the highest.

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1. Introduction

A solar chimney power plant consists of a greenhouse roof collector. The chimney is located at the center of the greenhouse roof collector. The greenhouse roof collector is usually made of plastic sheet or glass plate which traps the solar energy and increases the total air enthalpy. The chimney is used to direct and vent the low density air through the wind turbine. The wind turbine is used to convert the air enthalpy into mechanical work. The main advantage of a solar chimney system lies on the low maintenance cost, the simplicity to operate and the durability of the system.

Solar chimneys have been traditionally used in agriculture for air renewal in barns, silos, greenhouses, etc. as well as in drying of crops, grains, fruits or wood [1]. Natural ventilation in buildings is another popular application of solar chimney where natural passive ventilation is used to improve the quality of indoor air and increase the comfort index for inhabitants [2].

Recently, more interests are developed to utilize the solar chimney to produce energy [3–8]. Due to the rocket increase in the energy cost, a strong demand for renewable energy is raised. Scientists are exploring different techniques focusing on different aspects including minimizing operational costs, simplifying and lowering maintenance cost, minimizing the use of toxic materials due to health and environmental concerns, and increasing reliability. The solar chimney is one of the techniques that have a strong potential as a green source of energy, which has many advantages and has huge potential in energy generation including renewable eco-friendly energy, zero pollution and availability. Therefore it has a broad range of applications and can contribute substantially to our future energy needs.

In the Gulf countries there are urgent needs to accelerate the development of environmental friendly and sustainable energy policies. For example, the United Arab Emirates (UAE) announced in 2007 a 60% increase in the country's capacity to produce electricity by 2010. Today UAE produces 16.67 GW compared to 9.6 GW in 2001; the large bulk of it comes from fossil fuel. It is anticipated that the UAE will invest more than US $15.3 billion to triple the emirate's power generation capacity in the next 10 years. This investment is vital to keep paces of the massive development and vital to green energy business.

In the 1980s, a pilot plant was built and tested in Manzanares, Spain and data collected from this pilot plant were published by Haaf [4]. No full scale solar chimney power plant has been built to date until recently where a 200 MW solar tower project is being developed in Australia.

The cost of energy produced using solar chimney needs more investigation since it depends on location, labor cost and material

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cost which vary dramatically based on region. It was reported that the price of the electricity produced by a solar chimney power plant in the Mediterranean region is considerably higher compared to the other power sources [9]. Zhou et al. [10] reported that the maximum height for convection and the optimal height for maximum power output increase with larger collector radius. The assumption made by many researchers that the total efficiency of the power conversion unit of 80% has been investigated by different scientists [11]. Also they reported that the power conversion unit efficiency deteriorates significantly with increasing diffuser area ratio but improves only slightly with reducing the diffuser area ratio below unity. A numerical analysis performed by Maia et al. [12] showed a good agreement with earlier experimental work and that the height and diameter of the tower are the most important physical variables for solar chimney design.

The purpose of this work is to provide a simplified analytical model that can predict the solar chimney power plant’s performance and efficiency. The study provides information regarding the effect of chimney height and diameter, the collector area and the air temperature increase. The study presents the relation of pressure drop across the turbine to power generation.

2. Theoretical mathematical analysis

2.1. Theory and assumptions

A schematic diagram of the solar chimney power plant is presented in Fig. 1. A simplified model is used to describe the entire power plant including the three major components, which are the solar collector, the chimney, and the wind turbine. The physical dimensions investigated in this model focus on the chimney height, the chimney diameter and the collector diameter. In order to simplify the problem, some assumptions are adopted as follows:

1) The height of the collector from the ground was considered large enough to disregard the pressure drop in the collector section. This assumption is applicable since the cross-sectional flow area in the collector is much larger than the chimney cross-section area, hence the mean air velocity within the collector is much smaller than in the chimney, as reported by Koonsrisuk and Chitsomboon [13]. However, this assumption deviates in the district near the chimney inlet.

2) The heat radiated to the chimney is ignored since the surface area of the collector is much larger than the surface area of the chimney. Therefore, heat transfer equation is only considered for the collector. As reported by Zhou et al. [8] and Koonsrisuk and Chitsomboon [13], the temperature change across the chimney is small, hence $T_4 = T_3$.

3) The turbine efficiency is not considered in the calculation since it was shown by other researchers that efficiency of 80% or higher is feasible in such an application, Fluri and Backstrom [11]. The process across the turbine is assumed to be reversible and adiabatic.

4) Heat transfer from the system to the surrounding was ignored and only heat transfer from the surrounding to the collector is considered.

5) The analysis is based on steady flow assumptions which is an approximation because solar radiation is transient in nature. This assumption is very useful to investigate the overall effect of solar chimney size.

6) The flow is incompressible across the chimney since Mach number is below 0.3. Hence, as air gets heated under the greenhouse collector, its density drops initiating a natural flow toward the chimney which is driven by buoyance force. Experimentally, it was shown that the airflow velocity is much lower than the Mach number.
below the speed of sound which justifies the use of the incompressible model.

7) Uniform solar heat flux averaged over the day period is used in the calculation [14].

2.2. The atmospheric pressure and temperature

For standard atmosphere and using Fig. 1, the atmospheric temperature and pressure changes across the solar chimney are written as follows, Munson et al. [15]:

\[ T_a = T_1 - \beta z \] (1)

\[ P = P_{4a} = P_1 \left( 1 - \frac{\beta z}{T_1} \right)^{g/\gamma} \] (2)

Eqs. (1) and (2) show how the temperature and the pressure decrease with elevation from the sea level. The pressure at the outlet of the chimney can be calculated using Eq. (2) which is identified as \( P_4 \).

2.3. The collector

Across the collector, mass flow rate is conserved and pressure drop is neglected. \( P_2 = P_1 \) as explained in the assumption. The energy equation for the collector section is used to calculate the mass flow rate inside the solar chimney as follows:

\[ \dot{m} = \frac{q_{\text{in}} A_c}{h_2 - h_1} \] (3)

The main unknowns in Eq. (3) are \( \dot{m} \) and \( h_2 \). The heat flux used in the above equation represents the absorbed solar radiation excluding the thermal losses. It is recommended to use double glass collector to reduce the thermal losses. In order to improve the collector efficiency, the collector can be replaced by more sophisticated air heaters [16–18].

2.4. The turbine

Across the turbine, the pressure head is related to turbine head as shown in Eq. (4). Entropy across the turbine is constant hence the pressure expansion is assumed to be reversible and adiabatic.

\[ P_3 = P_2 - \rho_3 g H_t \] (4)

\[ s_3 = s_2 \] (5)

The main unknowns in Eqs. (4) and (5) are \( P_3 \) and \( s_3 \). The density of air across the turbine is assumed to be constant since the wind speed is not high, compared to the speed of sound, and there is no heat added or removed across the turbine. Also the pressure drop across the turbine is very small since the study assumes the use of a one stage wind turbine.

2.5. The chimney

The hot air will start rising when the density of air is less than the one on top of it and when it is capable to move against gravity head and friction head. This air draft is modeled using the following modified Bernoulli equation [15]:

\[ \frac{P_3 - P_4}{\gamma P_4} = \left( \frac{z_4 - z_1}{\gamma} \right) \text{Gravity Head} + \frac{m^2}{2 \rho_4 g A_f^2} \left( \frac{L}{D_3^2} + K_m + K_{\text{out}} \right) \text{Friction Head} \] (6)

The main unknowns in Eq. (6) are \( P_4 \) and \( \dot{m} \). From the second assumption introduced in the mathematical model, the temperature change across the chimney is small and is mathematically expressed as shown in Eq. (7).

\[ T_4 = T_3 \] (7)

The main unknowns in Eq. (7) is the chimney outlet temperature, \( T_4 \). In order to solve the set of algebraic equations, one needs to utilize the thermodynamics properties which are determined as long as two independent properties are know at each point in the chimney. Also since the fluid is assumed as an ideal gas, the enthalpy is determined using only temperature. Therefore, Eqs. (2–7) are algebraic equations that can be solved for all the unknowns \( \dot{m}, h_2, P_3, s_3, P_4 \) and \( T_4 \) using EES solver. For the solar chimney model, the three key independent design parameters are (1) the turbine head, \( H_t \), (2) the solar heat flux, \( q_{\text{in}} \), and (3) the solar chimney size and geometry.

The expected turbine power is calculated as follows:

\[ w_t = h_2 - h_3 \] (8)

The second-law efficiency of the solar tower power plant is defined as turbine extracted work over the available work (exergy) as follows:

\[ \eta_{II} = \frac{w_t}{2 \Psi_{1-4}} \] (9)

\[ \Delta \Psi_{1-4} = (h_4 - h_1) - T_1(s_4 - s_1) + g(z_4 - z_1) = \frac{v^2}{2} \] (10)

3. Results and discussion

The analysis is based on the analytical model developed in the above mathematical analysis section. The parameters used in the calculation of the system performance are given in Table 1.

In order to validate the developed model, the results of the current model are compared against published data [19], as shown in Table 2. The comparison study shows good agreement with published data with maximum discrepancy of 3%.

The effects of different parameters mainly chimney height, chimney diameter, collector diameter, and turbine head are

Table 1
The technical data used in the solar chimney power plant calculations.

<table>
<thead>
<tr>
<th>Parameters (conditions)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar irradiance [14]</td>
<td>185 W/m²</td>
</tr>
<tr>
<td>Turbine head, ( H_t )</td>
<td>200 m</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>303 K</td>
</tr>
<tr>
<td>Lapse rate [15]</td>
<td>6.5 K/km</td>
</tr>
<tr>
<td>( K_m )</td>
<td>0.5</td>
</tr>
<tr>
<td>( K_{\text{out}} )</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters (size)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height</td>
<td>1000 m</td>
</tr>
<tr>
<td>Chimney diameter</td>
<td>100 m</td>
</tr>
<tr>
<td>Collector diameter</td>
<td>2000 m</td>
</tr>
</tbody>
</table>

Table 2
A comparison study showing good agreement with experimental data [19].

<table>
<thead>
<tr>
<th>Parameters (conditions)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power block size</td>
<td>MW</td>
</tr>
<tr>
<td>Schlaich et al. [19]</td>
<td>5</td>
</tr>
<tr>
<td>Present model</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters (size)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimney height</td>
<td>m</td>
</tr>
<tr>
<td>Chimney diameter</td>
<td>m</td>
</tr>
<tr>
<td>Collector diameter</td>
<td>m</td>
</tr>
</tbody>
</table>

With solar global irradiance of 2300 kW/m² year – 263 W/m².
presented in Figs. 2–5 respectively. Fig. 2 shows that the second thermodynamics efficiency and the power generation are highly dependent on the height of the chimney and that as chimney height increases, one expects that power harvested increases. The higher the chimney means higher driving force which is the buoyancy difference. The rate of increase in this driving force is higher than the friction losses due to chimney length; therefore the second-law efficiency is expected to increase with the chimney height. The effect of chimney diameter on solar chimney is shown in Fig. 3. The figure shows that the chimney diameter has a prominent effect on the harvested power, mainly when chimney diameter is below a critical value. The critical diameter depends on Reynolds number and boundary layer thickness. If chimney diameter is larger than the critical diameter value, the effect of chimney diameter is minimal. As chimney diameter increases, the friction losses decrease which decreases as air velocity inside the chimney decreases. In Fig. 4 shows the relation between the collector diameter versus the second-law efficiency and the generated power. Fig. 4 shows that as collector diameter increases the amount of harvested energy increases. On the other hand, the second-law efficiency moderately decreases since as collector diameter increases the driving buoyancy force increases causing a higher velocity inside the chimney which causes higher friction losses. Since the friction losses related the second order velocity value, it is expected that the increase in velocity would cause higher losses and hence decrease the second-law efficiency. Fig. 5 shows the relation between turbine head versus the second-law efficiency and harvested power. The model results show that there is an optimum pressure head across the turbine for maximum harvested power since power generation depends on air mass flow rate and pressure drop across the turbine. Therefore, as the pressure drop increases across the turbine, the mass flow rate decreases and hence an optimum power generation is expected. Utilizing the design parameters from Table 1, the optimum second-law efficiency is calculated at turbine head of 50 m.

The results shown in Figs. 2–5 were calculated for average solar irradiance of 185 W/m² which is well below the UAE summer expected solar irradiance shown in Fig. 6 [14]. Hence, this is a very conservative calculation for a GCC country and higher energy harvesting is expected. For UAE climate, a higher solar energy production is expected during the summer season due to the higher solar radiation which meets the increasing summer demand for air-conditioning system. Similar results are expected for all other GCC countries since they have similar solar irradiances, as shown in Table 3 [20].
4. Conclusions

This work presents an analytical model to predict the performance of a solar chimney power plant. The model showed excellent agreement with other published experimental and theoretical work. The model shows that chimney height and diameter, collector diameter and turbine head are critical parameters for building a solar chimney power plant. The chimney height and turbine head have a very strong effect on the second-law efficiency and total harvested power. The chimney diameter has a small effect except for very small chimney diameter where friction becomes a dominant factor. The collector diameter has a very small effect on second-law efficiency since the friction losses minimized by the wide inlet area and low average velocity inside the collector.

References


