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Matlab graphical user interface (GUI) code for solar tower power plant performance calculations

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Abstract

In the present research, a Matlab program with a graphical user interface (GUI) has been established for studying the performance of a solar tower power plant (STPP). The program gives the ability for predicting the performance of STPP for different tower dimensions, ambient operating conditions and locations. The program is based on the solution of a mathematical model derived from the heat and mass balance for the tower components. The GUI program inputs are; tower dimensions, solar radiation, ambient temperature, pressure, wind velocity, turbine efficiency, emissivity and absorptivity for collector and ground and thermal conductivity and thickness for ground. However, the GUI program outputs are; temperature and pressure differences across the collector and tower, velocity in the tower, density of air in collector outlet, mass flowrate of air, efficiency for collector and tower, the overall efficiency and output power of STPP. The effect of the geometrical dimensions of STPP and some climatic variables on the plant performance was also studied. The results show that the output power increases with increasing the collector diameter, chimney diameter and solar radiation by an increasing of 0.282 kW/m, 0.204 kW/m and 0.046 kW/(W/m2) respectively.

Keywords: Matlab, graphical, solar tower power plant, GUI program.

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1. Introduction

Solar tower power plant also called a solar chimney power plant (SCPP) represents an important tool for converting solar energy into electric energy. It has the advantage of the ability of constructions in any region where solar energy is available. An STPP in general consists from three parts, as shown in Fig.1, collector, tower and wind turbine. The solar radiation is absorbed by the collector and converted to thermal energy. The air inside the collector warm up and finally, with the natural warm air displacement, the thermal power is converted to electrical power by installing a turbine. The performance calculations for STPP are important for estimation the best dimensions, location and operating conditions.

The first model around which studies and investigations have been conducted into the manufacture of the solar chimney in the city of built-in Manzanares, Spain in 1982 that produced 50 kW [1].

Through researches and studies presented by researchers during the last 38 years (1982-2020), it was found that most of these studies were aimed at knowing and improving the performance SCPP by knowing of factors that affect this performance.

Hammadi [2] presented a mathematical model for studying the influence of several parameters on the STPP performance such as collector diameter, height and diameter of the chimney, solar radiation and wind velocity according to Basrah climate conditions. Hannun et al. [3] presented a theoretical study to know the impact of the shape of the collector base and also the effect of several storage materials on the STPP performance. He concluded that a circular collector base and black Pebble storage plate increase the output power of the solar chimney.

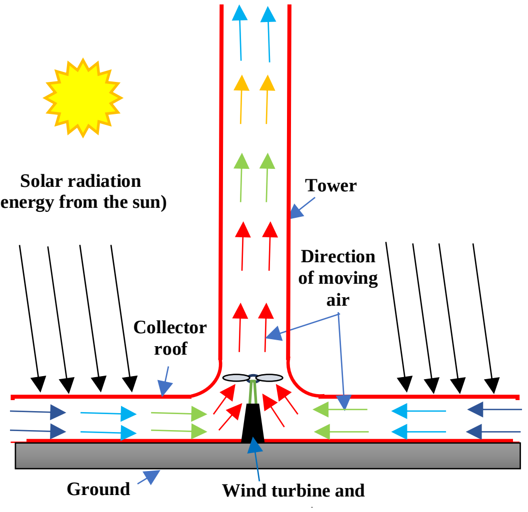


Fig.1 general diagram of STPP.

Ali [4] proposed a model of the solar tower and studied impact collector area, tower height, tower diameter and solar radiation on solar tower power output depending on Manzanares model and climate conditions of city Baghdad in Iraq. He concluded that with the increase of these variables, the output power of the solar tower increases in varying proportions of solar depending on the variable used. Khalaf [5] studied of theoretical and experimental behavior of the model solar chimney power plant conditions in the city of Nasiriya-Iraq. Hamdan [6] proposed a theoretical model for predicting the performance of an STPP. This model shows that, as the chimney height and diameter increase the exergy efficiency and power harvested also increase.

Tan and Wong [7] showed that the most important parameters that influencing the airspeed are the solar chimney width, the ratio of the length of the solar chimney to hydraulic diameter which is must not be less than 15 to ensure developed flow and another ratio which is the solar chimney stack height proportional to the width which should be less than seven this is when the airflow in the solar chimney is to be two dimensional.

Koonsrisuk and Chitsomboon [8] proposed the use of variables that is dimensionless to conduct the experimental study of flow in a small-scale power plant for a solar chimney to generate electricity. The similarity of the dimensionless variables that is proposed is confirmed by computing fluid dynamics. Jalil and Khalaf [9] showed that the increasing the inclination angle of heat flux and chimney thickness lead to increase the flow rate.

Aja et al. [10] slowed the influenced of wind velocity and wind direction on the performance of solar chimney facing toward south inclination then it was found that the wind velocity had more effect on convective heat loss through the walls and the cover to the ambient. Von Backstrom and Fluri [11] both have analyzed the influence of the volumetric airflow on chimneys power output and different working conditions for turbine and aerodynamic losses the range of the pressure value drop that was predicted from the analysis had an agreement with that which were predicted by different researchers.

The present study aims to design a Matlab GUI code for the performance calculations of STPP to be easily used by the users who works in the field of the design and evaluation of STPP.

2. Theoretical Analysis

The mathematical model for STPP is based on energy balance for each part of the collector and flow equation for chimney. Also, the equation of heat transfer for the coefficient of transfer by conduction, convection and radiation.

To solve the mathematical model, some of the following assumptions were used:

Steady state, one dimensional radial flow of the ideal gas (air) inside the collector, air friction losses are neglected, no heat losses from the chimney walls and the temperature of the air inlet to the collector is equal to the ambient temperature.

2.1. Heat balance equation of collector components

2.1.1. Collector roof

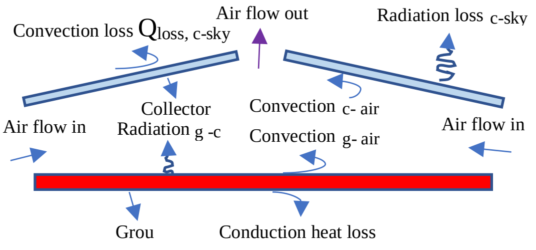


Fig. 2 Energy balance of the collector.

Equation of heat balance of collector roof shown in Fig. 2 can be given by the following equations.

$$S_C\,A_c + Q_{r,g-c}\,A_g = Q_{con,c-air}\,A_c + Q_{loss,c-sky}\,A_c \tag{1}$$

$$I.\alpha_c\,A_c + h_{r,g-c}\,A_g\left(T_g - T_c\right) = h_{con,c-air}\,A_c(T_c - T_{air}) + L_u\,A_c(T_c - T_{amb}) \tag{2}$$

Where;

L_u is the overall upper heat loss coefficient from the outer surface of the collector to the ambient. It represents the sum of the heat transfer coefficients by convection and radiation from the canopy to the ambient which expressed according to as [12]:

$$\mathrm{L_u} = \mathrm{h_{con,c-amb}} + \mathrm{h_{r,c-sky}} \tag{3}$$

The convection heat transfer coefficient can be given as [13]:

$$\mathrm{h_{con,c-amb}} = 2.8 + 3\mathrm{u_w} \tag{4}$$

Also, radiation heat transfer coefficient can be given as [14]:

$$h_{r,c-sky} = \frac{\epsilon_c \times \sigma \times \left(T_c^2 + T_{sky}^2\right)\left(T_c + T_{sky}\right)\left(T_c - T_{sky}\right)}{\left(T_c - T_{amb}\right)} \tag{5}$$

The sky temperature can be given by [15]:

$$T_{sky} = 0.00552 \times (T_{amb})^{1.5} \tag{6}$$

$h_{r,g-c}$: The radiation heat transfer coefficient from the base of the collector to the canopy and can be given by the following relation [16]:

$$h_{r,g-c} = \frac{\sigma\left(T_c^2 + T_g^2\right)\left(T_c + T_g\right)}{\left[\dfrac{1}{\epsilon_c} + \dfrac{1}{\epsilon_g} - 1\right]} \tag{7}$$

The convection heat transfer coefficient $hcon_{c-air}$ from the collector cover to the air inside the collector can be given by the following relation:

$$hcon_{c-air} = Nu_{c-air} * \frac{K_{air}}{D_h} \tag{8}$$

Where D_h is the hydraulic diameter it can be found by:

$$D_h \cong 2L_{g-c} \tag{9}$$

Nu_{c-air} is the Nusselt number and can be expressed by the following relation [17].

$$Nu_{c-air} = \left(0.825 + \frac{0.387\,Ra_{L,g-c}^{1/6}}{\left(1 + \left(\dfrac{0.492}{Pr}\right)^{9/16}\right)^{8/27}}\right)^2 \tag{10}$$

The Rayleigh number (Ra) is given the equation (11), as shown below [18].

$$Ra = Pr \times Gr = \frac{g \times \beta(T_g - T_{air}) \times {D_h}^3}{\nu^2} \times Pr \qquad (11)$$

Where:
β : Coefficient of thermal expansion.

$$\beta = 1/T_{\boldsymbol{air}} \qquad (12)$$

$$T_{air} = (T_{air-cin} + T_{air-co})/2 \qquad (13)$$

2.1.2. The ground

$$I.\tau_c\alpha_g.A_g = h_{r,g-c}.A_g(T_g - T_c) + h_{con,g-air}\,A_c(T_g - T_{air}) + L_g.A_g(T_g - T_{amb}) \qquad (14)$$

Where, L_g is the gross energy lost from the ground, it can be given as:

$$L_g = \frac{k_g}{z_g} \qquad (15)$$

2.1.3. The air flow inside collector

$$Q_{collector} = \dot{m}\,cp_{air}(T_{air-co} - T_{air-cin}) = h_{con,c-air}\,A_c(T_c - T_{air}) + h_{con,g-air}\,A_g(T_g - T_{air}) \qquad (16)$$

Properties of air (K_{air}, ν, ρ_{air} and cp_{air}) can be calculated at T_{air}.

Generally, the equations from (2) to (16) can be written as matrix form:

$$[A].[T] = [C]$$

Can be solved this matrix by using Matlab code to calculate values of temperatures (T_c, T_{air} and T_g) as follow:

$$[T] = [A]^{-1}[C]$$

2.1.3. For tower

Air velocity in tower can be calculated from follow relation [19]:

$$V_T = Cd\sqrt{\frac{2gH_T\Delta T}{T_{air-cin}}} \qquad (17)$$

Where; Cd = 0.6 [20].

$$\Delta T = T_{air-co} - T_{air-cin}$$

While air mass flowrate can be found:

$$\dot{m} = \rho_{air}\,.V_T\,.A_T \qquad (18)$$

Maximum output power generated by turbine from STPP can be written as [19]:

$$P_{max} = \frac{2}{3}.\eta_g\eta_t\eta_c.g.\frac{H_T\,A_c\,I}{cp_{air}.T_{air}} \qquad (19)$$

Where;
η_t : Turbine efficiency = 0.8
η_g: Generator efficiency = 0.95
η_c: Collector efficiency which can be defined as:

$$\eta_c = \frac{Q_{collector}}{A_cI} \qquad (20)$$

3. Validation of the Present Calculation

Among the calculations performed by the submitted mathematical model are the calculation of the velocity at the inlet of the solar chimney, the temperature difference between the inlet and exit of the solar collector and output power of STPP. When comparing these calculations with the Manzanares porotype under the same operating conditions, it is evident that there is a large convergence as shown in Table 1[1].

Table 1 calculated and measured data for STPP Manzanares.

Parameters At = 1000 (W/m^2)	**Present Model**	**Manzanares Prototype**	**Error (%)**
ΔT (K)	18.39	19	- 3.3
VT (m/s)	9.15	9.1	5.5
Output Power of STPP (kW)	49.97	45.6	8.7

4. A graphical User Interface (GUI)

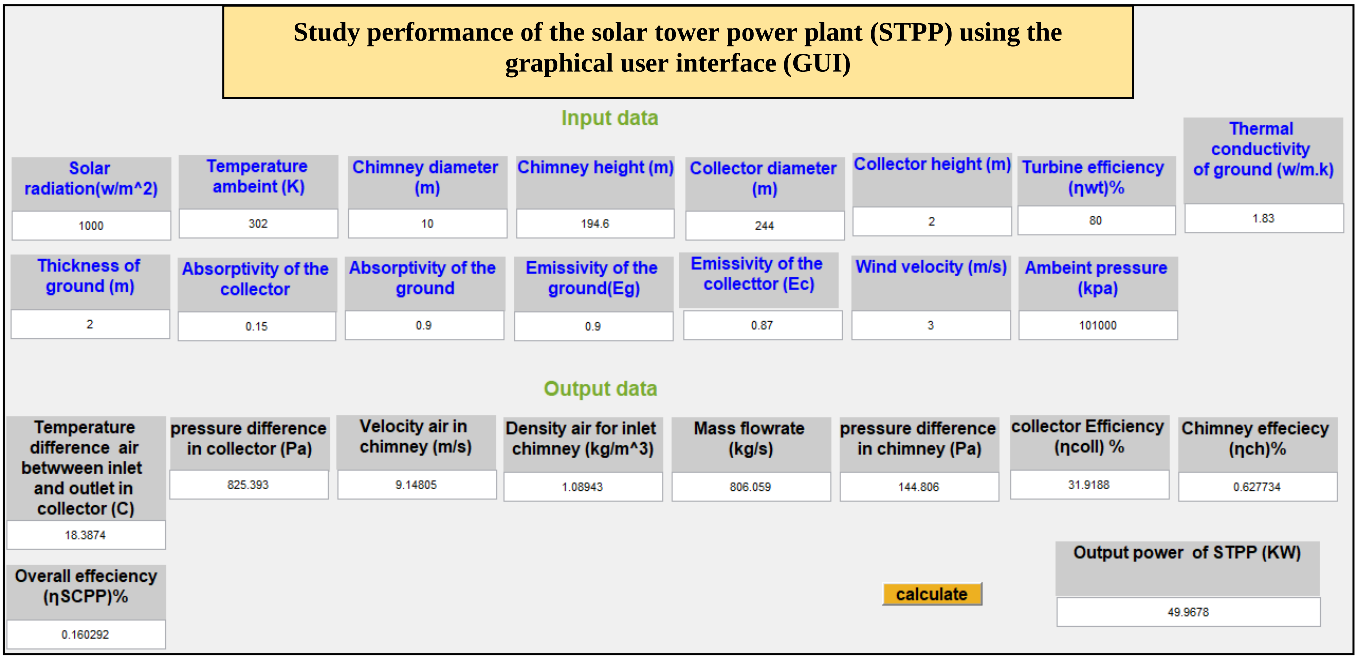
The GUI is a screen with graphics that creates one or more windows that contains devices or components called controls, which is used to perform or enable some tasks for the user. Texts commands are not needed to be created by GUI used to perform these tasks.

4.1 Design of Matlab GUI Code for Performance of STPP Calculations

In the present research, a Matlab program with graphical user interfaces (GUI) has been established in order to study the performance of STPP. Fig. 3 shows the main window for the developed code.

In this section, the programming procedure by graphical user interface constructed and designed to present the results of the STPP performance. The program gives the ability for predicting the performance of STPP for different tower dimensions, ambient operating conditions and locations.

The program predictions are validated by comparing its outputs with results of other study for same inputs. The GUI program inputs are; tower dimensions, solar radiation, ambient temperature, pressure, wind velocity, turbine efficiency, emissivity and absorptivity for collector and ground and thermal conductivity and thickness for ground. While, the GUI program outputs are; the temperature and pressure differences across the collector and tower, velocity in the tower, density of air in collector outlet, mass flowrate of air, efficiency for collector and tower, overall efficiency of STPP and output power of STPP.



Study performance of the solar tower power plant (STPP) using the graphical user interface (GUI)

Input data

Solar radiation(w/m^2)	Temperature ambeint (K)	Chimney diameter (m)	Chimney height (m)	Collector diameter (m)	Collector height (m)	Turbine efficiency (ηwt)%	Thermal conductivity of ground (w/m.k)
1000	302	10	194.6	244	2	80	1.83
Thickness of ground (m)	Absorptivity of the collector	Absorptivity of the ground	Emissivity of the ground(Eg)	Emissivity of the collecttor (Ec)	Wind velocity (m/s)	Ambeint pressure (kpa)	
2	0.15	0.9	0.9	0.87	3	101000	

Output data

Temperature difference air betwween inlet and outlet in collector (C)	pressure difference in collector (Pa)	Velocity air in chimney (m/s)	Density air for inlet chimney (kg/m^3)	Mass flowrate (kg/s)	pressure difference in chimney (Pa)	collector Efficiency (ηcoll) %	Chimney effeciecy (ηch)%
18.3874	825.393	9.14805	1.08943	806.059	144.806	31.9188	0.627734

Overall effeciency (ηSCPP)%: 0.160292

Output power of STPP (KW): 49.9678

Fig. 3 Design a graphical user interface (GUI) code of STPP performance calculations.

5. Results and Discussion

In the present study, the calculations were based on the weather conditions in Basrah city for the month of July. The solar heat gain is 864 (W/m^2) and the maximum monthly average ambient temperature 307.8 K [2].

The geometric dimensions of the solar power plant play an important role in influencing its performance, as shown in Figures 4 to 7.

Figure 4 illustrates the great dependence of the STPP on the solar collector area. Due to the increasing the amount of solar thermal energy that heats the air under the solar collector with increasing the diameter of the collector.

Figure 5 illustrates that the generated power declines with the height of the collector roof, where the percentage reduction is about 6.4 when the roof height is increased from 1 to 4 m. This fact can be explained by that the reduction of the space between the collector roof and the ground permits to the air to receive more heat radiated from the roof of the collector. According to Eq. (17), the air velocity increases and thus the power increases as a result with the decrease of the collector roof height. This fact is explained by the increase of the air velocity at the entrance of the chimney and the difference in temperature in solar collector which are related to the generated power.

Figure 6 clearly indicates the large impact of the height of the chimney on increasing the generated power due to the increase in pressure difference, which leads to an increase in the air velocity in the tower.

Despite the decrease in air velocity in the chimney, but the increase in the mass flow rate, which was associated with the increase in the diameter of the chimney, which in turn increased the value of the generated power as shown in Fig.7.

In Figure 8, the large increase in the output power is shown by the increase in the amount of solar radiation that falls on the surface of the solar collector. This due to the increase in the amount of heat emitted from the absorber (ground), which leads to an increase in air velocity and an increase in the air temperature difference between the outlet and inlet of the solar collector. Thereby increasing the amount of output power.

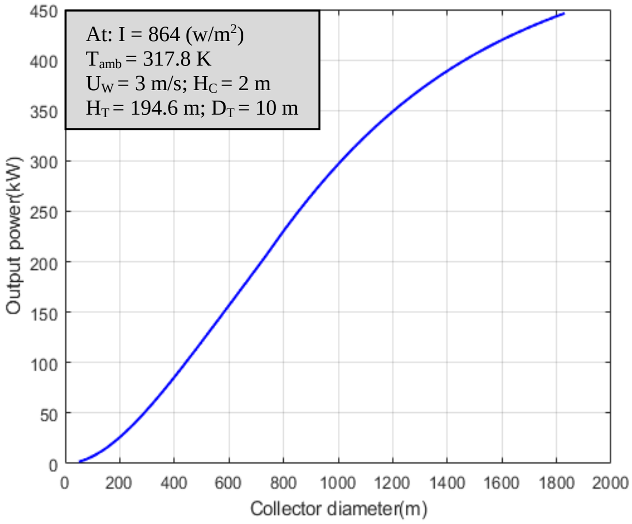


Fig.4 Effect collector diameter on output power.

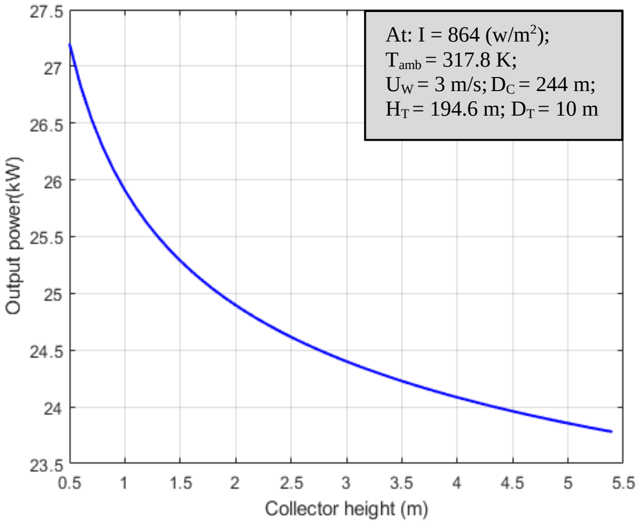


Fig.5 Effect collector height on output power.

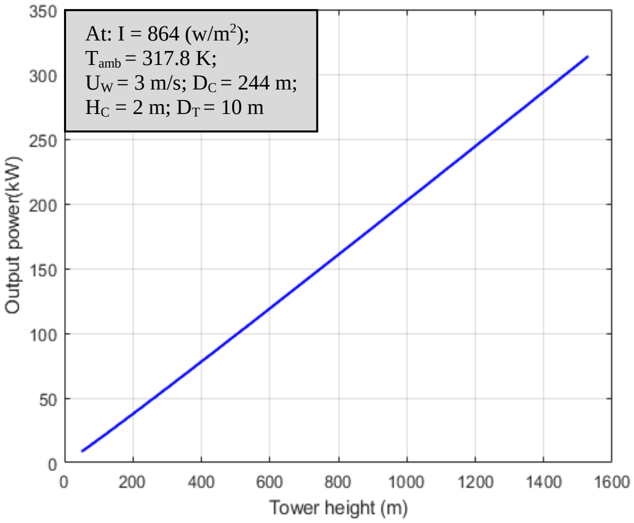


Fig.6 Effect tower height on output power.

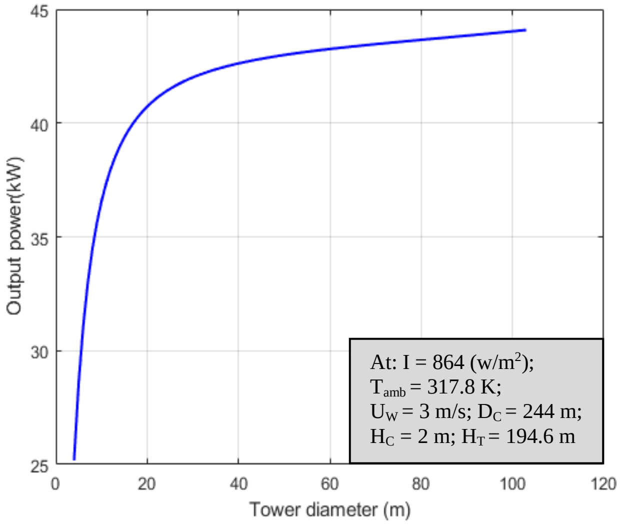


Fig.7 Effect tower diameter on output power.

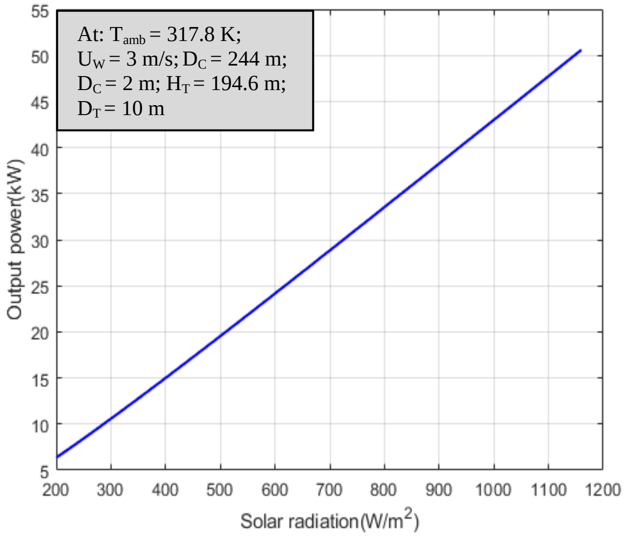


Fig.8 Effect solar radiation on output power.

Figure 9 shows the decrease in the amount of output power with increasing ambient temperature. As by increasing ambient temperature the difference in temperature between the inlet and outlet of the solar collector decreases, causing a decrease in air velocity and a decrease in the power generation.

Figure 10 shows the inverse relationship between wind speed and output power. It is noted that the higher the wind speed, the heat losses of the STPP (especially in the solar collector roof) increase, as the heat transfer coefficient increases, therefore, the output power the plant would be decreased.

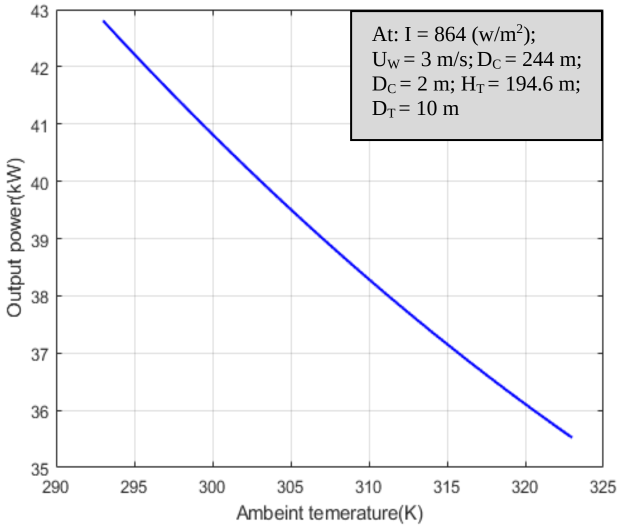


Fig.9 Effect ambient temperature on output power.

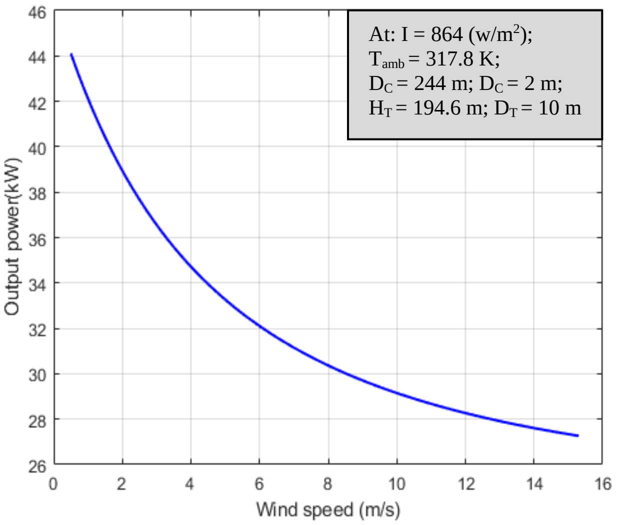


Fig.10 Effect wind speed on output power.

6. Conclusions

The main conclusions that can be drawn from this work are summarized as follows:

1. By designing an STPP performance GUI code, the behavior and impact of many variables on STPP performance can be known.
2. The main variables that affect the energy produced by STPP are the diameter of the solar collector, the chimney height and the intensity of the solar radiation.
3. The climate conditions such as wind velocity and ambient temperature have an important effect on the power generation of STPP.

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Nomenclature	
A_c , A_g	Area of collector and ground respectively (m^2)
A_T	Cross section area of tower (m^2)
cp_{air}	Specific heat capacity of air in collector (W/m^2. K)
g	Gravitational body force = 9.81 (m/s^2)
$h_{con,c\text{-}air}$	Coefficient of convection heat transfer between the inside surface of collector and inside air (W/m^2. K)
$h_{con,c\text{-}amb}$	Coefficient of convection heat transfer between the surface of collector and ambient air (W/m^2. K)
$h_{con,g\text{-}air}$	Coefficient of convection heat transfer between the surface of ground and inside air (W/m^2. K)
H_T	Tower height (m)
$h_{r,c\text{-}sky}$	Coefficient of radiation heat transfer from the outlet collector surface to the sky (W/m^2. K)
$h_{r,g\text{-}c}$	Coefficient of radiation heat transfer from the inlet ground surface to inside surface of collector (W/m^2. K)
I	Intensity of solar radiation (W/m^2)
K_{air}	Thermal conductivity of air (W/m. K)
K_g	Thermal conductivity of ground (W/m. K)
$L_{g\text{-}c}$	Roof collector height (m)
L_g	Ground thickness (m)
Pr	Prandtl number
Ra	Rayleigh number
T_{air}	Average temperature air in the collector (K)
T_{amb}	Ambient temperature (K)
$T_{air\text{-}cin}$	Temperature of air in collector inlet (K)
$T_{air\text{-}co}$	Temperature of air in collector outlet (K)
T_c	Temperature of collector surface (K)
T_g	Temperature of ground surface (K)
Uw	Wind speed (m/s)
Greek symbols	
ρ_{air}	Density of air (kg/m^3)
β	Coefficient of Thermal expansion (1/K)
v	Kinematic viscosity (m^2/s)
α_c , α_g	Absorptivity of the collector roof and ground respectively
ε_c , ε_g	Emissivity of the collector roof and ground respectively
σ	Stefan-Boltzmann constant (W/m^{2}K^4)
τ_c	Transmittance of the collector

Biographies

Ihsan N. Jawad received a B.Sc. degree in Mechanical Engineering and the M.Sc. degree in Mechanical from the University of Basrah, College of Engineering, Basrah, Iraq, in 2003 and 2011 respectively. He is currently working toward a Doctorate of Philosophy degree in Mechanical Engineering: renewable energy at the University of Basrah. He is currently a lecturer in the Department of Mechanical Engineering, University of Basrah.

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