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Novel concept for producing energy integrating a solar collector with a man made mountain hollow

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ABSTRACT

The concept of the solar chimney thermal power technology was proven with the successful operation of the Manzanares prototype built in the 1980s. However, all previous attempts at producing energy from a commercial solar chimney thermal power plant on a large scale have failed because of bad engineering and safety. A novel concept for producing energy by integrating a solar collector with a mountain hollow is presented and described. Solar energy is collected in the collector and heats the ground, which is used to store heat energy and heat the indoor air. Then, the hot air is forced by the pressure difference between it and the ambient air to move along the tilted segment and up the vertical segment of the 'chimney', driving the turbine generators to generate electricity. The mountain hollow, formed by excavation in a large-elevation mountain, can avoid the safety issues of erecting a gigantic concrete chimney, which is needed for commercial solar chimney thermal power plants. Furthermore, it can also save a great amount of construction materials for constructing a robust chimney structure and reduce the energy cost to a level less than that of a clean coal power plant, providing a good solution to the reclamation and utilization of undeveloped mountains, especially in mountainous countries.

1. Introduction

The concept of a solar chimney thermal power system was first conceived and designed by a German researcher, Hanns Gunther in 1931, and proposed again by Professor Schlaich in 1978 [1]. The power system (Fig. 1) combines three familiar techniques: the hot air collector, the chimney and the turbine generators. It works on the principle that in the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground, heating a large body of air, which then rises up the chimney due to the pressure difference between the chimney base and the surroundings of the chimney top, driving turbine generators to generate electricity.

In the early 1980s, the use of the system was proven with the successful operation of the Manzanares prototype [1]. The collector had a radius of 122 m and a chimney 194.6 m high, 0.00125 m in metallic wall thickness and 10.16 m in diameter [2]. The plant produced an upward velocity wind of 15 m s^{-1} under no load conditions. The highest power output reached 41 kW from July to September in 1982 [3]. Since then, more and more researchers have studied this solar power technology. In 1983, American scientist Krisst built a courtyard solar power setup with an energy production of 10 W. Its collector had a diameter of 6 m, while the chimney was 10 m high [4]. In 1985, a micro-scale model with a 2 m high chimney of 3.5 cm radius and a 9 square meter collector was built by Kulunk in Turkey [5]. In 1997, a solar chimney power demonstration model was built by Pasurmarthi and Sherif in Florida, and considerable theoretical and experimental research of their performance was done [6]. In 2002, a solar chimney power setup was built in China under the support of local government. It had a collector 10 m in diameter and a chimney 8 m high [7].

The common features of these prototypes are low-efficiency and high-cost. Accordingly, small scale and even middle scale power plants do not provoke interests at all, without any advantage over solar concentrating power systems.

However, the conversion efficiency of a solar chimney thermal power plant increases with the height of the chimney [1,8]. For commercial power plants producing energy economically, not only is a large collector area necessary for collecting a large amount of solar energy, but also a high gigantic chimney. The height is needed only for larger driving force as it is proportional to the height and also to make better use of the heat available. Furthermore, a higher conversion efficiency for larger-scale solar chimney thermal power systems will simultaneously produce a reduction of the energy cost.

Therefore, since 1990, several large-scale solar chimney thermal power plants were proposed to be built in large desert regions in some countries.

In the 1990s, a program in which a solar chimney power plant with an energy production of 100 MW was supposed be constructed in a desert, in Rajasthan, India, had been proposed and

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was about to be implemented. The programmed heights, too high to assure security with astonishing construction cost, could not stand up to a potential raid owing to the nuclear competition between India and Pakistan. The program was finally cancelled [9]. Recently, EnviroMission planned to build a 200 MW commercial plant including a solar chimney 1000 m high [10], and it was downsized to 50 MW plant including a solar chimney about 480 m high [11].

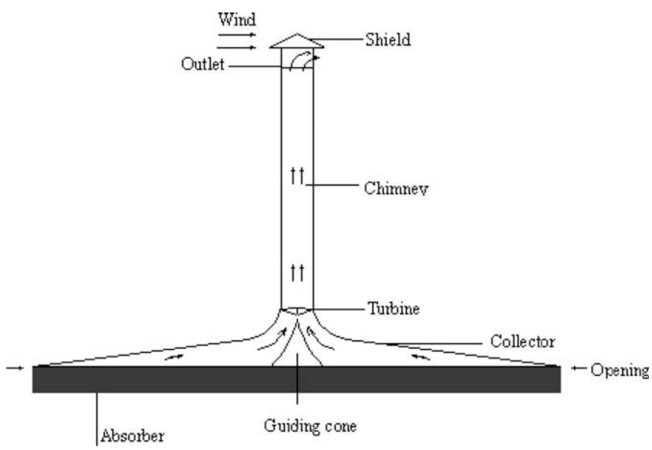

Fig. 1. Schematic diagram of solar chimney thermal power generating system.

The engineering challenges in the face of a massive structure have been major factors in the failure. The size is a constraint imposed by reasonably safe engineering practice. The massive structure requires the engineering expertise. For example, the originally proposed 1 km high solar chimney in Mildura, Australia, seems a little high because humans have no experience of constructing free-standing towers of 1000 m or more. There exist the safety issues which arise due to a very high chimney such as withstanding incidences, such as warfare, raid, earthquake and the likes.

However, some new combined power systems, making full use of each advantage, have the potential of solving the problems mentioned above. In this paper, a novel concept for producing energy integrating a solar collector with a man made mountain hollow is presented. Additionally, the detailed analyses on its performance and cost estimate are performed.

2. Description of a novel concept

The novel concept consists of a design for constructing a giant solar collector surrounding a hollow space excavated in a mountain in a steady-geology region. The hollow space can be used as an economical and safe structural updraft 'chimney' (Fig. 2).

The designs that can be used in this application are shown in Fig. 2. Fig. 2a and b, respectively, give a top view and a side view of a prototype with the novel concept for producing energy integrating a solar collector with a man made mountain hollow. As can be seen from Fig. 2, in the prototype, the giant hollow in the mountain is excavated as an updraft 'chimney', which produces a

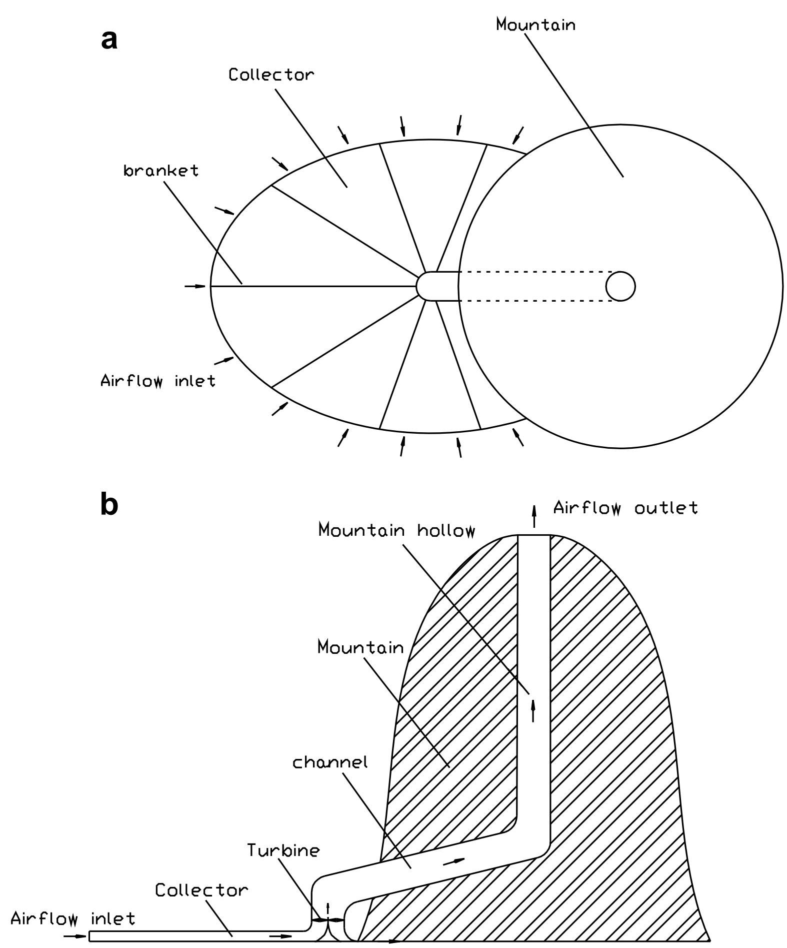

Fig. 2. Prototype of a novel concept for producing energy integrating a solar collector with a man made mountain hollow: (a) top view and (b) side view.

pressure difference as a driving force of the hot air flow, while the massive solar collector is constructed around the foot of a mountain and the turbine generators are installed over the collector outlet. The middle segment is excavated as an air flow channel linking the collector outlet with the hollow inlet and also acts as a tilted 'chimney'. All the structures are air tight. The ambient air drawn through the inlet into the collector is heated by solar energy and rises along the air flow channel, then up the hollow and out from the hollow outlet on the top of the mountain. The upward air current drives the turbine generators to generate electricity.

This novel design provides many unique features that add to its usefulness in producing electric energy from the collected heat.

1. The wall of the hollow in the mountain is covered by a smooth and insulated film for reducing the energy losses resulting from friction and heat dissipation through the wall.
2. In the prototype, all the corners are not angled but well rounded so that the hot air flow is diverted to vertical movement in the hollow with minimum resistance loss. Furthermore, stronger vortexes would occur in the angled corners and result in more energy loss.
3. The middle segment has some inclination for making the air flow better.
4. The turbine generators are installed outside the mountain for convenient operation and to reduce the energy loss for transporting energy outside the mountain.
5. The collector is located on the sunny side of the mountain for receiving solar radiation efficiently. When the area of the sunny side of the mountain is too small, the collector can be constructed around the mountain and other middle segments can be constructed to link the collector with the hollow.
6. The regions around the foot of a mountain are usually flat or slightly inclined. Collector is constructed along the landform. In addition, the efficiency of receiving solar radiation for inclined collector is usually a little higher than that of flatbed collector.

3. Heat transfer mechanism

According to the above principles, the energy conversion of the proposed combined power system can be divided into three phases: the collector converts solar energy to heat energy of air; the mountain hollow converts heat energy to air flow kinetic energy; and the turbine generators convert the air flow kinetic energy to electric power. Here a simple model is reported, which is expected to evaluate the performance in steady state for the proposed combined power system.

3.1. Collector effect

The solar collector is a large air heater in which the ambient inlet air flow with T_∞ can increase its temperature by ΔT_{in}. The energy balance equation is given by

$$GA_{\mathrm{coll}}\eta_{\mathrm{coll}} = \dot{Q} = c_p\dot{m}\Delta T_{\mathrm{in}} \tag{1}$$

where A_{coll} is the collector area; G stands for incident solar radiation; $\dot{Q}$ denotes the heat output of hot air; η_{coll} is the efficiency of the collector; $\dot{m}$ denotes the mass flow rate of hot air passing through the mountain hollow that can be calculated with the help of the following equation:

$$\dot{m} = \rho_{\mathrm{in}}A_{\mathrm{c}}u_{\mathrm{in}} \tag{2}$$

where A_{c} is the cross section area of mountain hollow; ρ_{in} is the density of the collector outlet air flow and u_{in} is the velocity of the collector outlet air flow.

3.2. 'Chimney' effect

The 'chimney' is the actual thermal engine of the power system. The 'chimney' converts heat into kinetic energy. Essentially, the flow in the 'chimney' is a direct result of the pressure difference (buoyancy), ΔP_{c}, which is produced by the 'chimney' and the temperature difference between the flow in the 'chimney' and the ambient. ΔP_{c} can be expressed as [1,12]

$$\Delta P_{\mathrm{c}} = g\int_0^{H+l\sin\alpha}(\rho_\infty - \rho)\mathrm{d}h = g\int_0^{H+l\sin\alpha}\left(\int_\rho^{\rho_\infty}\mathrm{d}\rho\right)\mathrm{d}h \tag{3}$$

where $H + l\sin\alpha$ denotes the total height of 'chimney' i.e., the elevation of a mountain; H is the height of hollow; l and α are the length and angle of tilt segment of 'chimney', respectively; ρ is the density of air at any altitude h of the mountain and ρ_∞ is the density of ambient air at any altitude h. Pressure is considered to be a constant at the heights from h to $h + \mathrm{d}h$, $\mathrm{d}\rho$ can be therefore given by [13]

$$\mathrm{d}\rho = -\beta\rho\mathrm{d}T \tag{4}$$

where β is the expansion coefficient of air; T is the temperature of air at any altitude h in the 'chimney'.

Based on the above equations, Eq. (3) can be rewritten as

$$\begin{aligned}\Delta P_{\mathrm{c}} &= -\int_0^{H+l\sin\alpha}\left(\int_T^{T_\infty}\beta\rho\mathrm{d}T\right)\mathrm{d}h\\ &= \int_0^{H+l\sin\alpha}((\beta\rho)_c(T - T_\infty))\mathrm{d}h\end{aligned} \tag{5}$$

where $(\beta\rho)_c$ is a constant value between the value of $\beta\rho$ in the 'chimney' and that of $(\beta\rho)_\infty$ in the ambient.

Assuming that the air temperature varies linearly with height, ΔP_{c} can be further expressed as

$$\begin{aligned}\Delta P_{\mathrm{c}} &= (\beta\rho)_c\int_0^{H+l\sin\alpha}\left((T_{\mathrm{in}} - T_{\infty\mathrm{in}}) + \left(\gamma_\infty - \frac{\Delta T_c}{H + l\sin\alpha}\right)h\right)\mathrm{d}h\\ &= (\beta\rho)_c(H + l\sin\alpha)\left(\Delta T_{\mathrm{in}} + \frac{1}{2}(\gamma_\infty(H + l\sin\alpha) - \Delta T_c)\right)\end{aligned} \tag{6}$$

where ΔT_c denotes temperature difference of air flows at the inlet and the outlet of the 'chimney'.

According to the mass conservation law, the following equation can be written:

$$\rho_{\mathrm{in}}u_{\mathrm{in}} = \rho_{\mathrm{out}}u_{\mathrm{out}} \tag{7}$$

where ρ_{out} is the density of the 'chimney' outlet air flow and u_{out} is the velocity of the 'chimney' outlet air flow.

The first law of thermodynamics for the air flowing out from the chimney inlet to the chimney outlet can be expressed as

$$e_{\mathrm{in}} + p_{\mathrm{in}}\upsilon_{\mathrm{in}} + k_{\mathrm{in}} + gp_{\mathrm{in}} + q = e_{\mathrm{out}} + p_{\mathrm{out}}\upsilon_{\mathrm{out}} + k_{\mathrm{out}} + gp_{\mathrm{out}} + w \tag{8}$$

where $e, p, \upsilon, k, gp, q, w$ are internal energy, pressure, volume, kinetic energy, gravitational potential energy, heat flow, and work.

For ideal gas

$$e + pv = he = c_pT \tag{9}$$

with he being enthalpy.

In the system, flow performs mechanical work only at the turbine installed at the chimney inlet. Then Eq. (8) can be further expressed as

$$\begin{aligned}&c_p\dot{m}(T_{\mathrm{in}} - T_{\mathrm{out}}) + \frac{1}{2}\dot{m}(u_{\mathrm{in}}^2 - u_{\mathrm{out}}^2) + \dot{m}g(0 - (H + l\sin\alpha))\\ &\quad - U(\overline{T} - \overline{T}_{\mathrm{m}\infty})\pi D(H + l) = \Delta P_{\mathrm{t}}A_{\mathrm{c}}u_{\mathrm{in}}\end{aligned} \tag{10}$$

where $\overline{T} = T_{\mathrm{in}} - \frac{\Delta T_c}{2}$, $U = 1/(1/U_w + 1/U_{w\infty})$, $T_{\mathrm{m}\infty}$ is the average temperature of the mountain, γ_∞ is the lapse rate of the ambient temperature, ΔP_t is the pressure drop in the turbine, U_w denotes the convective heat transfer coefficient between the 'chimney' wall and the air flow in the solar 'chimney' and $U_{w\infty}$ denotes the heat transfer coefficient in the rocks of mountain. ΔT_c can therefore be expressed from Eq. (10) as

$$\Delta T_c = \frac{\dot{m}g(H + l\sin\alpha) + \Delta P_t A_c u_{in} - \frac{1}{2}\dot{m}(u_{in}^2 - u_{out}^2) + U\pi D(H + l\sin\alpha)(T_{in\infty} + \Delta T_{in} - T_{m\infty})}{c_p\dot{m} + U\pi D(H + l\sin\alpha)/2} \tag{11}$$

Substituting Eq. (11) into Eq. (6), Eq. (6) becomes

$$\Delta P_c = (\beta\rho)_c g(H + l \times \sin\alpha)\left(\Delta T_{in} + \frac{\dot{m}(H + l\sin\alpha)(c_p r_\infty - g) + \Delta P_t A_c u_{in} - \frac{1}{2}\dot{m}(u_{in}^2 - u_{out}^2) - U\pi D(H + l\sin\alpha)(r_\infty H/2 - T_{in\infty} - \Delta T_{in} + T_{m\infty})}{2c_p\dot{m} + U\pi D(H + l\sin\alpha)}\right) \tag{12}$$

The pressure difference ΔP_c is usually spent by friction loss in the vertical and tilted 'chimney' ΔP_f, the 'chimney' inlet loss, ΔP_{in}, the local resistance loss at the transition sections ΔP_l, the vertical acceleration loss ΔP_a, and the exit kinetic energy loss ΔP_{out}. We then write

$$\Delta P_c = \Delta P_{in} + \Delta P_l + \Delta P_t + \Delta P_f + \Delta P_a + \Delta P_{out} \tag{13}$$

where

$$\Delta P_{in} = \varepsilon_{in}\frac{1}{2}\rho_{in}u_{in}^2 \tag{14}$$

$$\Delta P_l = \varepsilon_l\frac{1}{2}\rho_{in}u_{in}^2 \tag{15}$$

$$\Delta P_f = f\frac{H + l}{D}\frac{1}{2}\rho_{in}u_{in}^2 \tag{16}$$

$$\Delta P_a = \varepsilon_a\frac{1}{2}\rho_{in}u_{in}^2 \tag{17}$$

$$\Delta P_{out} = \varepsilon_{out}\frac{1}{2}\rho_{in}u_{in}^2 \tag{18}$$

where the pressure loss coefficients are those recommended by White [14] as the wall friction factor $f = 0.008428$, by Kirstein and von Backström as the 'chimney' inlet loss coefficient $\varepsilon_{in} = 0.056$ by assuming inlet guide vane angle and collector roof height are respectively 22.5 deg and 0.356 [15], by von Backström and Gannon as the vertical acceleration loss coefficient $\varepsilon_a = 0.27$ [16] and the exit kinetic energy loss coefficient $\varepsilon_{out} = 1.12$ [16] and by Zhao [17] as the local resistance loss coefficient at the transition sections ε_l.

3.3. Energy production

The electric power generated by the turbine generators, P_{out}, can be expressed as

$$P_{out} = \eta_{tg}\Delta P_t \cdot A_c \cdot u_{in} \tag{19}$$

where η_{tg} is the efficiency of the turbine generators.

3.4. Conversion efficiency

The total conversion efficiency η is involved in the process of conversion of solar energy into electric power. Associated with Eq. (19), η can be expressed as

$$\eta = \frac{P_{out}}{GA_{coll}} = \frac{\eta_{tg}\Delta P_t \cdot A_c \cdot u_{in}}{GA_{coll}} \tag{20}$$

3.5. Maximum height of 'chimney'

In the system where air flow is driven by the buoyancy, the 'chimney' outlet air flow temperature T_{out} usually should be higher than the ambient temperature $T_{out\infty}$ at the hollow outlet level. Otherwise, according to the state equation, the density of air flow at the 'chimney' outlet is higher than the corresponding density of the ambient air because of the same pressure. This counteracts a part of buoyancy. Therefore, the maximum length of the 'chimney' is obtained when the temperature of the air at the 'chimney' outlet is equal to the temperature of the ambient air for a given collector. It can be expressed as

$$T_{out} = T_{\infty out} \tag{21}$$

$T_{\infty out}$ can be expressed as

$$T_{\infty out} = T_{\infty in} - \gamma_\infty(H + l\sin\alpha) \tag{22}$$

Using Eq. (13), the 'chimney' outlet air flow temperature T_{out} can also be expressed as

$$\begin{aligned} T_{out} = T_{in} - \Delta T_c &= \frac{c_p\dot{m}T_{in} - \Delta P_t A_c u_{in} + \frac{1}{2}\dot{m}(u_{in}^2 - u_{out}^2) - \dot{m}g(H + l\sin\alpha) + U\pi D(H + l\sin\alpha)(T_{in}/2 - \Delta T_{in} - \gamma_\infty(H + l\sin\alpha)/2)}{c_p\dot{m} + U\pi D(H + l\sin\alpha)/2} \\ &= \frac{c_p\dot{m}T_{in} - \Delta P_t A_c u_{in} + \frac{1}{2}\dot{m}(u_{in}^2 - u_{out}^2) - \dot{m}g(H + l\sin\alpha) + U\pi D(H + l\sin\alpha)(T_{in}/2 - \Delta T_{in} - \gamma_\infty(H + l\sin\alpha)/2)}{c_p\dot{m} + U\pi D(H + l\sin\alpha)/2} \end{aligned} \tag{23}$$

The maximum height of the 'chimney' for a given collector area can therefore be calculated with help of the above equations.

4. Validation

Experimental validation of the mathematical model for the proposed combined solar power generating system is impossible since no such system has yet been constructed anywhere in the world. However, we can validate the model by comparing the data calculated for the model with the measurements in the only pilot prototype plant, i.e., the Manzanares plant. In this calculation, the

Fig. 3. Picture of a typical mountain located in China.

measurements including global solar radiations, air temperature rises and velocities are used to calculate the collector efficiency in the model.

The upcurrent in the chimney usually has some trouble in the morning especially in cool days [7]. So we compare the calculated and the measured power outputs during daytime in the afternoon. Fig. 4 shows the comparison of the momentary power outputs calculated using the model and the measurements in the Manzanares prototype during daytime from 12:00 to 17:00 on September 2, 1982. Table 1 compares the calculated and the measured power outputs during the time. The mean value of efficiency of turbine generators is calculated as about 64% by comparing the terminal output and potential output calculated from the measurements neglecting losses at turbine during the time [3].

As shown in Fig. 4 and Table 1, during the daytime, an agreement for power output is good. This strongly supports the idea that the simple mathematical model is reasonably valid for solar chimney power system.

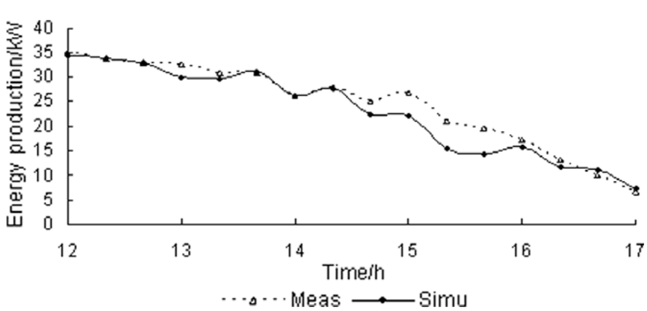

Fig. 4. Comparison of momentary power outputs calculated using the model and measurements in the Manzanares prototype during daytime from 12:00 to 17:00 on September 2, 1982.

Table 1
Comparison of the calculated and the measured power outputs during daytime from 12:00 to 17:00 on September 2, 1982

	Power outputs (kW h)
Calculation	127
Measurements	121
Difference to measurements (%)	4.96

5. Discussion

5.1. Advantages of the novel combined design

The proposed unique integration of a solar collector and a mountain hollow inside a mountain is shown schematically in detail in Fig. 2 with an actual undeveloped mountain shown in Fig. 3. This integration of the two systems has many attractive safety engineering principles and economic incentives, which are as follows:

1. The hollow, laterally airtight and insulated for producing a driving force and guiding the air flow, can be formed by excavation in a large-elevation mountain. This will avoid the safety issues of the erecting of gigantic concrete chimney that is needed for commercial solar chimney thermal power plants [1]. A mountain hollow cannot be destroyed in the steady geological domain where large geological variations normally do not occur in several thousand of years, which is nearly negligible compared with the period of geological variation.
2. A mountain hollow used as 'chimney' avoids the use of considerable construction materials and thus saves considerable resources.
3. Though the tunneling engineering cost of a mountain hollow may be more than the engineering cost of an equivalent reinforced chimney, a reinforced chimney is only used for several dozens of years, but the proposed mountain hollow can be used for a much longer period resulting in the reduction of the energy cost in the long term.
4. The use of an existing undeveloped mountain eliminates the need to purchase large areas of land for a solar power site. The acquisition of land is usually a very expensive activity for construction of large collectors. However, the novel design solves these problems, and provides a good solution to the reclamation and utilization of undeveloped mountains, especially in countries with large areas of high mountains. For example, China, with a vast land area, is a mountainous country with two thirds of its total land area covered by mountains (33%), hills (10%) and plateaus (26%) [18]. Out of the world's 12 highest peaks more than 8000 m high, seven are located in China. In the western part of China, which contain most of China's land, there is abundant sunlight, mostly more than 2000 h per year, and is comprised of mountains and deserts as well as plateaus that do not provide much arable land for agriculture [18]. This is therefore a suitable location for a combined system as discussed in this work. Consequently, it is a great task in the country's development to establish a relevant development tactics to take advantage of enormous undeveloped mountainous areas. Without any doubt, the construction of the combined power plant proposed in this work can aptly solve the energy problem which China seriously faces.

5.2. Performance

In order to determine the energy production, a parametric study with the proposed model was conducted to determine the effects of solar radiation, mountain elevation and collector area on the energy production. In the calculation, the values of the length and the angle of the tilted segment of the 'chimney' and the ratio of the total length to the cross section of the 'chimney' were found to be 150 m, 10° and 9.0. The collector area was denoted by effective diameter. In the steady analyses in this paper, the collector efficiency is assumed to be a constant at 31.3%, i.e., mean efficiency of the collector measured in the Manzanares plant [3], and the desired value of 80% for efficiency of turbine generators is taken into consideration [1,12].

The results of the parametric study are shown in some of the figures provided. Fig. 5 shows the variation of energy production with solar radiation for the plant with 1 km-elevation mountain and 19.3 km^2 collector. As expected, the energy production increases linearly with increasing solar radiation, and reaches 100 MW when solar radiation is 1000 Wm^{-2}.

To evaluate the effects of mountain elevation and collector area on the energy production comprehensively and to calculate the maximum mountain elevation, i.e., the maximum 'chimney' height for different collector areas, many combinations with different mountain elevations from 0 to 3000 m and effective collector diameters from 1000 to 5000 m, are respectively simulated with equal other conditions when solar radiation reaches 1000 Wm^{-2}. Fig. 6 shows the variation of energy production with mountain elevation and effective collector diameter and that of the maximum mountain elevation with effective collector diameter. In the figure, with an increase in mountain elevation or effective collector diameter, the energy production from the combined power plant with the novel concept obviously increases. It is also found that the maximum mountain elevation increases with increasing collector area. This depends on that the heat contained in larger collector is more. In contrast, there exists a maximum area of collector for any mountain.

Taking a 100 MW plant with 1 km-elevation mountain and 19.3 km^2 collector as an example, Figs. 7 and 8 show the variations of the energy production and conversion efficiencies with mountain elevation and effective collector diameter, respectively, keeping other conditions equal. As seen from Fig. 7, the energy production and conversion efficiency increase with increasing mountain elevation, but the increasing ratio gradually reduces with mountain elevation due to the gradual reduction of temperature rise between ambient and collector outlet. As seen from Fig. 8, the energy production increases from 7 to 148.5 MW with increasing effective collector diameter from 1500 m to 6000 m, but the conversion efficiency nearly keeps invariable, between 0.4% and 0.53%.

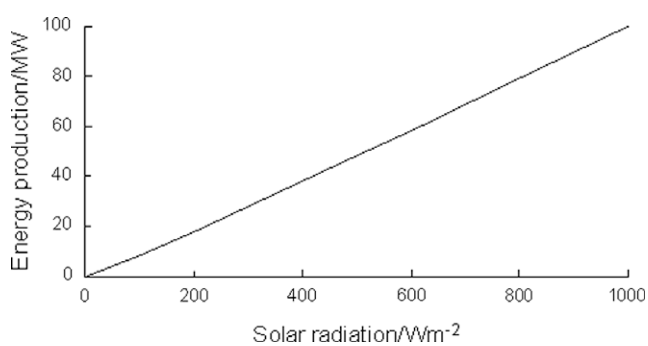

Fig. 5. Variation of energy production with solar radiation for a given plant with 1 km-elevation mountain and 19.3 km^2 collector.

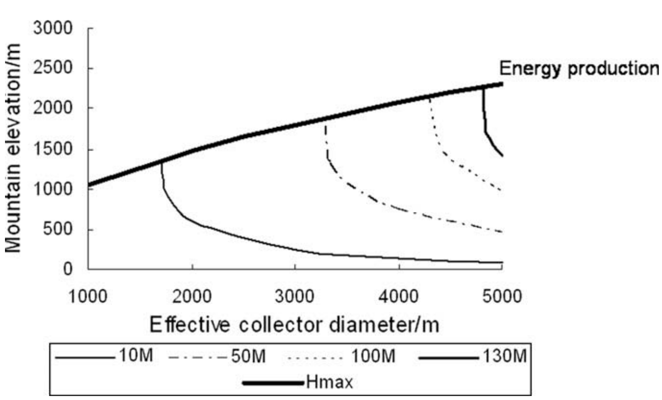

Fig. 6. Effect of mountain elevation and collector area on energy production of combined power plant proposed and variation of maximum mountain elevation, i.e., maximum height of 'chimney' with collector area.

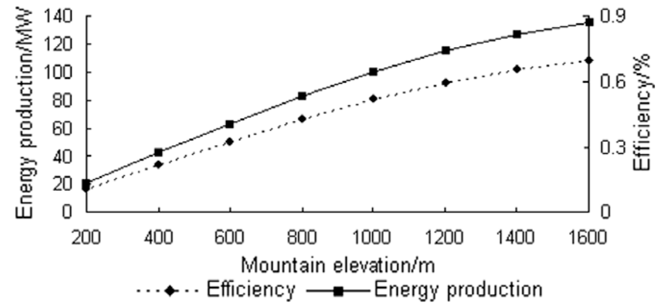

Fig. 7. Effect of mountain elevation on energy production and conversion efficiency of combined power plant proposed.

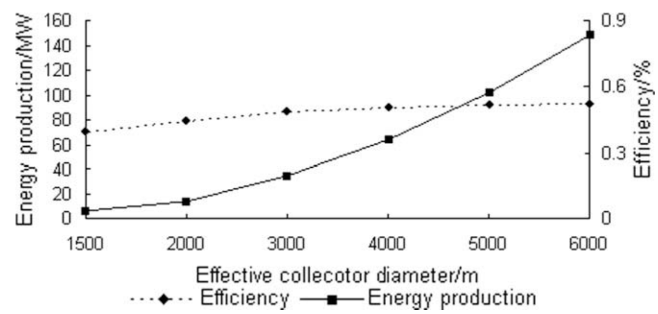

Fig. 8. Effect of collector area (denoted as effective collector diameter) on energy production and conversion efficiency of combined power plant proposed.

As seen from Fig. 6, both plants with larger collector and smaller-elevation mountain and those with smaller collector and larger-elevation mountain can obtain the same energy production. However, as seen from Figs. 7 and 8, the latter has a higher conversion efficiency and can save collector materials. So, a large-elevation mountain with enough large foot area usually is selected to construct the power plant.

5.3. Cost estimate

To determine the economic potential of such a novel combined power plant, a thorough cost study would be needed. In order to predict the investment cost of a proposed power plant with the novel concept and the energy cost, it would be necessary to discuss all the parameters, such as its construction cost, operating and maintenance cost, durability, amortization period, life span of mountain hollow, inflation, etc. Neither a particular site was kept in mind nor a detailed investigation on cost was intended for the purpose of this work. However, a rough cost estimate is desirable for a given design of a plant. Some investigations for some pilot chimney power plants give approximate construction costs of the collector per square meter. Some investigations for tunnel engineerings also give approximate engineering costs of the mountain hollow per m^3. The mountain where rock is high-rigidity and high-strength is selected in the analysis. Thick concrete or steel linings covered on the wall are not needed, but just a thin, smooth, insulated film. However, the excavation of vertical or tilted tunnel is more difficult and the additional hoisting of rock residue is needed compared with engineering of horizontal tunnel. In the cost estimate, an engineering expense of the hollow per m^3 is assumed to be 4/3 times as excavation cost of fifth class rock per m^3 for Maoshan Highway Tunnel in Guangdong Province, China which reaches at about 56.31 US dollars per m^3 [19]. The costs of the mechanical components, including turbines, generators, electronic control equipment and grid feed in apparatus, are added into the investment cost. The operation and maintenance costs are averaged every year.

A cost estimate is given here for a plant of a 100 MW peak energy production running for 24 h every day, 365 days every year at a site with an annual global solar radiation of 2300 kW h m^{-2} a^{-1}. That is, a predicted total energy of 210 GWh will be produced every year. The plant is selected to consist of a 1 km-elevation mountain with a 19.3 km^2 collector, and the mountain hollow ordinarily has an infinite life span in the steady domain where large geological variations nearly do not occur. Based on the above, the investment cost of each part of the proposed 100 MW power plant can be calculated and shown in Table 2. (Conversion rates for Yuan (China), Euro and US dollar are used in the analysis: 1.2 US dollars = 1 Euro and 1 US dollar = 8 Yuan (China)).

In order to estimate energy cost, the life span is considered to be 100, 150, 200 and 300 years, respectively, and the amortization periods are considered to be 20, 30 and 40 years, respectively, in this analysis. In this economic assessment, the land cost has not been added because the construction site is considered to be a free mountain. The life spans of the collector and the turbine generators are estimated at 30 years [12]. That is to say, in the additional years over the first amortization period, the collector roof and the turbine generators are nearly rebuilt at intervals of 30 years, but the mountain hollow is considered to be free except with a little maintenance cost. The investment cost in other amortization periods in the analyses is based on the price level in the first year of the first amortization period in order to compare its energy cost with the electricity cost of clean coal power plant which is hardly to be predicted in the future. Some cost factors in the aspects of an amortization period, interest, inflation and so on 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, compared with the electricity cost of clean coal power plants equipped for CO_2 sequestration, reaching US\$0.11 per kW h [20], the energy costs, estimated at a life span of 150 years with amortization periods, respectively, of 20, 30 and 40 years can be shown in Fig. 9. In the figure, the cost in the first amortization period is more than US\$0.11, while that in the additional years over the first amortization period is a little less than US\$0.11. The average cost in its life span approaches US\$0.14. Without doubt, the energy cost of the proposed power plant is competitive with clean coal power plants, even with conventional coal power plants increasing year by year when the externalities for sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particles are included in economic analysis which may amount to US\$0.25 per kW h in the conventional thermo-electric power plants using sub-bituminous coal like in Spain [21,22].

Table 2
Investment costs of each part of the proposed 100 MW power plant

Item	Cost/million US dollars
Chimney cost [19]	614
Collector cost [21,22]	113.4
Power conversion unit (PCU) [23]	48.9
Total	776.3

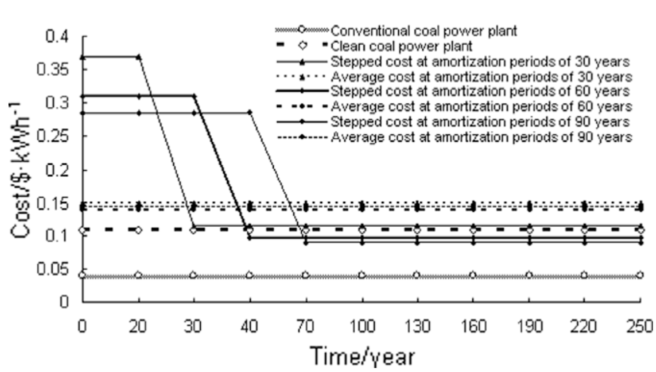

Fig. 9. Comparisons of average cost and stepped cost at different amortization period, respectively, of 20, 30 and 40 years in the proposed plant and cost of clean coal power plant.

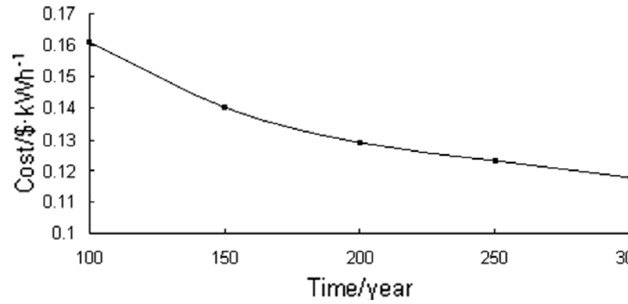

Fig. 10. Comparisons of average cost estimated at amortization period of 30 years for different life spans.

Furthermore, the energy cost will vary with the life spans of the mountain hollow. Fig. 10 shows the cost of the mountain estimated at an amortization period of 30 years, for different life spans. In the figure, with an increase in life span from 100 to 150 years to 300 years, the energy cost is reduced from US\$0.161 to US\$0.14 to US\$0.118. Without doubt, lower energy cost can be reached for longer life span.

In order to produce the same energy, the effect of an estimated life span of 300 years of the proposed mountain hollow can be reached only when a reinforced concrete chimney whose life span is assumed to be 80 years is considered to be built about 4 times. This will save considerable construction materials.

In addition, it is concluded from the previous discussion that with increasing plant dimension, the real physical efficiency increases. This will result in a reduction of energy cost of the plant [1].

In countries with very low wages and advanced tunneling technology, the investment costs and then the energy costs of the proposed power plant will be further reduced.

6. Conclusion

The proposed system that has been developed for this study is unique in the field of power generation and is appropriate for any mountain with enough large area at the foot in any place. The combined power model with different dimensions can be constructed according to the range and the elevation of the mountain. Thus, the combined power plant with any 'chimney' height can undoubtedly be built as long as a mountain with enough elevation and large foot area can be found. If so, it will be realistic that every mountain becomes a power plant and huge treasure like the hydroelectric power plants on the rivers. It effectively uses undeveloped mountains, avoids the safety issues, faced by the reinforced concrete chimney save a great amount of construction materials, and reduces the energy cost in a long term to less than that of clean coal power plants, even to less than that of conventional coal power plants increasing year by year. It effectively uses undeveloped mountains and also provides a solution to the reclamation and utilization of undeveloped mountains. These will accelerate the combined power plant to be put into practice in those mountainous countries that greatly need energy sources.

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