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Modeling of Solar Updraft Tower Power Plants: A Review

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Abstract: Solar updraft tower power plants, or SUTPP, are thermal power plants consisting of three parts: a solar collector, a power conversion unit (turbine), and a solar chimney. Different configurations of SUTPP models were presented in the previous studies. However, the type used in the modelling of SUTPP elements with the variables used is not highlighted. Therefore, a modelling approach to improving or investigating the SUTPP is reviewed in the present work. Modeling can be broken down by which part of the solar chimney power plant was used. Predictive, thermal, and simulation models were used for the solar collector and chimney, while analytical and simulation models were used for the wind turbine power unit. used in the modelling have been addressed, such as airflow velocity, the temperature distribution in the collector, air temperature and pressure leaving the collector, output temperature from the collector, coefficient of heat transfer by convection, power produced, SCPP efficiency, and the thrust factor of the wind turbine. The review study is of great importance to maximize the power produced and efficiency by comparing multiple models.

Keywords: Solar energy, modeling, solar chimney, solar collector, turbine, power generation

1. Introduction

To overcome the environmental pollution resulting from the use of fossil fuels as well as the decrease in the quantities of this fuel due to its consumption. Solar energy has emerged as a substitute use of fuels of fossil as well as reduces the negative impact on the environment [1]. The market for solar energy applications is still low, where the energy generated from photovoltaic cells is approximately 2.6 gigawatts, compared to 36.3 gigawatts used in the rest of the renewable energies applications [2-4].

The irradiance intensity on a particular location is a significant tool for designing the solar thermal power plant [5]. The solar map provides the annual global horizontal irradiance, GHI, as shown in Fig. 1. The average irradiance is based on hourly data of GHI provided by satellite imagery for more than 10 years [6].

The solar updraft tower power plant, SUTPP, or the solar chimney power plant, SCPP, are classified as low temperature thermal collectors (less than 100 °C) that utilize the natural air for transfer heat [7]. The main parts of the SCPP shown in Fig. 2 are the solar collector, updraft tower (chimney), and turbine. Surroundings air is heated under the diaphanous collector cover because of solar irradiance energy absorbed. Due to the opening of the solar collector cover around its perimeter, the hot air draws toward the center of the solar collector continuously from the perimeter of the collector to the tower. The solar chimney (or tower) acts as a heat engine that extracts the hot air vertically from the high-temperature zone at the tower base (collector center) to the low-temperature zone at the tower outlet. A wind turbine is placed at the base of the tower to transform the kinetic energy of inflow air into the tower to electrical energy. The geometrical parameters (height and diameter of chimney and collector) and operational parameters (solar radiation intensity, hot air temperature, and pressure difference in the chimney) for the SCPP are of importance in the design of the power plant [8-12].

The SUTPP technique and investigation were reviewed in different ways. Xinping and Yangyang [13] reviewed the SUTPP technology with a description of its characteristics and the factors used in the theoretical model. The electricity produced by SUTPP has no negative impact on the environment, and it can also be a promising alternative energy to

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fossil fuels. But, there are several drawbacks to the SUTPP which are high investment, low efficiency, and limited height of the tower (chimney). Pradhan et al. [14] presented a detailed review for designing and comprehension of the SCPP units. The dimensions parameters of the SCPP parts, power produced, heat transfer, fluid flow, and thermal efficiency have been described to achieve the desired effective design.

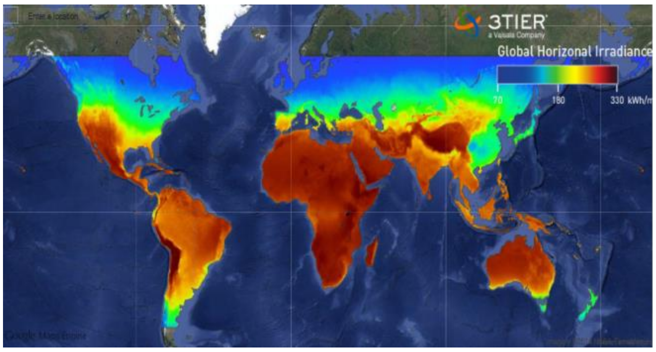

Fig. 1 - Global Horizontal Irradiance map dataset created by 3TIER [6]

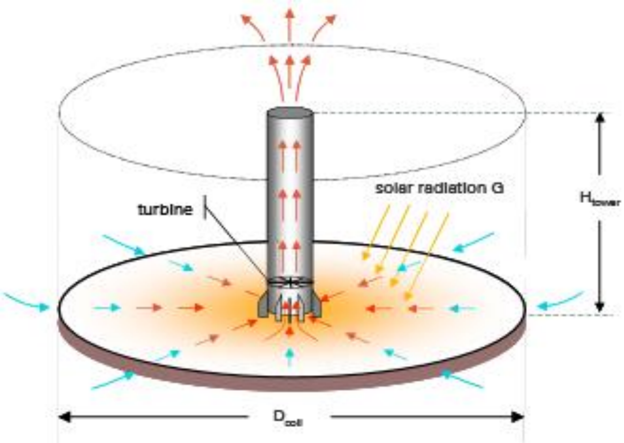

Fig. 2 - The main parts of the SCPP; solar collector, chimney, and turbine [12]

In this paper, the various configurations of the SUTPP were introduced, and the type of improving or investigating models performance was presented. Modeling different shapes with multiple variables can lead to a better understanding and improvement of system performance. Modeling can be categorized based on the part used in the SCPP. The present work aims to review the modeling state of the SUTPP used in the research approach to understand how to improve and maximize the power produced and efficiency by comparing multiple models. Validation of predictive modeling is of importance by comparing with experimental results as possible.

2. Modeling Methodology

2.1 Predictive Models

Several studies have been conducted to model the SUTPPs or SCPPs; part of it was implemented in the form of numerical models to solve the SCPP problems. The purpose of numerical models is to predict the power output and/or performance of the SCPP. Gholamalizadeh et al. [15] and Asnaghi et al. [16] presented a numerical model that was built to estimate the performance of the SCPP. Equations used for modeling show that the buoyant hot air under the collector cover aids the airflow, and the convection heat transfer is increased by forced flow, where the compressibility effects are modeled by the Boussinesq approach [16]. By applying the continuity or transport equation, the distribution of air velocity in the airflow domain is expressed as the following equation [15]:

$$v_{(r)} = \frac{R_c^2 \rho_{(r=0)}}{r H_{coll(r)} \rho_{(r)}} \sqrt{\frac{g H_c \left(T_{(r=0)} - T_a\right)}{6 T_a}} \tag{1}$$

While the temperature distribution in the collector is expressed as:

$$\frac{dT}{dr} = \frac{2r\left(q''_{gf} + q''_{rf}\right)}{\rho_{(r=0)} v_{(r=0)} R_c^2 C_p} \tag{2}$$

Otherwise, Chitsomboon [17] proposed a theoretical model for predicting the performance of the SCPP using the quasi-one-dimensional Euler's equation. Atit et al [18] constructed the SCPP elements according to a mathematical model which solved by repetition technique. The model is used to predict important factors for improving the SCPP performance such as the plant size, solar intensity, and turbine pressure drop. By applying the conservation equations for the airflow within the collector, the air temperature and pressure leaving the collector are expressed as follows:

$$P_2 = P_1 + \frac{mq''}{2\pi h_r^2 \rho_1 C_p T_1} ln\frac{r_r}{r_c} - \frac{m^2}{2\rho_1}\left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right) \quad (3)$$

$$T_2 = T_1 + \frac{q'' A_r}{mC_p} \quad (4)$$

Tingzhen et al. [19] developed a structural model of the SUTPP system with outside ambience. The heat transfer by air flow and output power of the system has been described by a mathematical model. While a comprehensive numerical model that describes the SCPP performance was developed by Bernardes et al. [20]. This model estimates the power produced from the plant and examines the influence of different structural dimensions and ambient conditions on the power produced. Dai et al. [21] provided an analytical model with various parameters, such as solar collector diameter, the height of the chimney, irradiance intensity, temperature of ambient, and the efficiency of the wind turbine, which affect the power generation for the SUTPP. At high latitudes, Bilgen et al. [22] designed the SCPP system to produce power and its performance has been assessed. A mathematical model and its solution have been built by a MATLAB code based on the data of the average monthly meteorological.

New investigation techniques were utilized to predict the power efficiency of the SCPP. Vieira et al. [23] studied the effect of construction factors on the SCPP and temperature of the ground surface (absorber) on the power produced numerically by using the Constructal theory. The freedom degrees were taken for the constraints of the present geometry as follows; R/H for the collector radius to height, R1/H2 for the chimney radius to height, and H1/H for the collector base height to inlet height. A 2D k-ε turbulence model with the conservation equations has been solved using the CFD procedure. It was concluded that the most obvious effect was the temperature of the ground over the power output and the geometrical factors. Hannes et al. [24] modeled numerically the humid air by using the gas dynamics principles within a tilt solar collector, solar chimney, and wind turbine that constructed the SCPP. The physical parameters with a compressible air in a low Mach number were modeled to simulate and optimize the process of hot air from the collector inlet to the chimney exit. Teja et al. [25] modeled the SUTPP parts for the power produced mathematically with validation of the model results against the Manzanares prototype data. Losses from the top surface of the solar collector have been considered in the current model, which is the radiation and convection heat transfer to estimate the efficiency of the collector. Furthermore, the influence of the radius of the collector and chimney, and the height of the chimney on the generated power was studied.

2.2 Thermal Models

Studies based on the thermal model have addressed the methodological problems of power generation by hot floating air with variable density, energy balance, and thermodynamic process. Mohammad [26] developed a mathematical thermal model to estimate the plant performance relied on the dimensions of SUTPP and working conditions. The discretization of this model with changeable density is extra convenient than using the Bernoulli approach through the solar chimney with fixed density. The greatest power could produce from the SUTPP is relying on choosing the best type of turbine used or the best airflow rate. The output temperature from the collector is calculated by:

$$T_2 = T_1 + \frac{q''}{U}\left[1 - exp\left(\frac{-\pi U(r_2^2 - r_1^2)}{mC_p}\right)\right] \quad (5)$$

Otherwise, thermal equilibrium in the collector takes account of the comprehensive theoretical model built by Jing-yin et al. [27], where the temperature distribution in the collector is described as follows:

$$\frac{dt_f}{dr} = \frac{2\pi r}{mC_p}\left[h_{w,f}\left(\frac{(I_{ra} - q_{w,c}) + h_{w,s}(t_s - t_f)}{h_{w,f} + h_{w,s}}\right) - h_{f,c}\left(\frac{h_{c,a}(t_f - t_a) - (q_{w,c} - q_{c,s})}{h_{c,a} + h_{f,c}}\right)\right] \quad (6)$$

Roozbeh [28] and Pasumarthi et al. [29] developed a mathematical thermal model that relied on the balance of energy to predict the power produced from the SCPP and to assay the influence of different geometrical dimensions and ambient conditions on the power produced. While Petela R. [30] carries out a simplified model of the SUTPP and develops various probable thermodynamic operations that happen within the SUTPP components, which are relying on the balance of energy.

Panse et al. [31] considered the total energy balance by a developed mathematical model that estimates the air velocity and temperature, and kinetic energy of the extracting airflow from an inclined solar chimney, also predicts the constructal dimensions of the solar chimney used. The Bernoulli's approach applied at the inlet end of the solar chimney is:

$$P_{AI} + H\rho_{AI}g = P_{AO} + H[0.5(\rho_{CI} + \rho_{CO})]g + (0.5)\rho_{CI}(V_{CI})^2 \tag{7}$$

For a variable air temperature and pressure, the Bernoulli's equation becomes:

$$P_{AO} + H(\rho_{AI})\left(\frac{1.9840}{2}\right)g = P_{AO} + 0.5\left[\rho_{CI} + 0.9774\rho_{CI}\left(\frac{T_{CI}}{T_{CO}}\right)\right]Hg + (0.5)\rho_{CI}(V_{CI})^2 \tag{8}$$

2.3 Simulation Models

Models used to simulate the performance of the SCPPs are involved with various methodologies types such as; numerical simulation using the CFD software FLUENT, the numerical model simulated for one-dimensional buoyancy flow, simulation of a simple mathematical model, or calculations using FLUENT as a simple model.

For sloped SCPP, Atit Koonsrisuk [32] built an advanced numerical model that relied on the state and conservation equations; in which the mathematical model was solved numerically using an iterative technique. While Fei Cao et al. [33] presented a simulation of the solar power plant to equip electrical energy for faraway rural towns. Increasing temperature and velocity of the airflow, the efficiency of the solar collector, and the performance of sloped SCPP are simulated with a simplified mathematical model.

Roozbeh et al. [34] introduced a numerical model that relied on the conservation equations of continuity, momentum, and energy to depict the working technique of the SUTPP. The k-ε turbulence model was carried out for the structural dimensions of the Manzanares prototype using ANSYS-FLUENT software. Because of the solar radiation transmitted through the glass cover of the collector, the coefficient of heat transfer by convection between the airflow inside the collector and the glass cover on the one hand, and between it and the collector floor surface, on the other hand, can be expressed respectively as follows:

$$h_c = \left(\left(Nu_f\frac{\lambda_f}{2H_c}\right)^4 + \left(Nu_c\frac{\lambda_f}{H_c}\right)^4\right)^{\frac{1}{4}} \tag{9}$$

$$h_e = \left(\left(Nu_f\frac{\lambda_f}{2H_c}\right)^4 + \left(Nu_e\frac{\lambda_f}{H_c}\right)^4\right)^{\frac{1}{4}} \tag{10}$$

Koonsrisuk et al. [35] carried out a comparative study of the performances of SCPPs that predicted from five numerical and theoretical models. A simulation model by using CFD software was managed and a comparison between the outcomes of the simulation and predictions was achieved. The results of power produced and the SCPP efficiency were utilized to contrast relative features of the theoretical models within the framework of this study according to the following authors:

Model (1) by Chitsomboon [36]:

$$\frac{1}{2}mV_3^2 = \frac{gh_c q''A_r/c_pT_3}{\left\{1 + \frac{gh_c}{\gamma RT_1}\left[\left(\frac{r_c^2}{2r_rh_r}\right)^2 - 1\right] + \frac{q''}{\rho_1V_3c_pT_1}\frac{r_c^2}{h_r^2}ln\frac{r_c}{r_r}\right\}} \tag{11}$$

$$\eta = \frac{\frac{1}{2}mV_3^2}{q''A_r} \tag{12}$$

Model (2) by Schlaich et al. [12]:

$$\frac{1}{2}mV_3^2 = \frac{1}{2}\rho_3A_c\left(2gh_c\frac{\Delta T}{T_1}\right)^{\frac{3}{2}} \tag{13}$$

$$\eta = \frac{gh_c}{c_p T_1} \tag{14}$$

Model (3) by Tingzhen et al. [37]:

$$W = \frac{\rho_1}{\rho_3}\frac{\pi g}{c_p T_1} h_c r_r^2 q'' \tag{15}$$

$$\eta = \frac{\rho_1}{\rho_3}\frac{gh_c}{c_p T_1} \tag{16}$$

Model (4) by Zhou et al. [38]:

$$W = 0.00353\,\frac{gh_c \pi r_r^2 q''}{c_p \rho_3} \tag{17}$$

$$\eta = 0.00353\,\frac{gh_c}{c_p \rho_3} \tag{18}$$

Model (5) by Koonsrisuk and Chitsomboon [39]:

$$\frac{1}{2} m V_3^2 = \frac{q'' A_r \beta}{c_p} gh_c \tag{19}$$

$$\eta = \frac{\beta g h_c}{c_p} \tag{20}$$

Comparing the results of the five models with the CFD results showed that; the best foretelling of qualitative values is obtained by model 1, while the rest of the models have the property of ease of application in addition to the preference in the reasonable results were observed through Model 2 and 5.

Henry et al. [40] simulated the turbine, the chimney, and the solar collector of SUTPP numerically to describe the plant operation and to improve the efficiency. The parameters of air mass inflow and drop of pressure through the wind turbine have a significant impact on the efficiency. Xinping et al. [41] investigated the power produced from the solar chimney with outlet flow across an atmospheric stream by using a 3D numerical model, while Xinping et al. [42] implemented a numerical simulation to examine the performance of the SCPP using a developed model. Also, the power generation has been tested under various parameters such as; the height of the chimney, the area of the collector, and the solar radiation.

Marco et al. [43] compared the analysis style used in the researches presented by Pretorius et al. [44] and Bernardes et al. [20], where the influence of various models of heat transfer on the SCPP performance have been investigated. The equations of convection heat transfer by natural and forced mode utilized in the Pretorius and Bernardes models were assessed numerically by writing the arithmetic code.

Modeling of the SCPP using the CFD technique to mimic heated airflow within the solar collector and the solar chimney has been achieved by Muhammed and Atrooshi [45] and Murena et al. [46], respectively. Models results were validated by comparing them with the experimental data for each research. Muhammed and Atrooshi [45] offered an optimization between operational parameters (air temperature, pressure, and velocity) and geometrical parameters (collector diameter and height) for the collector diameter ranging from 20 m to 220 m. The optimized relationships provide the possibility to choose the required dimension in the collector against the operating factors, or to choose the speed or temperature for the diameter of the collector that intends to implement for the SCPP. Murena et al. [46] modeled the solar chimney using the CFD technique to mimic the thermal-hydrodynamic behavior. The studied parameters provided correlation equations between the airflow in the stack and the temperature, solar radiation, and relative humidity, which are useful in the design of the solar chimney. The obtained correlation equation of the air velocity in the chimney in related to temperature difference is:

$$V = 0.0863\left[q\left(\frac{T}{T_a}\right)\right]^{0.446} \tag{21}$$

Where: q is solar radiation, T is air temperature within the chimney, and T_a is the ambient temperature.

2.4 Turbine Modeling

The power conversion unit used at the base of the tower (chimney) in the SUTPP is the wind turbine. The kinetic energy of the air leaving the solar collector is used to change it into mechanical energy. The type of wind turbine that can be used to extract energy from flowing air is either a horizontal axis wind turbine (HAWT) or a vertical axis wind turbine (VAWT) depending on the type of power plant design. Habtamu et al. [47] presented a mathematical model of unsteady air stream flowing through the VAWT. The purpose of applying the model is to predict the performance of a straight blade NACA0018 of VAWT structure at low air velocity. The thrust factor, C_T, of the wind turbine working can be described as the following expression:

$$C_T = \frac{Thrust\ force}{Dynamic\ force} = \frac{T}{\frac{1}{2}\rho A V^2} \tag{22}$$

The thrust force at any moment that impacts one blade of the turbine at a specific angle is shown below:

$$T_i = \frac{1}{2}\rho V_R^2 (h_c)(C_t cos\theta - C_n sin\theta) \tag{23}$$

The relative velocity, V_R, of the turbine blade to the velocity of the air stream banging the turbine blades can be described by:

$$\frac{V_R}{V_\infty} = \sqrt{\left(\frac{V_a}{V_\infty} sin\theta\right)^2 + \left(\frac{V_a}{V_\infty} cos\theta + \frac{\omega R}{V_\infty}\right)^2} \tag{24}$$

Denantes et al. [48] introduced an advanced model based on the efficiency at a design point for the type of turbines of counter-spinning with the performance model of off-design for this type of the turbines to predict the performance and the power produced. While Fluri et al. [49] investigated wind turbine models analytically and made the most effective mechanism to evaluate the performance based on different design parameters. Nianxin et al. [50] simulated the airfoils of wind turbines based on the 2D turbulence model k-ω to examine viscous airflow across the turbine blades under different surface roughness.

3. Discussion of Outcomes

The aforementioned SUTPP can be utilized for power production, the technical practicability of which has already been proven. The impact of operational, surroundings, and the unit dimensions parameters on the power generation can be explained and discussed. When the height of the chimney increases, the drop of pressure through the chimney grows. Therefore, the mass flow rate of air and the power produced will increase. The air temperature leaving the collector increases when the area of the collector increases. Thus, the mass flow rate of air and the power produced will increase too, as revealed in Fig. 3 [18][20][34][41][43][44].

Figure 4 shows the impact of solar radiation and temperature on the power produced. The results prove that the power produced increases when the solar radiation and surrounding temperature rises. The SCPP is capable of producing electricity up to 210 kW when the solar radiation is 700 W/m2 and the surrounding temperature is 25 °C. Fig. 5 shows that the greater electricity can be obtained from the SUTPP when the height of the chimney and the collector diameter are increasing. It is shown that the power produced raises non-linearly when the height of the chimney and the diameter of the collector increase. Also, the electricity of 800 kW can be obtained from the SCPP when the height of chimney is about 300 m and the collector diameter is 900 m [21][26][28].

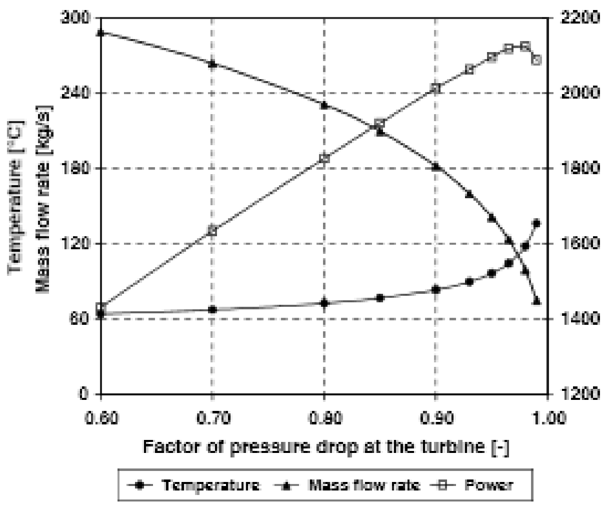

Fig. 3 - Air temperature, mass flow rate, and the power produced from the SCPP versus the turbine pressure drop coefficient [43]

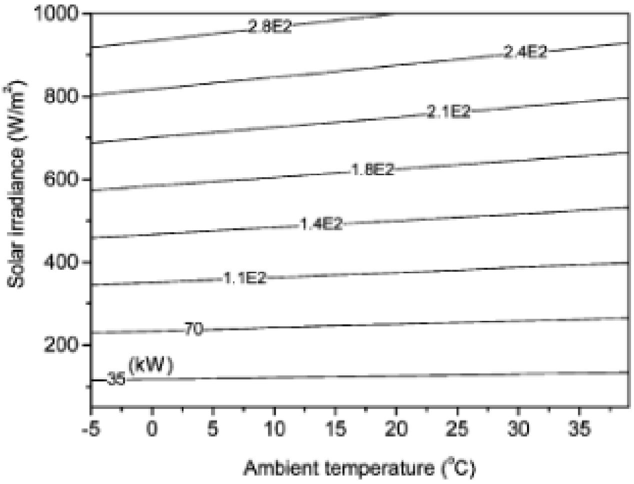

Fig. 4 - Impact of solar radiation and temperature on the power produced [44]

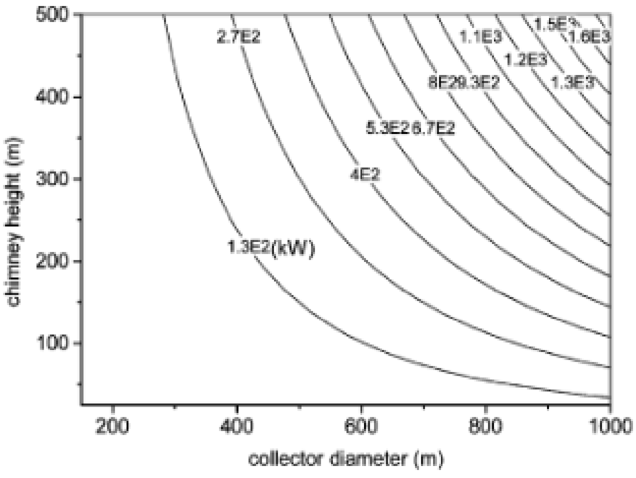

Fig. 5 - Impact of the height of the solar chimney and the collector diameter on the power produced [44]

4. Conclusions

Solar updraft tower power plants, SUTPPs, have been modeled by using different configurations. The present work highlights the type used in the modeling of SUTPP to understand how to improve the power produced and efficiency by comparing multiple models. The models equations were solved either numerically or analytically and the simulation models were achieved using the commercial program FLUENT. The results obtained are in a good agreement with the data measured from the Manzanares site.

It is found that the wind velocity has a significant effect on the airflow process, transport phenomenon of heat, the power produced, and the performance of the SUTPP. The power output increases with increasing mass flow rate obtained for two reasons; firstly by increasing the height of the chimney that raises the pressure drop through it, and secondly by increasing the diameter of the collector. The maximum power was obtained if the height of the chimney was equal to the optimum level of the tower from the ground. By increasing the coefficient of heat transfer, the transfer of heat intensity to the airflow increases while reducing heat storage in the ground.

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