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Renewable Energy 28 (2003) 1295–1304
RENEWABLE ENERGY
www.elsevier.com/locate/renene

Technical note

Case study of solar chimney power plants in Northwestern regions of China

Y.J. Dai [a,*], H.B. Huang [b], R.Z. Wang [a]

[a] *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, 200030, Shanghai, China*
[b] *Agriculture College, Ningxia University, Yinchuan, 750000, Ningxia Hui Autonomous Region, China*

Received 23 July 2002; accepted 15 October 2002

Abstract

A solar chimney power plant, which is expected to provide electric power for remote villages in northwestern China, has been analyzed in this paper. Three counties in Ning Xia Hui Autonomous region, namely, Yinchuan, Pingluo, and Helan, where solar radiation is better than other regions of China, were selected as pilot locations to construct solar power plant. The solar power plant chimney, in which the height and diameter of the chimney are 200 m and 10 m, respectively, and the diameter of the solar collector cover is 500 m, is able to produce 110~190 kW electric power on a monthly average all year. Some parameters, such as chimney height, diameter of the solar collector, ambient temperature, solar irradiance and the efficiency of wind turbine, etc. which influence the performance of power generation, are also analyzed.

1. Introduction

Solar energy is a renewable and clean energy resource, which produces neither greenhouse effect gases nor hazardous wastes through its utilization. Of many techniques utilizing solar energy, solar power generation seems to be one of the most attractive. Electric power can be obtained from solar energy by two means, photovoltaic effect and solar thermal generator. Solar cells form a semiconductor unit to produce electric current based on photovoltaic effect, and the solar thermal generator, is always driven by steam generated by large scale solar concentrator.

However, there is also another technique, which could affect power production,

* Corresponding author. Tel.: +1-8621-62933250; fax: +1-8621-62933250.
E-mail address: yjdai@sh163.net (Y.J. Dai).

0960-1481/03/$ - see front matter
doi:10.1016/S0960-1481(02)00227-6

Nomenclature

A_c	Cross-sectional area of solar chimney, m^2
A_{coll}	Solar collector area, m^2
C_p	Specific heat of air, kJ/kg.°C
g	Acceleration of gravity, m/s^2
G	Solar irradiance, W/m^2
H_{sc}	Solar chimney height, m
$\dot{m}$	Mass flow rate of air, kg/s
P_{tot}	Useful energy contained in the airflow, kW
$P_{wt,max}$	Maximum mechanical power taken up by the turbine, kW
P_e	Electric output from the solar chimney, kW
$\dot{Q}$	Heat gain of air in the collector, kW
T_0	Ambient temperature, °C
V_c	Inlet air velocity of solar chimney, m/s

Greek symbols

$(\tau\alpha)$	Effective product of transmittance and absorbance
β	Heat loss coefficient, $W/m^2.K$
η_{coll}	Solar collector efficiency
η_{sc}	Solar chimney efficiency
η_{wt}	Turbine efficiency
ρ	Air density, kg/m^3
ΔP_{tot}	Pressure difference produced between chimney base and the surroundings, Pa
ΔT	Temperature rise between collector inflow and outflow, °C

namely the solar chimney power plant. The concept was designed and put into use during the 1980s by J. Schaich and colleagues [1,2]. It works on the principle that the wind turbine could be driven by air flow caused by stack effect inside the solar chimney, owing to the heating process in the solar hot air collector. Their operational experience indicates that the power production cost for this plant is just DM 0.1/kW/h. The solar chimney combines three familiar techniques: the simple roof hot air collector, the chimney, and wind turbines with generators. It operates simply and has a number of merits. In particular, solar chimney can exploit diffused radiation when it is cloudy. The technology is suggested for use in remote regions, where there is sufficient land land, and solar radiation is good, but there is no electric power supply. Recent work related to the solar chimney power plant was reported by A.J. Gannon et al [3,4]. According to these authors, much work has been carried out on the cycle performance, heat transfer and fluid flow in the solar chimney.

In many rural locations of northwestern China, grid-connected electricity and supplies of other renewable sources of energy are either unavailable or unreliable. The authors have undertaken research on developing a suitable solar power plant for rural areas in northwestern China. The objective of this paper is to report this work and analyze the system performance.

2. Descriptions of the system and principles

A typical solar chimney power plant consists of a solar hot air collector, a solar chimney and a turbine with generator. All three essential elements have been familiar from time immemorial. A solar chimney power plant simply combines them in a new way [1,2,3], as is shown in Fig. 1. Air is heated by solar radiation under a low circular transparent cover open at the periphery; this and the natural ground below it form a hot air collector. In the middle of the cover is a vertical chimney with large air inlets at its base. The joint between the cover and the chimney base is airtight. As hot air is lighter than cold air it rises up the chimney. Suction from the chimney then draws in more hot air from the collector, and cold air enters from the outer perimeter. Thus solar radiation causes a constant up-draught in the chimney. The energy that the hot air contains is converted into mechanical energy by pressure-staged wind turbines at the base of the chimney, and into electrical energy conventional generators.

The characteristics of this solar chimney power plant are listed below.

- Efficient solar radiation use. The hot air collector used in the system, can absorb both direct and diffused radiation. Thus the solar chimney can operate on both clear and overcast days. The other major large-scale solar thermal power plants,

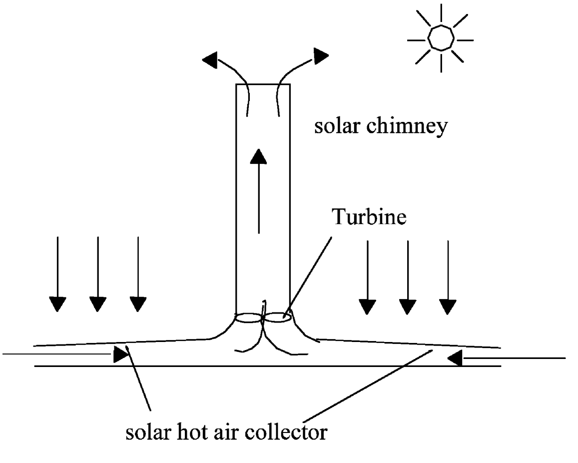

Fig. 1. Schematic diagram of a solar chimney power plant.

which are often driven by high temperature steam generated from solar concentrators, can only use direct radiation.

- Free dual functions, natural energy storage and greenhouse effect. The collector provides storage for natural energy, as the ground under the transparent cover can absorb some of the radiated energy during the day and releases it into the collector at night. Thus solar chimneys also produce a significant amount of electricity at night. The collector itself can also be used as a greenhouse, which will benefit agriculture production accordingly.
- Low operation cost. Unlike conventional power stations, and also other solar–thermal type power stations, solar chimneys do not need cooling water. This is a key advantage in northwestern China where there have already been problems with drinking water.
- Low construction cost. The building materials needed for solar chimneys, mainly concrete and transparent materials, are available everywhere in sufficient quantities. Particularly important is that no investment in a high-tech manufacturing plant is needed, as both wind turbine and solar collectors are well- developed industrial products.

3. Theoretical model

Many factors, such as the materials used to make the solar chimney, solar chimney height, solar collector materials, and the soil or rock contents under the solar collector, may influence the performance of the solar chimney plant. Also important for power generation is the wind turbine and the controlling system of the plant. Detailed analyses concerning heat exchange and fluid flow inside the solar chimney could be processed with CFD software [3,4]. Here a simple method is reported, which takes into account solar collection, useful work and electric power output of the turbine, and is expected to evaluate the performance of the solar chimney power plant reported.

3.1. Solar collector

The earth itself, which is covered by glass or other transparent materials, acts as a heat absorption layer. The periphery of the solar air collector is open to the elements, and its central part is connected with the base of the solar chimney.

The energy balance equation is given as,

$$\dot{Q} = \dot{m}C_p\Delta T = (\tau\alpha)A_{coll}G - \beta\Delta T_a A_{coll} = \eta_{coll}A_{coll}G \tag{1}$$

where, $\dot{m}$ denotes the mass flow rate of hot air passing through the solar chimney, and can be calculated with the following equation.

$$\dot{m} = \rho_{coll}A_cV_c \tag{2}$$

The air velocity at outlet of the solar collector is expressed by,

$$V_c = \frac{(\tau\alpha)A_{coll}G - \beta\Delta T_a A_{coll}}{\rho_{coll}A_c C_p \Delta T} \tag{3}$$

and the efficiency of the solar collector is given below.

$$\eta_{coll} = (\tau\alpha) - \frac{\beta\Delta T_a}{G} \tag{4}$$

In the above equations, A_c is the cross-sectional area of the solar chimney, A_{coll} is the area to receive solar radiation, G stands for solar irradiance, $(\tau\alpha)$ represents the product of absorbance and transmittance of the solar collector, β is the heat loss coefficient of the solar collector, ρ_{coll} is the density of air at the outlet of the solar collector. ΔT_a denotes the temperature difference between the heat absorption layer and the ambient air. Here it is assumed that the temperature of the heat absorption layer is equal to the average air temperature in the solar collector. $\triangle T$ denotes the temperature difference between the outlet air of the collector and the ambient air. If the air temperature flowing in the solar collector increases linearly along with the flow direction, $\triangle T$ could be estimated with the method recommended in reference [5].

$$\Delta T = \frac{2\dot{Q}}{A_c\beta F_R}(1 - F'') \tag{5}$$

where, the heat removal factor, F_R, can be approximately estimated by,

$$F_R = \frac{1}{\dfrac{1}{F' + \dfrac{A_{coll}\beta}{2\dot{m}C_p}}} \tag{6}$$

F' is the efficiency factor of the solar collector, F'' is the flow factor and is given as,

$$F'' = \frac{F_R}{F'} \tag{7}$$

Furthermore, ΔT_a can be expressed below, under the assumptions given above.

$$\Delta T_a = \frac{1}{2}\Delta T \tag{8}$$

3.2. Solar chimney

The chimney itself is the plant's actual thermal engine. It is a pressure tube with low friction loss because of its optimal surface volume ratio. The efficiency of the chimney, i.e. the conversion of heat into kinetic energy, is practically independent of the rise in air temperature in the collector. It is essentially determined by the ambient temperature at the ground level and the height of the chimney.

According to Ref [1], the chimney efficiency is expressed as follows:

$$\eta_{sc} = \frac{P_{tot}}{\dot{Q}} = \frac{gH_{sc}}{C_p T_0} \tag{9}$$

where, H_{sc} is the height of the chimney, P_{tot} is the power contained in the flow, which can be written as,

$$P_{tot} = \eta_{sc}\dot{Q} = \frac{gH_{sc}}{T_0}\rho_{coll}V_c\Delta TA_c \tag{10}$$

The pressure difference, ΔP_{tot}, which is produced between the chimney base and the surroundings, is calculated by,

$$\Delta P_{tot} = \rho_{coll}gH_{sc}\frac{\Delta T}{T_0} \tag{11}$$

3.3. Turbine

Turbines are always placed at the base of the chimney. Using turbines, mechanical output in the form of rotational energy can be derived from the air current in the chimney. Turbines in a solar chimney do not work with staged velocity as a free-running wind energy converter, but as a cased pressure-staged wind turbogenerator, in which similar to a hydroelectric power station, static pressure is converted to rotational energy using a cased turbine.

Schlaich [1] recommended that the maximum mechanical power taken up by the turbine is:

$$P_{wt,\max} = \frac{2}{3}V_cA_c\Delta P_{tot} \tag{12}$$

The above equation can be further expressed as below,

$$P_{wt,\max} = \frac{2}{3}\eta_{coll}\frac{g}{C_pT_0}H_{sc}A_{coll}G \tag{13}$$

If $P_{wt,\max}$ is multiplied by η_{wt} which contains both blade transmission and generator efficiency, this produces the electrical power from the solar chimney to the grid,

$$P_e = \frac{2}{3}\,\eta_{coll}\,\eta_{wt}\,\frac{g}{C_pT_0}H_{sc}\,A_{coll}\,G. \tag{14}$$

4. Performance analysis of the solar chimney power plant

Some parameters, which will be used in analyzing the system performance, are shown in Table 1.

Performance of the solar chimney power plant has been performed based on the mathematical model mentioned above. Fig. 2 shows the effect of the ambient temperature and the solar irradiance on chimney power productivity. It is found that

Table 1
List of dimensions and some parameters used in the solar chimney power plant

Parameters	Value	Parameters	Value
Chimney height (H_{sc})	200 m	Product of transmittance and absorbance of the collector ($\tau\alpha$)	0.65
Chimney diameter (D_{sc})	10 m	Cover heat loss coefficient (β)	10.0 W/m^2.K
Collector diameter (D_{coll})	500 m	Solar irradiance (G)	600 W/m^2
Distance from ground to the cover (H_{coll})	2.5 m	Collector efficiency factor (F')	0.8
Efficiency of the turbine (η_{wt})	0.8	Ambient temperature (T_0)	20 °C

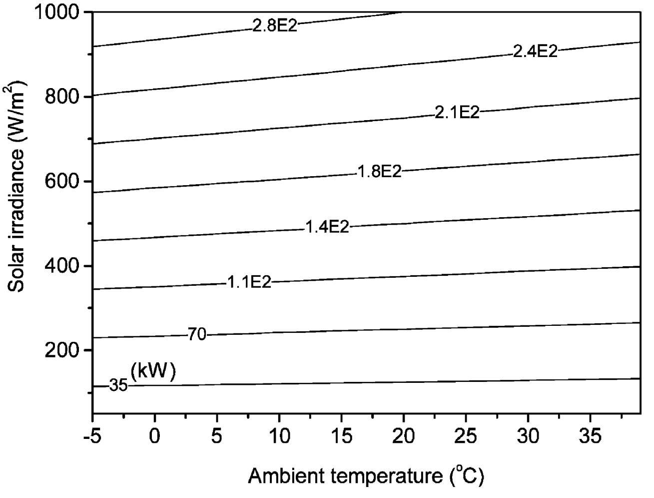

Fig. 2. Effect of ambient temperature and solar irradiance on power generation.

power productivity increases with the increase of solar irradiance and the ambient temperature. The solar radiation, however, is in a dominant position to affect the power generation in the solar chimney, in comparison to the ambient temperature. The solar chimney power plant, is able to output electric power up to 180 kW, when the ambient temperature is 20 °C, and the solar irradiance is 600 W/m^2. This is sufficient to meet the needs of supplying power for the neighboring villages.

Also discussed are the variations of collector diameter and the chimney height. Fig. 3 indicates that the larger the collector size and the higher the chimney height, the greater will be the power production of the solar chimney power plant. Also demonstrated in Fig.3 is that the production of chimney power increases nonlinearly with the increase of collector diameter and the chimney height. It increases rapidly when the sizes of collector and the chimney are small, but slowly with an increase in size. About 670 kW electric power can be produced in the solar chimney when the diameter of the collector is 1000 m, and the chimney height is 200 m.

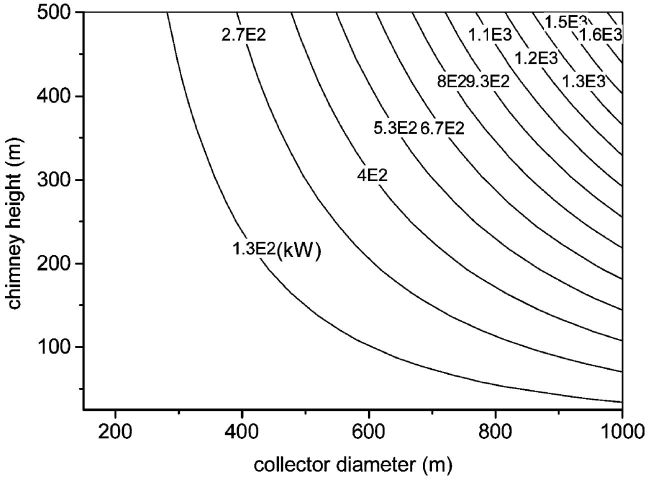

Fig. 3. Effect of solar chimney height and diameter of collector on power generation.

5. Application in NingXia Hui Autonomous region

Ningxia Hui Autonomous region lies in northwestern China, where the solar radiation is good. The yearly total energy from solar radiation ranges about 4935–6118 MJ/m^2/y, which is just less than that in the Tibetan region of China. It is, however, higher by almost 412 MJ/m^2/y than that in Shanxi province and Shandong province which are at the same latitude, and is higher than that in regions along the Chinese Yangtze river by 1000–1600 MJ/ m^2/y. In recent years, the government in this region made great efforts to popularize the solar greenhouse technique, in order to extend the time period for vegetable production. The results proved that this technique is feasible in this region. The configuration of the solar collector used by the solar chimney power plant is similar to that of a solar greenhouse. It is thus possible to extend the use of the solar chimney power plant into agriculture production. The plant is expected to produce power and benefit agriculture production at the same time.

Fig. 4 gives the variations of monthly average solar irradiance and temperature in three counties, namely, Yinchuan, Pingluo and Helan [6,7]. It can be observed that the temperature variations for the three counties change similarly. The minimum mean temperature at monthly base occurs in January for each year, about –10 °C, and the maximum mean temperature at monthly base occurs in July at about 22 °C. The variation in solar irradiance is different from that in the monthly average temperature. Yinchuan and Pingluo have the best solar insolation in June, but Helan receives its strongest solar radiation in July. The minimum solar radiation level for the three counties exist at the same period, namely, in December.

The performance of the solar chimney plant located in the three counties has been compared. Fig. 5 shows the results. The capacity of power generation ranges between 110 and 190 kW for a whole year, the plant can produce more power from March to August each year, because the solar radiation is good. Also shown in Figs 4 and

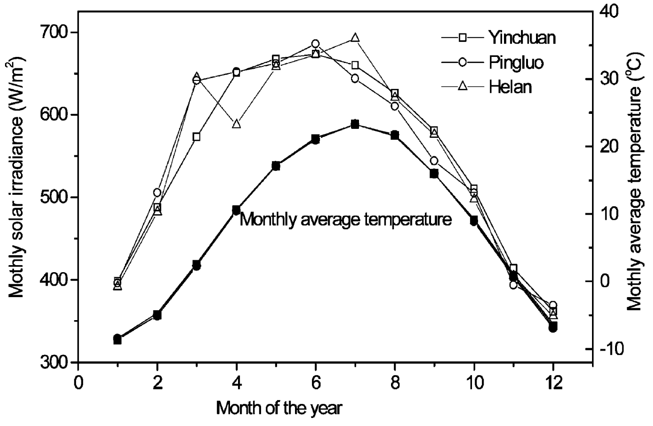

Fig. 4. Monthly average temperature and solar irradiance at three different regions.

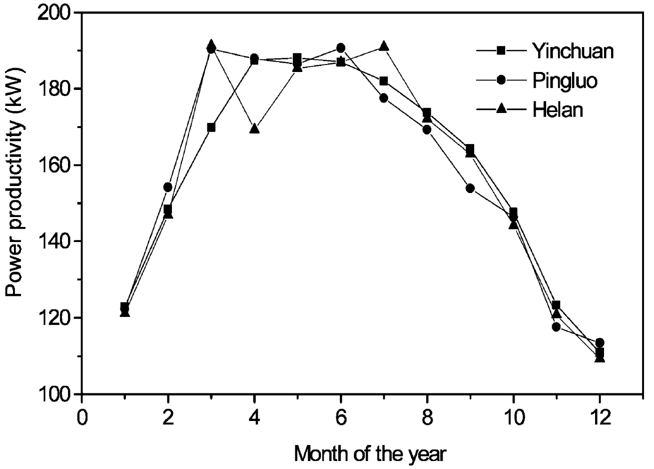

Fig. 5. Monthly average solar power plant generation rate at three different regions.

5 is that the variations in solar irradiance and power production behave similarly. The better the solar radiation, the higher the capacity of power production will be. The power generation may be further increased if the chimney efficiency, which increases with the increase of chimney height, could be improved.

6. Conclusions

A solar chimney power plant, which is intended for use in northwestern China, has been designed and analyzed, with regard to three typical counties in Ningxia Hui Autonomous region. The main points of the conclusion are:

1. The solar chimney power plant is able to produce 110–190 kW electric power with sunshine at the monthly average all year round, and is sufficient to meet the needs of neighboring villages. The solar collector in the plant can also act as a greenhouse for agricultural purposes.
2. The capacity of power generation is dependent on solar irradiance, ambient temperature, etc. Also important for system performance is solar chimney height, collector efficiency, turbine efficiency and surface roughness inside the chimney. Under given conditions, the power generation capacity increases with the increase in solar chimney height and solar collector area. It is also found that the higher the solar irradiance, the higher the efficiencies of the components and the greater the power generation will be. The ambient temperature, however, plays a minor role in affecting power generation for the solar power plant.

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