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Simulation of a pilot solar chimney thermal power generating equipment

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Abstract

A pilot experimental solar chimney thermal power generating equipment was set up in China. A simulation study was carried out to investigate the performance of the power generating system based on a developed mathematical model. The simulated power outputs in steady state were obtained for different global solar radiation intensity, collector area and chimney height. By intercomparison, it is found that the simulated power outputs are basically in agreement with the results calculated with the measurements, which validates the mathematical model of the solar chimney thermal power generating system. Furthermore, based on the simulation and the specific construction costs at a specific site, the optimum combination of chimney and collector dimensions can be selected for a required electric power output.
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Keywords: Solar collector; Chimney; Turbine generator; Power output

1. Introduction

The concept of solar chimney thermal power generating system (Fig. 1) was firstly designed by Professor J. Schaich in 1978 [1]. The power system includes three familiar techniques: the hot air collector, the chimney and the turbine generators. Solar radiation is used to heat a large body of air in the collector, and the hot air is forced by the buoyancy to

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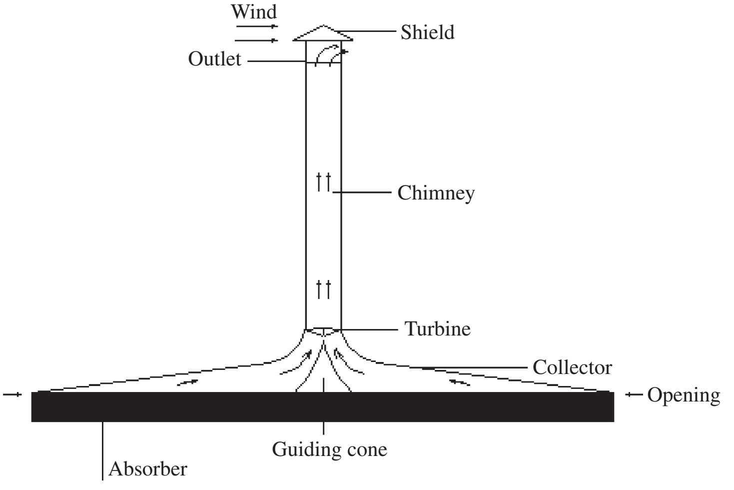

Fig. 1. Schematic diagram of solar chimney thermal power generating system: 1—composite layer bed; 2— Water filled in the pipes; 3— Yellow sand layer;4— Heat insulator ; 5— Ground.

move up the chimney as a hot wind, driving the turbine generator to generate electricity. In the early 1980s, the system has been proven with a successful pilot plant constructed in Manzanares, Spain, with the support of both Germany and a Spanish electric company [1]. The plant had a collector with a radius of 122 m, and the chimney had a diameter of 10 m with the height of 194.6 m. The highest power output of the plant reached 41 kW from July to September in 1982 [2].

Since then, more and more researchers have shown strong interest in and studied such solar thermal power generating technology for its huge potential of application all over the world [2–11]. In 1983, Krisst built a courtyard solar chimney thermal power generating facility with an power output of 10 W in America. Its collector had a diameter of 6 m and the chimney was 10 m tall [9]. In 1997, a solar chimney thermal power generating demonstration model was built and modified twice on the campus of the University of Florida, and both theoretical and experimental investigation on their performances was carried out [10]. A micro-scale model with a chimney of 3.5 cm in radius and 2 m in height on a patch of area of 9 m^2 was built by Kulunk in lzmit, Turkey [11], which produces an electric power of 0.14 W.

On the basis of the above measurements, the performance of the solar chimney thermal power generating system has been investigated. However, the experimental measurements are cumbersome and taxing. To predict their performances for different conditions, a simulation study is usually convenient. Generally speaking, there are many combinations of chimney and collector dimensions for a required electric power output. In order to predict the power output of any dimension conveniently, and to find out the optimum combination of chimney and collector dimensions for a required power output by considering the associated construction costs at a specific site, a simulation study a developed mathematical model is carried out in this paper. The mathematical model is validated by the comparison of simulated results with the results calculated with the measurements of different experimental equipment dimensions.

2. Experimental equipment

The pilot experimental prototype was built in December 2002, and rebuilt several times for different purposes. In order to perform an investigation on the performance of solar chimney power systems with different dimensions, the equipment was rebuilt again. The rebuilt equipment constructed as shown in Fig. 2 consisted of a chimney with variable height and a collector with variable radius. Considering the effects of the cost and strength, eight PVC pipes measuring 0.35 m radius × 1 m height were used as the chimney. The chimney height may vary from 1to 8 m as shown in Fig. 2(a). The framework under the collector was separated into 35 parts as shown in Fig. 2(b), which can be freely moved away when necessary. They were welded by angle iron to ensure enough strength to resist strong outdoor wind or heavy rain and be safely moved. Therefore, the radius of the collector may vary from 1to 5 m. A heat insulator was used to pack the steel-frame structure of the collector to avoid diffusing heat through it. In order to allow greenhouse effect, transparent material was used to cover the collector onto the bracket. Generally, there are three kinds of cover materials: glass, glass–steel plastic shingle and PVC plastic film. We choose PVC plastic film because it is not fragile and strong enough to resist the severe movements during experiments. The absorber on the ground consists of five main components as schematically shown in Fig. 2(c). The function of the absorber under the collector was absorbing and storing solar energy. The water in the pipes (2) (6 cm in diameter) was selected as the storing body [12]. Heat storage with water worked more efficiently than with soil alone since the heat capacity of water is about five times higher than that of soil. Therefore, it is advantageous for generating electricity continuously at night by the water releasing the heat stored during daytime. One centimeter thick

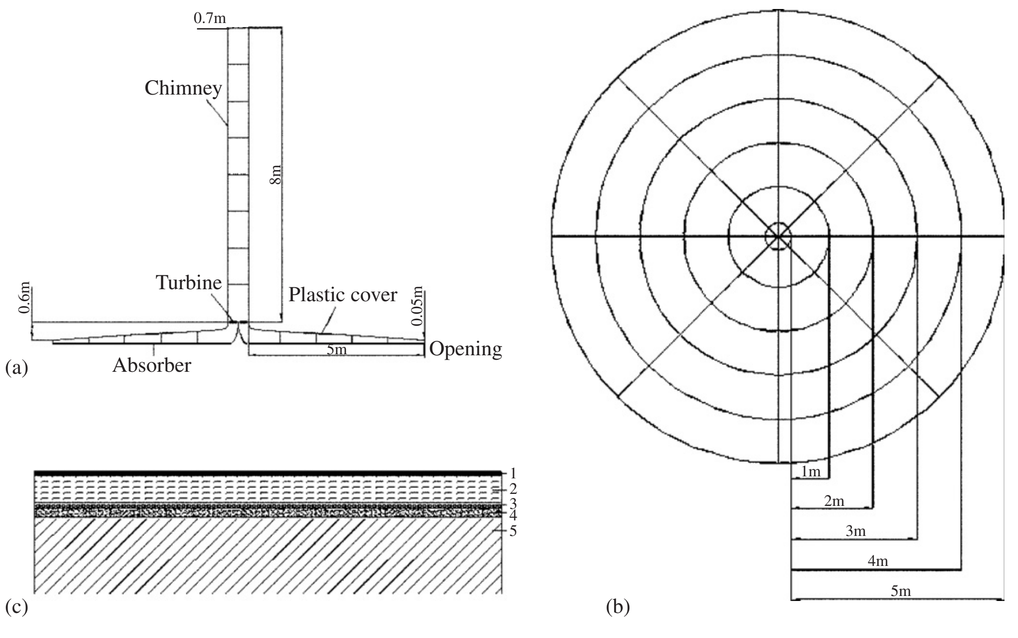

Fig. 2. Schematic diagram of experimental equipment: (a) side view of experimental equipment, (b) top view of the bracket of solar collector, (c) detailed side view of absorber.

composite layer bed (1) with asphalt and black gravel was applied as the top layer to absorb solar energy, and then heat was transferred from the top layer to water pipes (2). The black composite layer materials can convert solar radiation to heat energy efficiently [13]. To avoid heat loss due to heat conduction from the absorber to the earth, a 2 cm thick heat insulator (4) is applied on the ground (5). A 1 cm thick yellow sand layer (3) was applied between the water pipes (2) and heat insulator (4) as a heat buffer to avoid hot water pipes directly touching the heat insulator (4).

A multiple-blade designed on the operating principle of turbine blade was installed at the base of the chimney. The generator, commercially available, was a permanent magnetism motor with direct current. The updraft drove the turbine, which drove the generator to generate electricity.

In the course of experimental measuring, the turbine-generator is under no load conditions. Platimum resistance thermometer sensors (Pt 100) were used to measure hot air temperatures; a mercury thermometer with an accuracy of $\pm 0.5\,^{\circ}\mathrm{C}$ was fixed outside the equipment to measure ambient temperature; a thermal anemometer with an accuracy of ± 0.01 m/s was used to measure the velocity of airflow. Measurements were sampled every 10 min.

3. Mathematical model

A mathematical model based on energy balance has been developed to predict the performance of the solar chimney thermal power generating equipment for different conditions. The following assumptions are made:

1. Air follows the ideal gas law.
2. The mathematical model is considered to be in steady state.
3. There is no friction or leakage considered in the system.
4. Only the buoyancy force is considered, and wind-induced natural ventilation in the ambient is not included.
5. The temperature of the natural ground under the heat insulator bed is equal to that of the ambient.

Fig. 2 shows the physical model for the solar chimney thermal power generating system. The absorber and the plastic cover can be heated to temperatures of T_{a} and T_{p}, respectively, due to solar energy and the greenhouse effect produced in the solar collector. Air at the ambient temperature T_{∞} enters into the collector and is heated to the mean temperature T_{f} in the solar collector.

The energy balance equations for the different components of the system are given as follows,

For the plastic cover:

$$S_1 + h_{\mathrm{rap}}(T_{\mathrm{a}} - T_{\mathrm{p}}) + h_{\mathrm{p}}(T_{\mathrm{p}} - T_{\mathrm{f}}) = U_{\mathrm{t}}(T_{\mathrm{p}} - T_{\infty}), \tag{1}$$

where S_1 denotes solar radiation absorbed by PVC plastic cover; h_{rap} is the radiation heat transfer coefficient between absorber and PVC plastic cover; h_{p} is the convective heat transfer coefficient between PVC plastic cover and airflow in the solar collector; U_{t} denotes the overall heat loss coefficient from PVC plastic cover to ambient, including convection by wind, radiation heat transfer from PVC plastic cover to sky and conduction through PVC plastic.

For the absorber:

$$S_2 = h_a(T_a - T_f) + h_{rap}(T_a - T_p) + U_b(T_a - T_\infty), \quad (2)$$

where, S_2 denotes solar radiation absorbed by absorber; h_a is the convective heat transfer coefficient between absorber bed and airflow in the solar collector; U_b denotes the overall heat transfer coefficient from the absorber to the earth.

For the airflow:

$$h_a(T_a - T_f)A_{coll} = h_p(T_p - T_f)A_{coll} + \dot{Q}, \quad (3)$$

where, A_{coll} is the collector area; $\dot{Q}$ denotes the useful heat energy transferred to the moving airflow by convection.

The mean temperature of hot air, T_f, can be given by,

$$T_f = \varepsilon T_\infty + (1 - \varepsilon)T_o \quad (4)$$

where, T_o is the collector outlet airflow temperature; ε denotes the constant in mean temperature approximation, which is recommended as 0.25 by Hirunlabh et al. [14],

$$\dot{Q} = c_p\dot{m}(T_o - T_\infty) = c_p\dot{m}(T_f - T_\infty)/(1 - \varepsilon), \quad (5)$$

where, c_p is the specific heat of air; $\dot{m}$ denotes the mass flow rate of hot airflow in the solar collector, which is equal to the mass flow rate of hot airflow passing through the solar collector outlet and can be calculated by the following equation,

$$\dot{m} = \rho A_{ch} V, \quad (6)$$

where ρ is the air density at the solar collector outlet; A_{ch} is the section area of solar chimney; V denotes hot air velocity at the solar collector outlet. According to Ref. [1], V can be expressed as

$$V = \sqrt{2gH_{ch}(T_o - T_\infty)/T_\infty}, \quad (7)$$

where g is the acceleration due to gravity and H_{ch} is the height of the chimney.

For the system:

Power output P_{out} can be found as ref. [1],

$$P_{out} = \tfrac{1}{3}\eta_w \rho A_{ch} V^3, \quad (8)$$

where η_w is the turbine generator efficiency, usually between 50% and 90%.

4. Results and discussions

To validate the mathematical model, a computer program has been written in C+ + language. The power outputs simulated are the program are obtained for different conditions, as shown in Figs. 3–5. The results show that power outputs of the power generating systems increases with global solar radiation intensity, collector area and chimney height. As can be seen in Figs. 3–5, it is concluded that the simulated results are in close agreement with the results calculated with the measured temperatures and velocities, which are the mean of those measured from 11:30 to 13:30 each day. However, difference

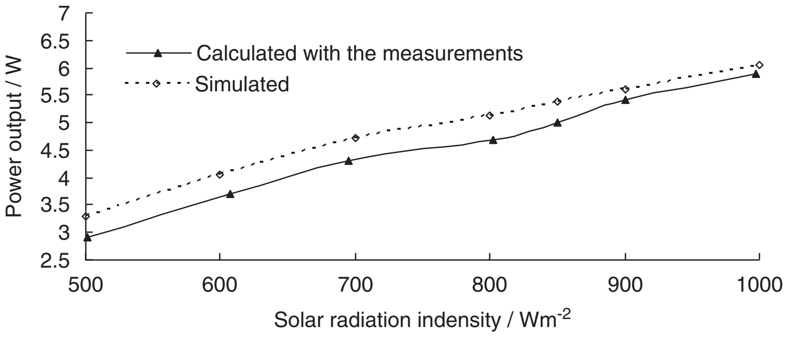

Fig. 3. Power output profiles for different global solar radiation intensity (collector radius: 5 m; chimney height: 8 m).

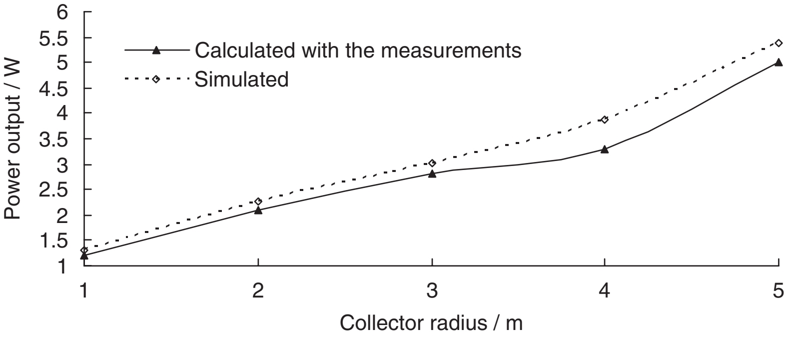

Fig. 4. Power output profiles for different collector area (solar radiation intensity: 850 W/m^2; chimney height: 8 m).

exists because some assumptions were made in the simulation. For example, the heat loss due to the friction and so on was ignored, resulting in the power output difference between the simulated and calculated results the measurements. Fig. 3 shows that the difference accounts for 12% of the respective calculated values with the measurements at radiation intensity of 500 W/m^2, while it is within 9% at a global solar radiation intensity of over 600 W/m^2, because low-intensity solar radiation can not usually produce enough driving force and part of the heat energy is absorbed and stored by the thick absorber. Figs. 4 and 5 show that the difference between the simulated results and measured results with the measurements for different collector areas is within 15%, for different chimney height within 12% of the respective calculated values with the measurements, and this reduces from 11.8% to 7.1% with the increase from 1 to 8 m in chimney height because larger height can produce larger driving force, inducing more heat converted to electric power in the experimental testing rig force.

It is concluded that the mathematical model can predict the performance of the pilot equipment well, and this approach is also applicable to different-scale solar chimney thermal power generating systems.

For a required electric power output, we can obtain many combinations of chimney and collector dimensions by the simulation. However, according to the specific construction

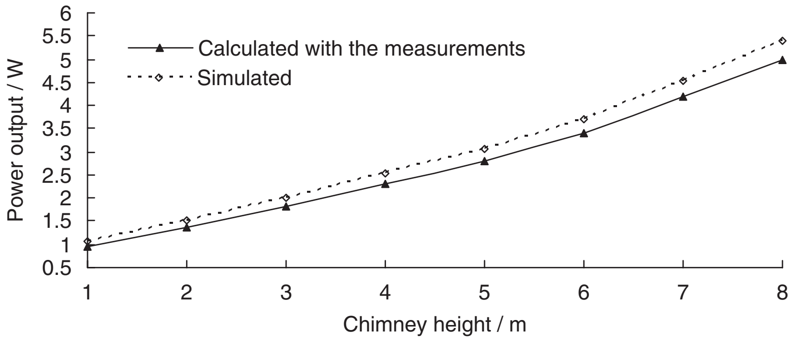

Fig. 5. Power output profiles for different chimney height (solar radiation intensity: 850 W/m^2, collector radius: 5 m).

costs at a specific site, the optimum combination of the dimensions can be selected by a comparison based on their investments, TC, which can be calculated by the following equation,

$$TC = \pi R^2 C_{\text{coll}} + 2\pi r H_{ch} C_{ch} + C_{\text{other}}, \tag{9}$$

where, R and r denotes the radius of the collector and the chimney, respectively; C_{coll} and C_{ch} denote the investment per m^2 collector and per m^2 chimney, respectively, including material cost and engineering cost, etc;C_{other} denotes the other costs, including turbine cost, tests, misc.

C_{coll} and C_{ch} usually vary widely at different sites, especially material costs and labor cost. According to Eq. (9), among a group of combinations of chimney and collector dimensions by simulation for the same required power output, only the combination is considered to be the optimum when TC reaches the lowest, corresponding to the lowest electricity generation cost. Therefore, for a required power output, different countries may develop different types of solar chimney thermal power generating plants based on the TC comparison of every possible combination of chimney and collector dimensions according to local conditions.

5. Conclusion

(1) A pilot experimental solar chimney thermal power generating equipment was built in China.
(2) A mathematical model is developed for simulation study on the performance of the solar chimney thermal power generating system. The simulated power outputs are in close agreement with the results calculated with the measurements in the experimental testing rig. It is concluded that the mathematical model is basically valid for the solar chimney thermal power generating system, and the simulation with the model can be used conveniently to predict the performance of the system, instead of using cumbersome and taxing experimental measurements.
(3) The optimum combination of chimney and collector dimensions can be selected for a required power output, based on the simulation and the specific construction costs at a specific site.

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