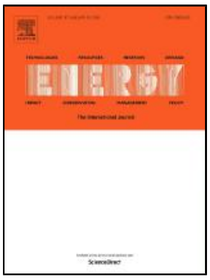

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Performance of a modified solar chimney power plant for power generation and vegetation

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ABSTRACT

This paper develops a mathematical model to investigate the performance of a modified solar chimney power plant (MSCPP) for purposes of both power generation and vegetation. It then estimates the net added benefit. Results show that with the vegetation area enlarging, the MFR of the vapor increases, and more heat is used as the latent heat for water evaporation, leading to considerable reduction of the power. Condensation from the saturated air occurs only for very large vegetation area. On a cooler day, the plant produces less power and the condensation occurs for smaller vegetation area. Higher relative humidity of ambient air results in clear reduction of the MFR of the vapor evaporating from the vegetation area, and accordingly the great enhancement of the power. The benefit from agricultural products is larger than the benefit loss caused by the electricity loss, and the benefit of fresh water condensed from the saturated air is negligible. This leads to net added benefit for the MSCPP compared to the conventional plant. The net added benefit becomes greater with larger vegetation area. When the chimney is heightened from 1000 m to 1500 m, the power is enhanced greatly; however, the net added benefit becomes smaller.

Keywords: Solar collector; Solar chimney; Power generation; Vegetation; Latent heat; Fresh water

1. Introduction

Solar energy is an abundant clean and renewable energy resource [1]. A solar collector [2] can be used for growing vegetation as a greenhouse, drying, ventilation, and power generation. A high solar chimney can enhance the flux of the air current inside the collector. Accordingly, a large solar collector by aid of a high chimney can be used to generate electricity [3-6]. This device is called solar chimney power plant (SCPP).

Researchers conducted a great amount of research on the SCPPs. The performance of SCPPs including the fluid flow, pressure drop and heat transfer process inside them was studied by different researchers [7-10]. The effects of meteorological parameters [9,14] and structural parameters [15-23] to the SCPP performance were investigated. A small top-divergent angle of chimney can enhance the SCPP performance effectively [21-23]. The optimal turbine pressure drop factor was studied for achieving the maximum fluid power [24-26]. The “few large and many small” arrangements of multi-scale plants in a given area were proposed to maximize solar radiation extracted [27]. Replacing a conventional horizontal collector, a sloped collector has a chimney effect besides producing a greenhouse effect, and thus leads to enhancement of the plant performance [28-32]. Instead of a reinforced concrete solar chimney, a lightweight inflatable free-standing flexible solar tower was designed. It was claimed that the novel design could simplify the construction and reduce the cost of the chimney [33]. No high levelized cost of electricity of large-scale plants estimated [34] possibly will stimulate further research and development of the SCPPs.

Besides producing electric power, SCPP is proposed to produce additional products (for example, fresh water by seawater desalination [35-38], and fresh water from atmosphere by solar cyclone [39]), or for other purposes, for example, of dispersion of air pollution [40, 41], or cooling [42].

Can the SCPP be used to generate electricity and produce vegetation products, simultaneously? Dai et al. [43], Cao et al. [44], Asnaghi and Ladjevardi [45], and Larbi et al. [46] respectively proposed to build SCPPs to produce agricultural products in their countries. However, they have not further evaluated the performance of the modified SCPP (MSCPP), where vegetation grows in the solar collector besides electricity is generated. In the MSCPP, water is needed for growing vegetation. This is accompanied by water evaporation, which leads to the use of some heat as the latent heat of phase transformation. The collector temperature rise (CTR) and the resulting power output will be reduced greatly.

Recently researchers and engineers have also discussed about the MSCPP. Stinnes [47, 48] claimed that the MSCPP could produce lots of benefits, including stopping climate change by CO_2 sequestration, causing green revolution in agriculture, soil rehabilitation, forestry, desert cultivation, and others. Ademes [49] thought use of water for energy storage could improve the plant performance. Hummel [50] conducted a profitability and risk analysis of power from SCPPs and MSCPPs. Thomashausen [51] claimed that the MSCPPs could solve shortages of power, fuel, food and water and reduce conflict potentials in the world. Pretorius [52] performed numerical simulations of the MSCPP with vegetation incorporated under the collector roof from the collector perimeter of radius of 2500 m to respective radii of 1978 m and 1012 m. He investigated the radial distribution of the ground surface temperature and the relative humidity of the air under the roof and further evaluated the influence of the temperature lapse rate.

In the MSCPP, water evaporation and vapor condensation are two key processes. Water sources mainly consist of the water vapor evaporating from the vegetation area and the vapor contained in the ambient atmosphere. With gradual changes of the vegetation area and the relative humidity of ambient atmosphere, the variation of the main properties of air current inside the MSCPP should be well understood, including the total pressure potential (TPP), the CTR, the mass flow rates (MFRs) of the moist air current and the water vapor evaporating from the vegetation area, and the MFR of condensed water (MFRCW) if condensation occurs. How much vegetation area and how much vapor content of ambient atmosphere will lead to occurrence of vapor condensation in the plant? The chimney height also can affect occurrence of vapor condensation in the MSCPP. Another important issue for the MSCPP development is whether or not the benefit of vegetation is over the benefit loss due to the loss of power output. To date, little comprehensive research that can answer the above questions has been reported.

In this paper, a simplified mathematical model is developed for the MSCPP for both power generation and vegetation, the performance of the MSCPP is studied, and the economics of the MSCPP is compared with those of the conventional SCPP.

2. Mathematical model

Schematic of a MSCPP for both power generation and vegetation is shown in Fig. 1. The height of the collector roof, H, along a radius r (r=0 at the center of the SCPP) is assumed as,

$$H = H_1 \left(\frac{r_1}{r} \right)^b = H_1 r_1^b r^{-b} \tag{1}$$

where b is the exponent. In this paper, the vegetation is located at the area along the radius from point 1 to point 2, where soils are assumed to be wet. The ground along the radius from point 2 to point 3 is considered to be dry.

The energy balance equation can be expressed as:

$$A_{veg}q_{veg} = c_p\dot{m}\left(T_2 - T_1\right) + c_{p,v}\dot{m}_v\left(T_2 - T_v\right) + L\dot{m}_v \tag{2}$$

$$\left(A_{coll} - A_{veg}\right)q_{non-veg} = c_p\dot{m}\left(T_3 - T_2\right) \tag{3}$$

where, T_v is the mean temperature of vapor from the wet soils for vegetation, which is estimated by

$$T_v = \frac{1}{2}\left(T_1 + T_2\right) \tag{4}$$

The constant-pressure specific heat capacity for vapor is $c_{p,v} \approx 1.9c_{p,d}$ and the constant-pressure specific heat capacity for moist air is approximated as $c_p \approx \left(1+1.9w\right)c_{p,d}$. The specific latent heat L can be calculated by [53]: $L = 2502535.259 - 2385.76424\left(T - 273.16\right)$. The MFR of water vapor evaporating from vegetation area $\dot{m}_v$ is given by $\dot{m}_v = \psi A_{veg}$ with ψ being the rate of evapotranspiration from the wet soils per unit area for vegetation. ψ is estimated by

$$\psi = \frac{\dot{m}_v}{A_{veg}} = \frac{kq_{veg} + \left(p_{vs} - p_v\right)h}{\left(k+\alpha\right)L} \tag{5}$$

where, k is the average slope of the curve of the saturated vapor pressure, which is estimated by

$$k = \frac{Lp_{vs}}{R_vT^2} \tag{6}$$

α is the adjusted psychrometric constant, and is given by

$$\alpha = \left(1 + \frac{70h}{\rho c_p}\right)\frac{c_p p}{0.622L} \tag{7}$$

where, p is the static pressure, which is approximately equal to the ambient pressure at the ground level. The saturated vapor pressure within the temperature range between 0 and 100 °C is presented by [54]: $p_{vs} = a\exp\left[\frac{\left(b-(T-273.15)/d\right)(T-273.15)}{(T-273.15)+c}\right]$, where $a = 611.21$ Pa, $b = 18.564$, $c = 255.57$ °C, and $d = 254.4$ °C. The partial pressure of water vapor p_v and the humidity ratio w denoting the vapor mass in 1 kg of dry air, are respectively given by $p_v = \phi p_{vs}$, and $w = 0.622\frac{p_v}{p-p_v}$.

The convection heat transfer coefficient used here is [55]:

$$h = 3.87 + \frac{0.011986 v \rho c_p}{Pr^{2/3}} \tag{8}$$

The MFR of the dry air is

$$\dot{m} = \rho A_{ch} v = \rho A_{ch}\sqrt{\frac{2\Delta p_{poten}}{\rho}} = A_{ch}\sqrt{2\rho\Delta p_{poten}} \tag{9}$$

The density of the moist air ρ is calculated using an equation of state based on the volumetric fractions of two phases [56, 57]:

$$\rho = \frac{p}{R_d T}\frac{0.622(1+w)}{0.622+w} \tag{10}$$

The humidity ratio of the indoor air is considered to be equal to that of the ambient atmosphere here. The expressions of the TPP for unsaturated moist air [56] and saturated moist air [57] have been derived in the forms of:

$$\Delta p_{poten} = p_1 \left(1 - \frac{\left(1 - \Gamma_{um\infty} \dfrac{H_{ch}}{T_1} \right)^{\gamma_\infty / (\gamma_\infty - 1)}}{\left(1 - \Gamma_{um} \dfrac{H_{ch}}{T_3} \right)^{\gamma / (\gamma - 1)}} \right) \tag{11}$$

$$\Delta p_{poten} = p_1 \left(1 - \frac{\left(1 - \Gamma_{um\infty} \dfrac{H_{ch}}{T_1} \right)^{\gamma_\infty / (\gamma_\infty - 1)}}{\left(\left(1 - \Gamma_{um} \dfrac{H_s}{T_3} \right)^{\gamma / (\gamma - 1)} \left(1 - \Gamma_m \dfrac{\left(H_{ch} - H_s \right)}{T_s} \right) \right)^{0.021233(1+w_s)/(\Gamma_m (w_s + 0.622))}} \right) \tag{12}$$

where $\Gamma_{um\infty}$, Γ_{um} and Γ_m are the adiabatic lapse rates of temperature for the ambient unsaturated moist air, the inward unsaturated moist air and the inward saturated moist air, respectively. The air current undergoes cooling during the ascending process, and the three adiabatic temperature lapse rates are in the forms of [56, 57]: $\Gamma_{um\infty} = \dfrac{g\left(1 + w_\infty\right)}{c_{pd}\left(1 + 1.9 w_\infty\right)}$, $\Gamma_{um} = \dfrac{g\left(1 + w\right)}{c_{pd}\left(1 + 1.9 w\right)}$, and $\Gamma_m = g \dfrac{\left(1 + \dfrac{L w_s}{R_d T_s}\right)}{\left(c_{pd} + \dfrac{0.622 L^2 w_s}{R_d T_s^{\,2}}\right)}$, where w_s and T_s are respectively the air humidity ratio and the temperature at the condensation level in the solar chimney. T_s can be given by $T_s = T_3 - \Gamma_{um} H_s$ where H_s is the height of the condensation level inside the SC. The temperatures in the chimney at an arbitrary height under the two conditions can be expressed as, respectively,

$$T = T_3 - \Gamma_{um} h \text{, for non-occurrence of condensation} \tag{13}$$

$$T = T_3 - \Gamma_{um} H_s - \Gamma_m \left(h - H_s \right) \text{, for occurrence of condensation} \tag{14}$$

The MFRCW is estimated by

$$\dot{m}_{con} = \dot{m}\frac{w}{1+w} - \dot{m}\frac{w_{4m}}{1+w_{4m}} \tag{15}$$

The TPP is the sum of the turbine pressure drop and the total pressure loss. Here, the total pressure loss of the SCPP is given by [58]

$$\Delta p_{TL} = \frac{1}{2}\dot{m}^2 \begin{pmatrix} \varepsilon_{coll,i}\dfrac{1}{\rho_1 A_1^2} + \dfrac{c_{f,roof}+c_{f,p}}{4\pi^2(3b-1)H_1^3\rho_{coll}}\dfrac{r_1^{3b-1}-r_3^{3b-1}}{r_1^{3b}} + \dfrac{C_{sD}d_s}{4\pi^2\rho_{coll}P_t H_1^2 r_1^{2b}}\displaystyle\sum_{r=r_3}^{r=r_1} r^{2(b-1)} \\ +\varepsilon_{turb,i}\dfrac{1}{\rho_3 A_3^2} + \left(f_{ch}\dfrac{H_{ch}}{D_{ch}} + nK_{SA}\right)\dfrac{1}{\rho_{ch}A_{ch}^2} + \left(1+\varepsilon_{ch,o}\right)\dfrac{1}{\rho_4 A_4^2} \end{pmatrix} \tag{16}$$

The power produced from the turbine-generators is expressed as,

$$P = \eta_{tg}\dot{m}\frac{\Delta p_{turb}}{\rho_3} = \eta_{tg}\dot{m}\frac{\Delta p_{poten} - \Delta p_{TL}}{\rho_3} \tag{17}$$

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

3. Model validation

The present model is validated by comparing the simulation results with the published data from experiments [59]. This pilot SCPP was built in Manzanares, Spain in 1982, and was in continuous operation for about seven years. The geometric parameters of the Manzanares prototype and the climate conditions are introduced in the simulations. The chimney is about 194.6 m in height and 5.08 m in radius. The collector is 122 m in radius and the roof height is about 1.85 m above the ground. The measured solar radiation, ambient pressure and ambient temperature at 12:00 on September 2nd, 1982 were 850 W/m^2, 93900 Pa, and 23.5 °C, respectively [59]. The collector efficiency obtained by [59] in the pilot plant and the turbine pressure drop factor recommended by [59] are used. The vegetation under the collector and air humidity are not considered in the validation work. The losses due to the collector support drag force and the drag force by the chimney internal appurtenances are not considered. Comparison between the simulation results and experimental data is given in Table 1. The calculated power output in this paper is in good agreement with the theoretical power output of 40 kW estimated by Haaf [59] based on the CTR of 17.5 K, but is slightly higher than the measured power output of 36 kW. The losses at the turbine in the experiments should be responsible for the small decrease in the power output [59].

4. Results and discussion

A reference plant is used for the study of the performance of the MSCPP. The main parameters of the reference plant, the main conditions of the ambient atmosphere, and some parameters of the turbines are presented in Table 2. The effective heat flux of the collector section without vegetation covered and that of the collector section with vegetation covered definitely will influence the performance of the MSCPP, but the influence of the two effective heat fluxes is not considered here. Accordingly, the two effective heat fluxes are specified as the same constant.

Figs. 2 and 3 shows the effect of the ratio of the vegetation area to the collector area (RVC) on the CTR, the MFR of air current, the MFR of the vapor from the vegetation area and the MFRCW, and the power output on a hot day. As expected, with the vegetation area enlarging, more heat is used as the latent heat for water evaporation. Accordingly, the CTR becomes lower as well as the MFR of the air current. The resulting power output for RVC=1 decreases by 74.3% compared to the conventional SCPP. Besides, the MFR of the vapor evaporating from the vegetation area increases. When the RVC is bigger than or equal to 0.95, the condensation from the saturated air occurs, and the MFRCW for the RVC of 0.95 reached 1.16 kg/s (Table 3).

Solar radiation intensity and ambient temperature can change the performance of the SCPPs more or less. Weaker solar radiation decreases the power output considerably, while lower ambient temperature increases the power output slightly [56]. In order to demonstrate the influence of the solar radiation intensity, we investigate the performance of the MSCPP on a cool day when the effective heat flux of the collector with or without vegetation covered is specified as 250 W/m^2 and the ambient temperature as 10 °C, as shown in Figs. 4 and 5. Due to weaker solar radiation, the CTR and the MFR of air decrease, and so the plant produces less electric power. The condensation occurs when the RVC is bigger than or equal to 0.86 and once the condensation occurs, the MFRCW becomes larger for the same RVC as that on the hot day as shown in Fig. 3. This is attributed to the fact that lower inward temperature due to both lower ambient and weaker solar radiation gives rise to lower saturated vapor pressure and increases the possibility of condensation and the volume of the condensed water for the same humidity ratio of ambient air as that on the hot day. However, whether on a hot day or on a cool day, in the chimney 1000 m in height, the volume of the fresh water condensed is very small.

The humidity ratio of the air will influence the volume of fresh water condensed. In order to study the influencing degree, the variations of the CTR, the TPP, the MFRCW and the power output for RVC=0.93 on the hot day with the relative humidity of ambient air are shown in Figs. 6 and 7. Higher relative humidity of ambient air results in clear reduction of the MFR of the vapor evaporating from the vegetation area. Accordingly, the product of the CTR and the MFR of air current determined by the TPP increases by based on the relationship $A_{veg}q_{veg}+\left(A_{coll}-A_{veg}\right)q_{non-veg}=c_p\dot{m}\left(T_3-T_1\right)+\dot{m}_v\left(c_{p,v}\left(T_2-T_v\right)+L\right)$ obtained from Eqs. (2) and (3). This leads to the increase of the values of the three parameters, i.e., the CTR, the MFR of air and the TPP. Finally, the power output is greatly enhanced. When the relative humidity of ambient air is not lower than 96%, the vapor condensation will occur in the chimney. The MFRCW reaches 0.36 kg/s for the relative humidity of ambient air of 96%.

Fig. 8 shows the CTR, MFRCW, and power output for the chimney height of 1500 m on a hot day versus RVC. In this figure, the power output is enhanced greatly, and the volume of the condensed water is increased, as compared to the case for the chimney 1000 m in height. Higher chimney of 1500 m leads to the improvement of the TPP and the MFR of the air current, and therefore the reduction of the CTR for a constant effective heat flux of solar collector. This causes considerable enhancement of the power output as the chimney height increases from 1000 m to 1500 m. In the chimney 1500 m in height, the air entering the chimney through the collector outlet becomes cooler due to lower CTR, and undergoes longer-distance temperature lapse process. This results in lower saturated vapor pressure and the clear increase in the probability of condensation and the volume of the condensed water.

Without doubt, the considerable reduction of the power output leads to a great loss of benefit. However, the agricultural products brings additional benefits together with fresh water condensed from the saturated air. The net added benefit analysis due to the agricultural products estimated according to the market prices of the electricity, agricultural products, and fresh water is performed and shown in Fig. 9. Here, the electricity price is specified as 0.6 CN Yuan, the net income per m^2 agricultural area in a greenhouse as 30 CN Yuan, and the price of fresh water per ton as 2.5 CN Yuan. The location site of the plant is assumed with an annual global solar radiation of 2000 kWh/m^2 and the collector efficiency is assumed to be 60%. From this figure, it is found that the benefit due to fresh water condensed from the saturated air is negligible, and the benefit from the agricultural products is larger than the benefit loss caused by the electricity loss.

This leads to net added benefit for the MSCPP compared to the conventional plant. Moreover, the net added benefit becomes greater with larger vegetation area.

The net added benefit analysis due to the vegetation for the chimney height of 1500 m is shown in Fig. 10. For the same RVC, the loss of electricity for the chimney height of 1500 m is much larger than that for the chimney height of 1000 m. The increase of the benefit from much larger volume of fresh water condensed from enough large vegetation area due to the heightening of the chimney is very small. Therefore, the net added benefit becomes smaller when the chimney height increases from 1000 m to 1500 m.

5. Conclusions

This paper develops a mathematical model of MSCPPs. The performance of an MSCPP for purposes of both power generation and vegetation is investigated. The influence of main parameters including solar radiation, ambient temperature, relative humidity, and chimney height is examined. Finally, the net added benefit of the products including electricity, agricultural products and fresh water for the chimney heights of 1000 m and 1500 m is estimated. The following conclusions are obtained.

(1) With the vegetation area enlarging, more heat is used as the latent heat for water evaporation, and therefore both the CTR and the MFR of the air current become lower. The resulting power output for RVC=1 on a hot day decreases by 74.3% compared to the conventional SCPP. Besides, the MFR of the vapor evaporating from the vegetation area increases. When the RVC is bigger than or equal to 0.95, the condensation from the saturated air occurs.

(2) As compared to the situation on the hot day, on a cool day, due to weaker solar radiation, the CTR and the MFR of air current decrease, and the plant produces less

electric power. The condensation occurs when the RVC is smaller and once the condensation occurs, the MFRCW becomes larger for the same RVC.

(3) Higher relative humidity of ambient air results in clear reduction of the MFR of the vapor evaporating from the vegetation area, and accordingly the increase of the CTR, the MFR of air and the TPP, thus leading to the greatly enhancement of the power output.

(4) When the chimney is heightened from 1000 m to 1500 m, the power output is enhanced greatly, and the volume of the condensed water is clearly increased.

(5) The benefit due to small volume of the fresh water condensed is negligible. The benefit from the agricultural products is larger than the benefit loss caused by the electricity loss. This leads to net added benefit for the MSCPP compared to the conventional plant. The net added benefit becomes greater with larger vegetation area, but smaller due to the chimney height increasing from 1000 m to 1500 m.

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Nomenclature

A	area (m^2)
b	roof shape exponent
c_p	constant-pressure specific heat capacity (J/kg K)
D	diameter (m)
g	gravitational acceleration, 9.81 (m/s^2)
H	height (m)
h	convection heat transfer coefficient (W/m^2 K)
k	slope of curve
L	specific latent heat (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	power (W)
Pr	Prandtl number
p	pressure (Pa)
q	effective heat flux (W/m^2)
R	specific gas constant (J/kg K)
T	temperature (K)
v	velocity (m/s)