Special Climate around a Commercial Solar Chimney Power Plant

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Abstract: A simple thermal model is developed for solar chimney thermal power system and validated by the comparison between the simulated results and those simulated by Schlaich et al. Based on a proposed 200 MW power plant in a desert in western China a special climate, which is formed around the giant solar chimney power plant by the volume of warm air flowing from the chimney outlet to a high altitude, is simulated and analyzed. An atmospheric circulation and rainfall are formed. It is found that the solar chimney power plant increases the chance of rainfall, especially for low-humidity air in the desert region, supporting the agriculture in the local area and promoting a part of the desert region to be reformed to fertile soil. Further, the effects of many factors on the rainfall area around a commercial solar chimney thermal power plant are also analyzed. It is concluded that by keeping other conditions equal, solar radiation of more than 706 W/m^2, a collector area of more than 10.45 km^2, a chimney height of less than 1250 m, a horizontal wind velocity of less than 15 m/s, and an ideal relative humidity from 23.5 to 30% are, respectively, chosen for rainfalls around the collector area.

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Introduction

Energy is the motive force of economic development. Energy demand gradually increases with population expansion and industrial development. However, energy consumption, at present generally based on fossil energy sources (petroleum, coal, and natural gas) in both developed and developing countries, has led to the global greenhouse effect and air pollution, which aggravate the deterioration of living conditions. Unfortunately, low-priced fossil energy will be exhausted in the near future. The demand for renewable and clean energy is increasing. In recent years, the development of new technologies utilizing renewable and clean energy has become an important area of worldwide research.

Solar energy is a renewable and clean energy source. Of the many techniques utilizing solar energy, the most attractive ones seem to be: solar photovoltaic technology and solar concentrating thermal power technologies such as solar parabolic trough power systems, solar tower power systems, and Dish/Stirling power systems. These power technologies are already relatively mature, but their costs, including mainly investment and running, remain high. So it is by far impractical to popularize it all over the world, especially in developing countries.

Solar chimney power systems, an ingenious yet simple design, proposed by Schlaich in 1978, has been proven with the successful operation of a 50 kW pilot plant in the early 1980s (Schlaich 1995). The solar chimney combines three familiar components: an air collector, a chimney, and turbine generators. It works on the principle that turbines are driven by airflow produced by buoyancy derived from hot air heated inside the collector.

In general, solar chimney power system has the following characteristics:

1. It is simple and reliable. Construction materials are economical and available in sufficient quantities. Construction sites may be wastelands. It is accessible to the technologically less developed countries that are sunny and often have limited raw materials resources;
2. In the case of a solar collector, it is able to absorb diffuse radiation when the weather is overcast so that solar chimney power plants can operate 24 h on pure solar energy, with reduced power output during night time due to the soil or water bags under the collector working as a heat storage system absorbing heat during the day and releasing it during night time (Schlaich 1995; Schlaich et al. 2005). This is crucial for tropical countries where the sky is frequently overcast;
3. Maintenance expense is minimal. For example, cooling water is not needed. This would be a key advantage in many countries that are sunny but short of water;
4. The technology is completely pollution free. It can even be used to suppress pollution (Lodhi 1999); and
5. Power output and conversion efficiency increase with a larger-scale power plant, but then energy cost decreases.

Therefore, solar chimney power system on a large scale at low cost (Lodhi 1999; Schlaich 1995; Schlaich et al. 2005; Pan et al.

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2003) without pollution is thought of as suitable for solving the present energy crisis. Recently, the Australian government has decided to support a proposed solar power prototype involving a 1,000 m solar chimney in Mildura, Australia, which can produce 200 MW of electric power (Stephen 2005). Such a large-scale power plant would take full advantage of solar energy and wasteland resources, especially in developing countries with abundant solar energy and vast inexpensive wasteland.

Recent studies related to solar chimney power systems were reported by Pasurmarth and Sherif (1997), Bernardes et al. (1999), Gannon and Von Backström (2000), Von Backström and Gannon (2003), Bernardes et al. (2003), Schlaich et al. (2005), Zhou et al. (2007), and others. Previous studies on solar chimney power technology have focused mainly on the energy conversion performance, heat transfer, and fluid flow in the solar chimney power system. However, the effect of the volume of warm air transferring from the ground level to a high altitude on the variation of local climate and surroundings around the solar chimney power plant has seldom been reported.

In this paper, a simple thermal model of a solar chimney power system is presented and validated with the proposed 200 MW solar chimney power plant referred to by Schlaich et al. (2005). Taking the proposed 200 MW solar chimney power plant referred to by Schlaich et al. (2005) in a desert in western China as an example a special climate, which is formed around the giant solar chimney power plant by the volume of warm air flowing from the chimney outlet to a high altitude, is simulated and analyzed. Further, the effects of many factors on the variation of local climate and surroundings, especially the rainfall area around the commercial solar chimney thermal power plant, are also analyzed.

Physical Principle of Solar Chimney Power System

A solar chimney power system is comprised of three parts: the air collector, the chimney, and the turbines. A gigantic circular glass or plastic roof is constructed above ground, open at the perimeter, and the natural ground or black water bags lying on the ground are allowed to absorb and store heat energy during the day and release it into the collector during night time. Together these form a warm air collector (a "greenhouse"). A vertical chimney with large air inlets at its base stands at the center of the glass roof. Turbines are installed at the base of the solar chimney. Its working principle is that direct and diffuse solar radiation heats a large body of air in the collector, which is then forced by the laws of physics (warm air rises and creates a convective flow) to move up the chimney as a warm wind, driving the turbines to generate electricity. Finally, the warm wind flows out from the top of the chimney (Fig. 1).

Thermal Model

The energy conversion for the whole solar chimney power system can be divided into four phases: the collector converts solar energy to heat energy of air, the chimney converts heat energy to airflow kinetic energy, and the turbine converts airflow kinetic energy to electric power, and the remaining kinetic energy and heat energy of the warm current of air is converted to gravitational potential energy. A thermal model based on energy balances has been developed to predict the performance of the solar chimney thermal power generating equipment described in different conditions. For this, the following assumptions are made:

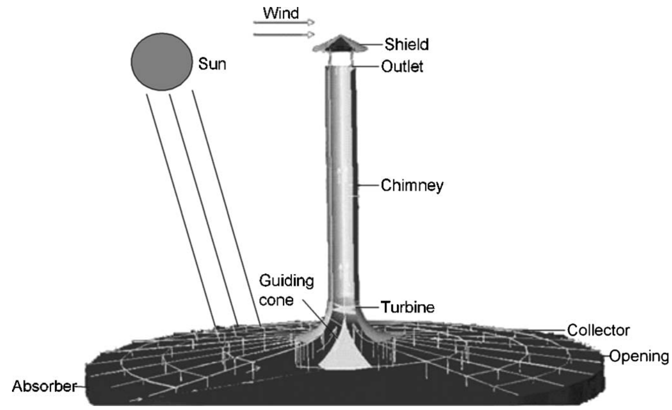

Fig. 1. Schematic diagram of solar chimney power system

1. The air follows ideal gas laws;
2. The system is at steady state;
3. There is no friction or leakage in the system;
4. Only the buoyancy force is considered;
5. The wall is adiabatic; and
6. The influence of the Coriolis force on the fluidity of air is negligible.

For convenience, define 1, 2, 3, and ∞ as the collector opening, the chimney inlet, the chimney outlet, and the ambient, with f and ∞f as the airflow out from the chimney and the corresponding ambient air at the same altitude, respectively.

Collector Effect

The solar collector is a large air heater, in which ambient inlet airflow at T_∞ increases by ΔT_{12}. The energy balance equation is

$$G \cdot A_{\text{coll}} \cdot \eta_{\text{coll}} = \dot{Q} = c_p \cdot \dot{m} \cdot \Delta T_{12} \tag{1}$$

where G=solar radiation; A_{coll}=collector area; $\dot{Q}$=heat output of warm air; c_p=specific heat capacity of air; η_{coll}=collector efficiency, the daily mean of which is typically 31.3% (Haaf 1984); and $\dot{m}$=mass flow rate of warm air passing through solar chimney, which can be calculated from the following equation

$$\dot{m} = \rho_2 \cdot A_c \cdot V_2 \tag{2}$$

where ρ_2=chimney inlet airflow density; and V_2=chimney inlet airflow velocity. The physical properties of air are assumed to vary linearly with air temperature because of the low-temperature range encountered. ρ can be denoted as the empirical relationship for air properties between 300 and 350 K (Ong and Chow 2003) by

$$\rho = 1.1614 - 0.00353(T - 300) \tag{3}$$

Chimney Effect

The chimney is the actual thermal engine of the power system. The chimney converts heat into kinetic energy. Actually, the energy conversion is determined by both the temperature rise of ambient airflow from the collector inlet to outlet and the height of the chimney.

The pressure difference between the chimney airflow and the ambient air, $\Delta P_{c\infty}$, which is produced between the chimney base and the ambient air, is calculated from

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$$\Delta P_{c\infty} = g\int_0^H (\rho_\infty - \rho)dh \tag{4}$$

Substituting Eq. (3) into Eq. (4) gives

$$\Delta P_{c\infty} = 0.00353 \cdot g\int_0^H (T - T_\infty)dh \tag{5}$$

Considering the temperature lapse of ambient air T_∞ is given by

$$T_\infty = T_{\infty 1} - \gamma_\infty h \tag{6}$$

Assuming that air temperature linearly varies with chimney height, T can be given by

$$T = T_2 - \frac{h}{H}(T_2 - T_3) = T_2 - \frac{h}{H}\Delta T_c \tag{7}$$

The temperature difference between the chimney inlet airflow and outlet airflow, ΔT_c, can be given by

$$\Delta T_c = \gamma H \tag{8}$$

where γ=lapse rate of airflow temperature in the adiabatic chimney, calculated by Von Backström and Gannon (2000) as 0.00976°C/m.

Therefore ΔP can be further expressed as

$$\begin{aligned}\Delta P_{c\infty} &= 0.00353 \cdot g\int_0^H \left((T_2 - T_1) + \left(\gamma_\infty - \frac{\Delta T_c}{H}\right)h\right)dh \\ &= 0.00353 \cdot gH\left(\Delta T_{12} + \frac{(\gamma_\infty - \gamma)H}{2}\right)\end{aligned} \tag{9}$$

When the turbines are no load, the maximum chimney airflow rate can be reached and expressed as follows (Lodhi 1999)

$$V_{\mathrm{Max}} = \sqrt{\frac{2\Delta P_{c\infty}}{\rho_2}} \tag{10}$$

Ge and Ye (2004) pointed out that the maximum power is drawn when the chimney airflow rate V_2 is one third of V_{Max} in the case of the turbines being on load. From Eqs. (9) and (10), V_2 can be expressed as follows

$$V_2 = \frac{1}{3}\sqrt{\frac{2\Delta P_{c\infty}}{\rho_2}} = \frac{1}{3}\sqrt{\frac{0.00353gH(2\Delta T_{12} + H(\gamma_\infty - \gamma))}{\rho_2}} \tag{11}$$

Further Rise of Warm Airflow above Chimney Outlet Level

There usually exists a temperature difference between the warm air flowing out from the chimney outlet and the ambient air, $\Delta T_{3\infty}$. The air flowing out of the chimney will keep on rising because of the combination of the initial upward momentum and buoyancy resulting from $\Delta T_{3\infty}$. The maximum height that it can rise to, ΔH_{top}, can be separated into two parts: ΔH_m, the rise induced by the initial upward momentum, and ΔH_t, the rise induced by the buoyancy effect. They can be calculated from the Bosanguet I equation (Guo and Ruan 2001) as follows

$$\Delta H_m = \frac{4.77 \cdot \sqrt{Q_v V_3}}{u\left(1 + \dfrac{0.43 \cdot u}{V_3}\right)} \tag{12}$$

$$\Delta H_t = \frac{6.37 \cdot gQ_v \Delta T_{3\infty}\left(\ln J^2 + \dfrac{2}{J} - 2\right)}{u^3 T_f} \tag{13}$$

$$J = \frac{u^2}{\sqrt{Q_v V_3}} \cdot \left(0.43 \cdot \sqrt{\frac{T_f}{g\gamma_{\infty f}}} - \frac{0.28 \cdot V_3 T_f}{g\Delta T_{3\infty}}\right) + 1 \tag{14}$$

In engineering calculations, the lapse rate of ambient air at high altitude, $\gamma_{\infty f}$, is usually chosen as 0.0033°C/m (Guo and Ruan 2001).

The time of air transferring from the chimney outlet, to the maximum height, t, can be approximately estimated as

$$t = \frac{\Delta H}{\dfrac{V_3}{2}} \tag{15}$$

Simultaneously, the air flowing out of the chimney will be driven horizontally by the horizontal wind which is assumed to have a constant average velocity u at the chimney outlet level. The horizontal transferring distance L_{top} of warm air at its maximum height ΔH_{top} can be estimated as

$$L_{\mathrm{top}} = \frac{2 \cdot u \cdot \Delta H_{\mathrm{top}}}{V_3} \tag{16}$$

When the warm airflow reaches the maximum height ΔH_{top}, there is no temperature difference or velocity difference between the ambient and the airflow transferring from the ground level, which is in a relatively steady state.

Therefore the average vertical lapse rate of warm air can be approximately estimated as

$$\gamma_f = \frac{T_3 - T_{\mathrm{top}}}{\Delta H_{\mathrm{top}}} \tag{17}$$

where T_{top} can be calculated from

$$T_{\mathrm{top}} = T_{\infty 3} - \gamma_{\infty f} \cdot \Delta H_{\mathrm{top}} \tag{18}$$

Validation

Solar chimney power systems on a large scale are thought to be suitable for power output at low cost. Many researchers have carried out studies on the performance of large-scale solar chimney power systems (Mullett 1987; Lodhi 1999; Gannön and Von Backström 2000; Pan et al. 2003; Schlaich et al. 2005). Schlaich et al. (2005) simulated the performance of a projected 200 MW solar chimney power plant, which has a 7,000-m-diameter solar collector, and a chimney 1,000 m high and 120 m in diameter.

To validate the proposed model, the steady-state simulated results with average solar radiation of 750 W/m^2 on sunny days are compared with those simulated by Schlaich et al. (2005), as shown in Table 1.

As shown in Table 1, an agreement to within 2.8% for average chimney outlet airflow rate and within 15% for average tempera-

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Table 1. Comparison between Simulated Results of Average Chimney Outlet Airflow Rates and Average Temperature Rises with Thermal Model and Those Simulated by Schlaich et al. [Adapted from Previously Published Paper Written by Schlaich et al. (2005)]

Parameter	Average chimney outlet air flow rate (m/s)	Average temperature rise (°C)
Simulated results by Schlaich et al. (2005)	11	18
Simulated results with the thermal model	11.5	20.7
Difference of the thermal model results from simulated results by Schlaich et al. (2005) (%)	2.8	15

ture rise is obtained. Therefore, our simple thermal model is consistent with Schlaich et al.'s and valid for the solar chimney thermal power system to a certain extent.

Case Study

There is abundant solar radiation with the average value between 1670 and 2,550 $kW \cdot h/(m^2\,year)$ and radiated duration between 2,200 and 3,200 h/year, and also large desert or regions, occupying 1.26 million km^2 in Western China with 6.8 million km^2 area, occupying most of China's land but the least of China's population, although providing little arable land for agriculture. For example, the desert area occupies about half the area of Sinkiang and Tibet (Pan et al. 2003). In addition, diurnal temperature ranges are usually over 10°C in most of Northwest China. For example, the diurnal range reached 32.3°C in Minqin, Gansu on March 15, 1995 (Huang and Shi 2005). Large diurnal ranges, helpful to continuous operation of the turbines after sunset, are a valuable resource for solar chimney power plants. These regions are suitable for power generation by solar chimney power plants. In addition, there are many low-cost construction materials and labor and abundant construction experience in China, potentially leading to lower cost of electric power from solar chimney power generating plants than in the developed countries.

The Badain Jaran Desert is situated west of Inner Mongolia. It is the country's second and world's fourth largest desert, and covers an area of 44,300 km^2. It would be a suitable location for constructing the proposed 200 MW solar chimney power generating plant having a 7000-m-diameter collector and 1,000 m high concrete chimney of 120 m diameter (Schlaich et al. 2005). This study is carried out for the Badain Jaran Desert for which annual meteorological data (solar radiation, temperature, and wind velocity, see Table 2) are available. The location is selected to obtain a case study to evaluate the performance of a large-scale solar chimney power generating plant.

To determine the economics of such a novel power plant occupying large land imprints, a rough cost estimate would be needed.

In order to predict investment cost and the energy cost of a proposed solar chimney power plant, it is necessary to discuss all parameters, such as its construction cost, running and maintenance cost, durability, amortization period, life span of the chimney, inflation, etc. Some investigations into some pilot ex-

Table 2. Climate Parameters in Badain Jaran Desert

Annual precipitation (mm/year)	50–60
Annual evaporation (mm/year)	3,700
Annual atmospheric temperature (°C)	7–8
Maximum atmospheric temperature (°C)	38–43
Maximum temperature of desert surface (°C)	70–80
Diurnal range (°C)	13–17
Annual wind speed (m/s)	4.2
Major direction of the wind	Northwest
Relative humidity (%)	<35
Annual solar radiation ($kW \cdot h/(m^2\,year)$)	2,100
Annual solar duration (h/year)	3,394

perimental solar chimney power generating plants have given approximate constructional costs of the collector per square meter. The collector may be built either of plastic film or glass. Their costs and amortization periods both differ. We choose to estimate for a glass collector. Likewise, there are different chimneys: a same-section chimney and hyperbolic chimney like cooling tower. Although there is better thermodynamic performance, higher investment cost is needed for the gigantic hyperbolic chimney. We choose to estimate for a 1000-m-high same-section chimney. Some investigations by engineers have also given approximate engineering costs of the chimney per square meter. The costs of mechanical components, including turbines, generators, electronic control equipment, and grid feed-in apparatus, are added into the investment cost. The running costs, mainly including the expenditure of maintenance, are averaged every year. Desert land is considered to be free land in this economic assessment.

In order to estimate energy cost, the life span of the chimney is considered to be 90 years. The life spans of the glass collector and the turbine are estimated at 30 years. That is to say, the collector roof and the turbine generator are nearly rebuilt at intervals of 30 years. The amortization period for the plant is considered to be 30 years in this analysis. The discount rate of investment after the amortization period was not considered in the rough cost estimate for a convenient comparison in the analysis. Some cost factors in the aspects of an amortization period, interest, inflation, etc., would also affect the energy cost. This is estimated at a nominal interest rate of 6% and inflation rate of 3.5%. In that case, an estimated at life span of 90 years, amortization period of 30 years, the energy cost in the amortization period, that after the amortization period, and the average cost in its life span, respectively, being calculated to be 0.124, 0.099, and 0.107 yuan, compared with 0.25 yuan, are all less than 0.25 yuan, the current energy cost of a coal-fired station in China. Without doubt, the energy cost of the proposed power plant is competitive with that of a coal-fired station, increasing largely year by year.

Importantly, the Chinese government increasingly attaches importance to solar power generating technology, and then invests more capital to support the development of renewable energy. Further, a new policy, the renewable energy law, was released on January 1, 2006. Therefore, the proposed project utilizing solar energy and finding an effective approach to exploitation of the untilled deserts is supported by the Chinese government and protected by law.

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Results and Discussion

Forming Special Climate

Taking the proposed 200 MW large-scale power plant in the Badain Jaran Desert, in Inner Mongolia for an example, the average upward vent flux out from the chimney outlet, Q_v, reaches 14,5002 m^3/s when solar radiation is 1,000 W/m^2. That is, about 14,5002 m^3 volume of air transfers from the ground level to a high altitude every second. Undoubtedly, the transferring of the volume of air will have some influence on local regular atmospheric circulation.

ΔH_{top} and L can be calculated as 2,333 and 3,640 m, respectively, according to the thermal model. So, the warm airflow reaches 3,333 m of the maximum rising altitude above the ground level with 3,640 m of horizontal distance away from the collector center, where there is no temperature difference between the ambient and the airflow transferring from the ground level, which is in a relatively steady state. The ambient temperature at the altitude of 3,333 m is calculated to about $-1.67°C$ according to Eqs. (6) and (18). Finally, the airflow transferring from the ground level together with ambient air flows horizontally.

In the course of rising, the warm and moist air rises with adiabatic cooling along a slope, and the relative humidity gradually increases, eventually to 100% at 0.99°C (it is calculated with the assumption of relative humidity of 30% for the airflow at the ground level according to the Appendix) at an altitude which is called the condensation level where moisture in the warm airflow saturates, and starts to coagulate. The location of the condensation point away from the chimney outlet can be approximately confirmed with ΔH_{con} and L_{con} by

$$\Delta H_{con} = (T_3 - T_{con})/\gamma_f \tag{19}$$

$$L_{con} = 2 \cdot u \cdot \Delta H_{con}/V_3 \tag{20}$$

In the example, according to Eqs. (19) and (20), ΔH_{con} and L_{con} are calculated to 2,166 and 3,378 m, respectively.

Since the relatively steady temperature of $-1.67°C$ at the maximum altitude of 3333 m is less than the condensation temperature of 0.99°C (Appendix), the warm air would continue rising in the effect of buoyancy, whose temperature continues dropping, and the moist air further coagulates above the condensation level.

In addition, a large quantity of tiny granules comprising the rising airflow from the ground level can be used as effective condensation nuclei of moisture. Therefore, a cloud system would be formed on the slope, with various clouds distributed at various altitudes. It can produce rainfall in a slim area which begins with L_{con}. In this example, the rainfall area begins with the approximate horizontal distance of 3,378 m, covering a part of the collector.

The inclined flow of warm air would simultaneously drive the cold air to descend onto the ground to make up the mass loss of air because the volume of air is sucked into the collector and then pushed to a high altitude, where a local atmospheric circulation is formed.

In conclusion, a new climate would be formed around the solar chimney power plant (Fig. 2). The solar chimney power plant increases the chance of rainfall, especially for low-humidity air in the desert region, supporting the agriculture in the local area, and promoting the desert region to be reformed even to fertile soil. In order to reduce the block of solar radiation resulting from rainfall clouds L_{con}, which is more than the collector radius, is usually preferred.

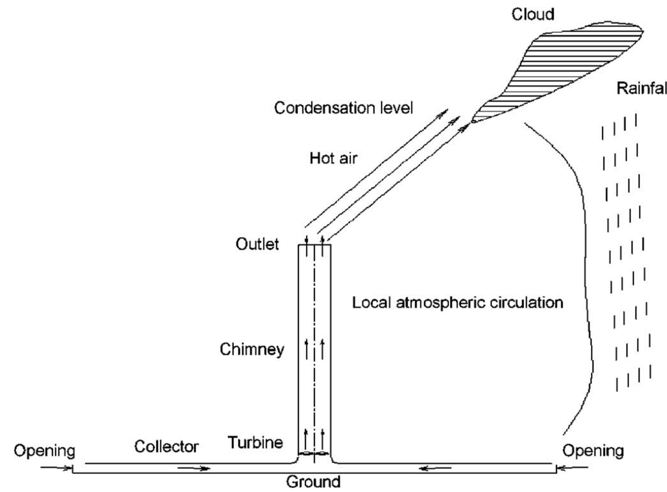

Fig. 2. Schematic diagram of special climate around proposed 200 MW solar chimney power plant

Analysis of Effects of Factors

Many factors, such as solar radiation, horizontal wind velocity at high altitude, solar collector area, solar chimney height, relative humidity of ambient air at the ground level, etc., may influence the effect of a commercial solar chimney thermal power plant on the variation of local climate, especially the rainfall area. Detailed analyses concerning heat exchange and fluid flow inside and outside the solar chimney thermal power system could be processed with the proposed model. Based on the proposed 200 MW solar chimney power plants, here the effects of the factors on the rainfall area are reported by varying a factor equal in other conditions, which take into account the combination of the vertical rise and the horizontal transfer from the chimney outlet to a high altitude, and is expected to show the variation of rainfall area beginning with the horizontal distance of L_{con} to further evaluate the effect of the commercial solar chimney thermal power plant on local climate in different conditions.

Effect of Solar Radiation

To evaluate the effect of solar radiation on the rainfall area, the conditions with different solar radiations of 100, 200, 400, 600, 800, and 1,000 W/m^2, respectively, are simulated. All the other conditions are kept equal to those of the proposed plant.

In Fig. 3, comparisons between ΔH_{con} and ΔH_{top} and that between L_{con} and L_{top} are given for different solar radiation. ΔH_{con} and ΔH_{top} increase with larger solar radiation. Since stronger solar radiation usually gives a larger external energy source, producing larger chimney outlet airflow rate, V_3, and $\Delta T_{3\infty}$, lead to higher ΔH_{top} and ΔH_{con}. However, the horizontal transferring distance L_{top} increases but L_{con} decreases with larger solar radiation. Since L_{top} and L_{con}, respectively, are proportional to ΔH_{top} and ΔH_{con}, they are also proportional to the chimney outlet airflow rate V_3, as seen from Eqs. (16) and (20). Compared with the increase of V_3, faster increase of ΔH_{top} and slower increase of ΔH_{con} results in the increase of L_{top} and the decrease of L_{con}, respectively. In the figure, ΔH_{con} and L_{con} are less than ΔH_{top} and

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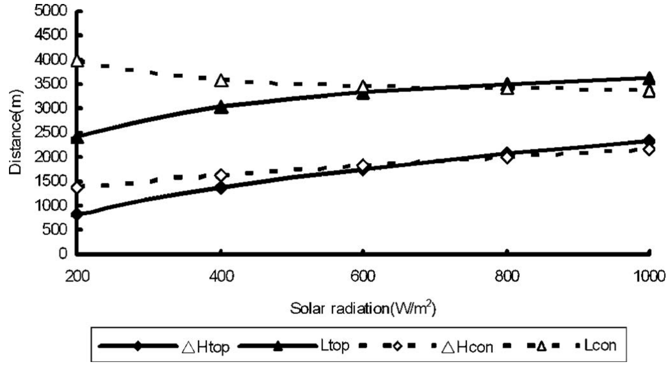

Fig. 3. Variation of height rise and horizontal transferring distance with solar radiation

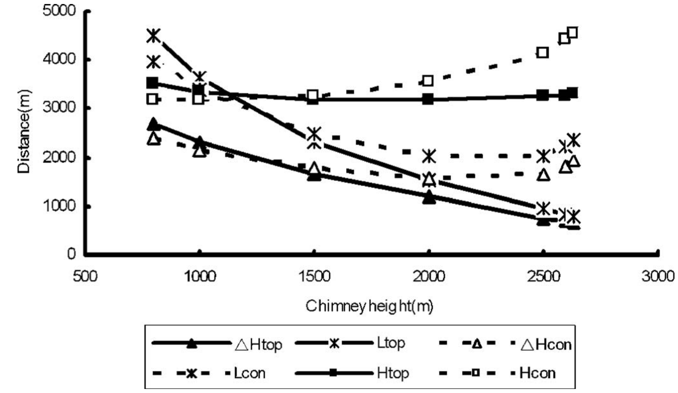

Fig. 5. Variation of rainfall area with chimney height

L_{top} when solar radiation is less than 706 W/m^2, they are more than ΔH_{top} and L_{top} when solar radiation is more than 706 W/m^2. This shows that the rainfalls around the plant can take place only when solar radiation is more than 706 W/m^2, but the special atmospheric circulation cannot go with rainfall when solar radiation is less than 706 W/m^2 because the warm air cannot reach the condensation level.

In summary, solar radiation of more than 706 W/m^2 is available for the dimension producing rainfalls.

Effect of Collector Area

To evaluate the effect of collector area on rainfall area, several systems with different collector area of 0.25, 0.5, 1, 1.5, 2, 2.5, and 3 times the proposed collector area of 14.52 km^2 are simulated in steady state, respectively, in equal conditions. Fig. 4 shows that all of ΔH_{top}, L_{top}, ΔH_{con} increase, but L_{con} decreases with a larger collector, and the difference between ΔH_{con} and ΔH_{top} and that between L_{top} and L_{con} increases when the collector area is over 0.72 times the proposed collector area. That is, a larger collector is inclined to produce a larger sloped rainfall cloud, most of which exceeds the collector area, as seen in Fig. 5. While, when the collector area is less than 0.72 times the proposed collector area, ΔH_{con} and L_{con} are more than ΔH_{top} and L_{top}, respectively, showing that the special atmospheric circulation cannot go with rainfall.

It is found that for the large-scale solar chimney power plant, the collector area should exceed 10.45 km^2 for rainfall.

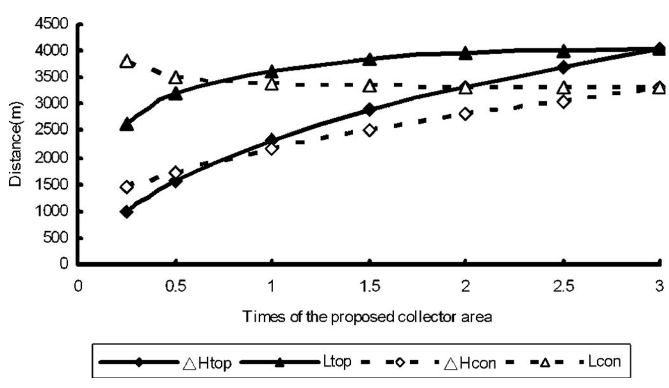

Fig. 4. Variation of rainfall area with collector area

Effect of Chimney Height

Keeping other conditions equal, the systems with chimney heights of 800, 1,000, 1,500, 2,000, 2,500, 2,600, and 2,633 m are simulated in steady state, respectively. The simulated results shown in Fig. 5 are used to evaluate the effects of chimney height on ΔH_{top}, L_{top}, ΔH_{con}, and L_{con}.

As seen in Fig. 5, ΔH_{top}, L_{top}, decrease with larger chimney height. The lapse rate of the chimney rising airflow temperature is larger than that of the ambient air temperature. As for a higher chimney, there is usually a larger chimney outlet rate and lower temperature difference between the outlet of the higher chimney and the ambient for the warm air, as shown in Fig. 6, producing smaller buoyancy and then smaller ΔH_{top}. Both smaller ΔH_{top} and larger chimney outlet rate usually produce smaller horizontal transferring distance, L_{top}, as shown in Eqs. (16) and (20).

In Fig. 5, ΔH_{con} initially decreases from 2,382 m when the chimney height is 800 m to the minimum, reaching 1,556 m when the chimney height is 2,000 m, and then slowly increases to 1,927 m when the chimney height is 2,633 m, and L_{con} maintains a similar variation. The initial decrease of ΔH_{con} is mainly determined by the decrease of $\Delta T_{3\infty}$, while the latter increase of ΔH_{con} is mainly determined by the increase of the temperature lapse of airflow out from the chimney, γ_f, resulting from a faster decrease of ΔH_{top} than that of $(T_3 - T_{top})$, as shown in Eq. (17).

The altitude above the ground level, H_{top} and H_{con}, initially increases and then slowly decreases with the increase of chimney height, resulting from the addition of rising height of chimney outlet airflow and chimney height from 800 to 2,633 m.

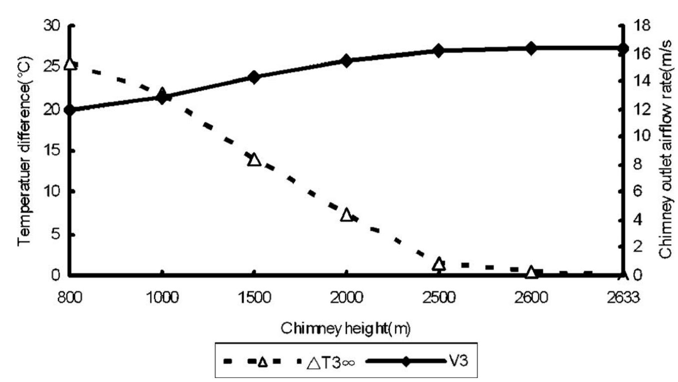

Fig. 6. Variation of temperature difference between chimney outlet and ambient with chimney height

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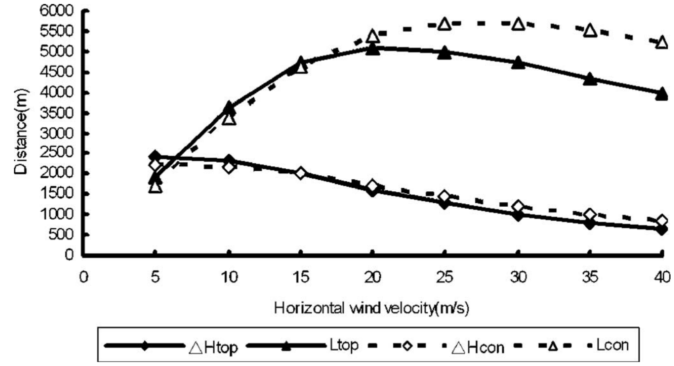

Fig. 7. Variation of rainfall area with average horizontal wind velocity at high altitude

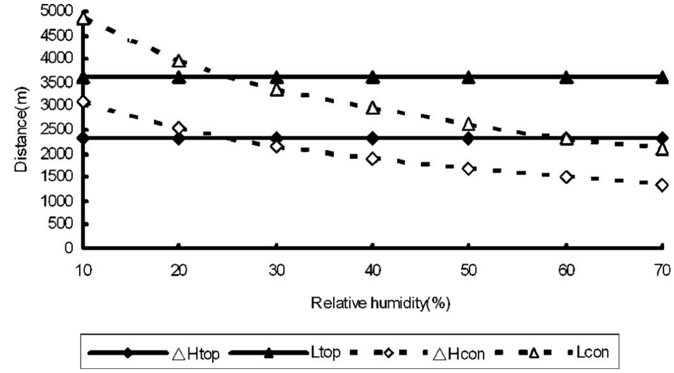

Fig. 8. Variation of rainfall area with relative humidity of ambient air at ground level

In Fig. 5, ΔH_{con} and L_{con} are, respectively, equal to ΔH_{top} and L_{top} for the system with a 1,250 m high chimney. This shows that rainfall would take place only when chimney height is less than 1,250 m.

In Fig. 6, the temperature difference between the chimney outlet and the ambient reduces to 0 when the chimney height is 2,633 m. The chimney outlet airflow temperature is less than the ambient temperature when chimney height is more than 2,633 m, since the lapse rate of air in the chimney is larger than that of the ambient air. This shows that the maximum height for the chimney is 2,633 m. That is, the solar chimney power plant with more than 2,633 m of chimney height cannot operate normally.

In conclusion, keeping other conditions equal, the height of the chosen chimney should not exceed 2,633 m for normal operation, it should not exceed 1,250 m for rainfall, and it should not exceed 950 m for rainfall being away from the collector based on L_{con} exceeding the collector radius of 3,500 m.

Effect of Horizontal Wind Velocity at High Altitude

Keeping other conditions equal, some simulations in steady state are performed to determine ΔH_{top}, L_{top}, ΔH_{con}, and L_{con} across different horizontal wind velocity at the 1,000 m level of 5, 10, 15, 20, 25, 30, 35, and 40 m/s, respectively. The results are shown in Fig. 7.

Fig. 7 shows that ΔH_{top} and ΔH_{con} decrease with higher horizontal wind velocity. That is, lower wind velocity usually induces better development of vertical rise of the warm airflow. But L_{top} and L_{con} first increase with higher horizontal wind velocity, reach the maximum peaks at a wind velocity of 30 m/s, and finally decrease. This mainly depends on the horizontal transferring distance increases with the increase of horizontal wind velocity and height rise, and the decrease of chimney outlet airflow rate. When wind velocity is less than 30 m/s, the effect of the increase of horizontal wind velocity and height rise on the increase of the horizontal transferring distance is dominant. When wind velocity is more than 30 m/s, the effect of the increase of chimney outlet airflow rate on the decrease of the horizontal transferring distance is dominant.

As seen in the Fig. 7, ΔH_{con} and L_{con} are usually smaller than ΔH_{top} and L_{top} only when average horizontal wind velocity is less than 15 m/s. Without doubt, this will not produce rainfall at a horizontal wind velocity of more than 15 m/s.

It is concluded that a horizontal high-altitude wind velocity of less than 15 m/s is helpful to rainfall.

Effect of Relative Humidity

In 1 day, the relative humidity of ambient air at the ground level varies with time. Keeping other conditions equal, ambient air with relative humidity of 20, 30, 40, 50, 60, and 70% is simulated in steady state, respectively. The simulated results shown in Fig. 8 will be used to evaluate the effects of relative humidity on the increase of ΔH_{con} and L_{con}.

As seen in Fig. 8, ΔH_{top} and L remain constant with any relative humidity of ambient air at the ground level. However, ΔH_{con} and L_{con} decrease with higher relative humidity of ambient air at the ground level. This depends on larger relative humidity causes moisture to coagulate at higher condensation temperature of moisture, which usually is obtained at relatively lower altitude.

In Fig. 8, ΔH_{con} and L_{con} are usually smaller than ΔH_{top} and L_{top} for relative humidities above 23.5%, and larger for relative humidities of below 23.5%. This shows that the warm air transferring into a high altitude can produce rainfall as long as the relative humidity is more than 23.5%. However, when relative humidity is less than 23.5%, ΔH_{con} and L_{con} are usually higher than ΔH_{top} and L_{top}, and warm air can't reach the condensation level.

In Fig. 8, the difference between ΔH_{con} and L_{con} and that between ΔH_{top} and L_{top} increases with the increase of relative humidity which is more than 23.5%, producing a larger rainfall area.

The ideal relative humidity is though of as 23.5–30% due to most of the rainfall area being away from the collector.

Conclusion

Limited fossil energy resources, which account for serious air pollution, will be exhausted in the near future. Therefore it is urgent to develop a new renewable and clean energy system. A solar chimney thermal power system, producing power from solar energy, is proven to be a good choice. The vast desert is the optimal location for a solar chimney thermal power system because the solar chimney thermal power system can take full advantage of the vacant wasteland and abundant solar radiation. In this paper, on the basis of the proposed 200 MW commercial solar chimney power plant, a thermal model has been developed, and some conclusions are obtained on the basis of the analyses and listed as follows:

1. Based on a proposed 200 MW power plant in a desert in western China, a special climate will be formed around the

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plant. The climate is induced by the volume of warm outflow transferring from a chimney outlet to a high altitude in the effects of the initial ejecting momentum, the buoyancy effect, and the high-altitude horizontal wind. In the course of inclined flow of the warm air, there are few clouds at a corresponding high altitude over a slim collector area. Atmospheric circulation and rainfall are formed. It is found that the solar chimney power plant increases the chance of rainfalls especially for low-humidity air in the desert region, supporting the agriculture in the local area, and promoting a part of the desert region to be reformed to fertile soil. This is crucial for a dry region with abundant solar radiation and vast desert;
2. A simple thermal model is developed for the airflow transferring inside and outside the solar chimney thermal power plant. Average simulated temperatures rises and chimney outlet airflow rates in steady state with the model are obtained and then compared with those by Schlaich et al. (2005). Both results are in agreement to a certain extent. Therefore, the simple thermal model is basically valid for the solar chimney thermal power system; and
3. Furthermore, the effects of many factors on the rainfall area around the commercial solar chimney thermal power plant are also analyzed. It is concluded that keeping other conditions equal, solar radiation of more than 706 W/m^2, a collector area of more than 5510.45 km^2, a chimney height of no more than 12,50 m, a horizontal wind velocity less than 15 m/s, and an ideal relative humidity from 23.5 to 30%, respectively, are chosen for rainfalls around the collector area.

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Appendix

Zhou et al. (1984) gave the calculation of the absolute humidity, a, as follows

$$a = \frac{f \cdot E}{R_w \cdot T} \tag{21}$$

where f=relative humidity; E=saturation vapor pressure; R_w =specific gas constant of vapor, 4.6 M erg/(g K); and the absolute humidity, a, varying very slightly in the course of the flow of air, is generally considered to be invariable. So, an equation can almost be given in two different states

$$\frac{f_I \cdot E_I}{T_I} = \frac{f_{II} \cdot E_{II}}{T_{II}} \tag{22}$$

where E can be calculated by Zhou et al. (1984)

$$\log_{10} E = 23.5518 - \frac{2{,}937.4}{T} - 4.9283 \log_{10} T \tag{23}$$

It is found that E and f are both relative to T in the course of rising of warm airflow. Taking the proposed solar chimney power plant referred in the paper as an example, according to Eq. (22), E at 20°C is calculated to 23.39 mb, and E at 35.3°C to 57.25 mb. Further, f at 20°C around the collector inlet is assumed as 30%. It changes to 12.9% at 35.3°C at the chimney outlet, and reduces with higher altitude above the chimney outlet, eventually to 100% at 0.99°C at an altitude that is called the condensation level where moisture in the warm airflow goes saturated, and starts to coagulate.

Notation

The following symbols are used in this paper:

A = area or sectional area (m^2);
a = absolute humidity (g/m^3);
c_p = specific heat capacity, 1007 [J/(kg K)];
E = saturation vapor pressure (mb);
f = relative humidity;
G = solar radiation (W/m^2);
g = gravitational acceleration, 9.81 (m/s^2);
H = chimney height or rising height of chimney outlet airflow (m);
h = height (m);
J = parameter in Bosanguet I equation;
L = horizontal transferring distance of chimney outlet airflow (m);
$\dot{m}$ = mass flow rate (kg/s);
P = static pressure (Pa);
P_{out} = electric power output (W);
P_{tot} = power contained in the airflow (W);
$\dot{Q}$ = heat output of warm air (W/s)
Q_v = average vent flux of upward airflow (m^3/s);
R_w = specific gas constant of vapor, 4.6 [M erg/(g K)];
T = temperature (°C);
t = transferring time of air from chimney outlet (s);
u = average ambient horizontal wind velocity around chimney outlet (m/s);
V = velocity (m/s);
γ = average lapse rate of air temperature (°C/m);
η = efficiency (%); and
ρ = density (kg/m^3).

Prefix

Δ = change in value.

Subscript

B = Bosanguet I equation;
b = buoyancy effect;
c = chimney;
coll = collector;
con = location of condensation point away from chimney outlet;
f = airflow after flowing out from chimney;
m = initial upward ejected momentum;
t = turbine generator;
top = maximum rising height of chimney outlet airflow;
1 = collector inlet;
2 = chimney inlet, i.e., collector outlet;
3 = chimney outlet;
∞ = ambient air; and
I, II = two different states for air.

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