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Application of a Solar Chimney Power Plant to Electrical Generation in Covered Agricultural Fields

Hasanain A. Abdul Wahhab[1], **Wisam Abed Kattea Al-Maliki**[1]
[1] Mechanical Engineering Department, University of Technology, Baghdad, Iraq.

Abstract. Greenhouses are an ideal plant production environment, providing high quality products in all seasons of the year and removed from climatic influences such as wind, frost and rain. However, this type of farming involves costly construction, and it is necessary to consider using it in other aspects, in addition to agriculture. The purpose of the current work is to study the possibility of using a solar chimney power plant (SCPP) in the generation of electric power, thereby meeting the need for energy in agriculture, including lighting, pumps, drip irrigation and other applications. This paper describes an analytical study of solar chimney power plant in a greenhouse environment. The investigation was based on experimental calculations to identify out power from varying the air flow intensity inside the farm, depending on its conditions. The modelling was carried out in an ANSYS environment and the simulation of solar plant used a FLUENT k-ε Module for solving and post-processing the problem. Results showed that a solar chimney power plant, in which the chimney height and diameter were 20 m and 0.3 m, respectively, and the dimensions of the green farm collector 70 m × 50 m, could produce a monthly average of 1.31~2.42 kW electric power throughout the year.

1. Introduction

Renewable energy is of great interest to the world today because it is important to many fields including life activities, technological improvement, economics and security. [1]. Global energy demand continues to increase as a result of economic advancements and world population growth [2]. Generally, the growing global energy demand is currently supplied from the available natural resources such as oil, gas, coal, nuclear, biomass, hydro and solar sources. However, the use of these natural resources has adverse effects on the environment such as deforestation, greenhouse gas (GHG) emissions, global warming, acid rain and other environmental problems [3].

Solar energy drives the universe, while other energy sources directly or indirectly derive their sources from it [4]. Solar energy has attractive qualities; it is free and unlimited in supply by nature, and environmentally friendly in use. However, there are limitations to solar energy systems for commercial power generation. These include the high initial investment cost for the relevant energy conversion system, and the cost of energy generation, which is high compared to conventional energy power plants [5].

The solar chimney power plant (SCPP) has potential as a commercial electrical power generation system, combining the technology of greenhouse, chimney and turbine to generate electricity using air as its working fluid. The SCPP comprises a solar collector, chimney and turbine(s). The solar collector absorbs solar radiation and converts it to heat, thereby creating a greenhouse effect within the transparent canopy. The chimney induces buoyancy by stack effect, thus enhances the velocity of buoyant air generated at the collector area of the system. The turbine is designed to use buoyant air energy and converts it to electrical energy.

Solar chimney power plant technologies are well established, but the indirect conversion of energies from one form to another leads to a low value of plant efficiency, which is currently rated below 2% for a system with 1000 m chimney height. The total efficiency of a system is a result of the efficiencies of the collector, the chimney and the turbine. The chimney has the least efficiency whereby a chimney of 1000 m high is about 3% efficient. This is because the chimney efficiency is dependent on the chimney height.

The SCPP is favoured for its stability, achieved by utilizing the global solar radiation for its operation. To compensate for the chimney's poor efficiency, improvements in collector turbine efficiency can considerably improve the total plant efficiency. Some of the relevant enhancements to the SCPP collector include the introduction of water-filled tight tube [6] as a heat storage medium, the use of intermediate absorber plate [7] to minimise heat loss, and the use of canvas [8, 9] to enhance heat transfer. Heat storage enhances the night-time operation of the plant, thereby improving the operational efficiency of the plant and consequently reducing heat loss to the atmosphere.

The turbine used for energy conversion in SCPP can be a wind turbine of either vertical or horizontal axis. Two main proposed locations for the installation of the turbine of SCPP are the chimney exit [10] and the conventional chimney base location [10-12]. Comparing the two locations for turbines in SCPP, Von Backström et al. [13] showed there to be relative negative pressure in the chimney when the turbine is situated at the chimney base; a relative positive pressure was observed when the turbine was placed at the chimney top. Many researchers [10-14] have claimed that output is maximized if the pressure drop at the turbine is about 80% of the total pressure differential available. The optimum efficiency depends on the plant's characteristics, such as friction losses.

In this study, a solar chimney electric power generating plant of simple design was installed on one of the covered agriculture farms in Kut, a city in the south of Iraq. It had a collector area of 50×70 m, while the chimney had a diameter of 0.3 m and was 20 m tall. Most of the works in this paper have been carried out numerically and mathematically and this work presents the results under the same covered farm conditions. The analysis was carried out using ANSYS FLUENT software.

2. Functional Principle

Figure 1 illustrates the principle of a solar chimney [15]. As a result of the solar radiation falling on the transparent roof of the farm, the air is heated. This can be very helpful where the conditions are suitable for the implementation of agricultural projects and at the same time, capable of appropriate storage of solar energy. The chimney is installed in the middle of the roof, to allow the air to enter the base, because the hot air is lighter than the cold air and it rises through the chimney. Thus, the air gradually pulls out of the collator and into the chimney, venting outside air to replace it. Continuous operation can be achieved for 24 hours, through the presence of plants within the covered farm (under the roof). Thus, the energy contained in the updraft is converted into mechanical energy by the turbine operating at the base of the chimney, and to electrical energy by conventional generators [10].

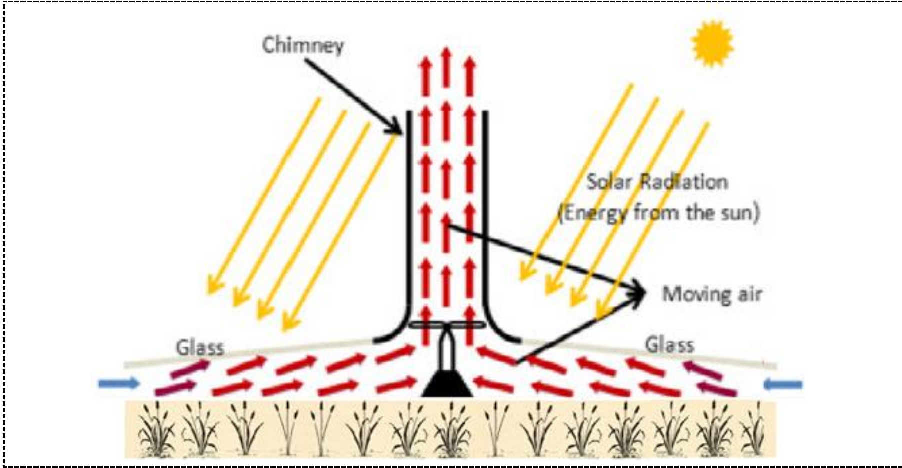

Figure 1. Schematic view of SCPP [15].

The SCPP has three main components: a solar collector, chimney and turbine. Traditionally, the collector component is formed from the ground plus a transparent cover, which creates a greenhouse over the ground of an area 50×70 m. At the centre of the greenhouse is a chimney, which enhances the stack effect required for the heated air at the collector to be exhausted to the atmosphere. The chimney can be as tall as 20 m height. The size of the chimney determines the efficiency of the chimney component and the stack effect. The chimney basically enhances the buoyancy effect in the system, thus air velocity and air mass flow rate. The kinetic energy in the buoyant air can be converted into useful energy using a wind turbine and generator. The energy output of the wind turbine is the product of the available energy in the buoyant air and the efficiency of the turbine, as is shown in Figure 2.

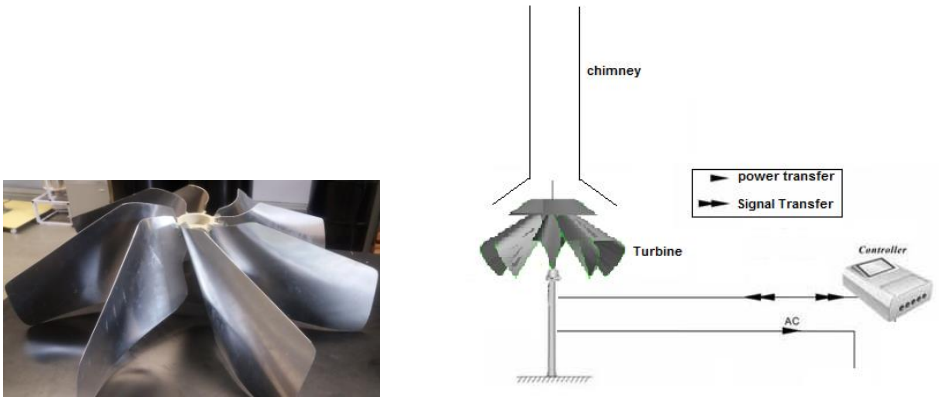

Figure 2. Schematic view of turbine system.

This enhances the pressure difference, Δp_{tot}, between the ambient air and the system air, thus creating a continuous air flow in the system which increases as the chimney height increases. The pressure difference developed as a result of the chimney is described as shown in Eq. 1 neglecting frictional losses [16, 17].

$$\Delta p_{tot} = g\int_0^{H_{tot}} (\rho_{amb} - \rho_{air})dh \qquad (1)$$

Fluri [14] has reported that the efficiency of the wind turbine in the chimney is about 80%. The air power generated by a SCPP is determined as Eq.2. The air power depends on the air mass flow rate and the air velocity generated. The power in the buoyant air is the energy available to the turbine that can be converted to electricity. Following Eq. 2, the air power is a product of the system air mass flow rate, $\dot{m}_{air}$, and system air kinetic energy, KE_{air}. The kinetic energy for a unit mass of air is determined using Eq. 3:

$$P_{air-tot} = \frac{\dot{m}_{air} V_{air-base}^2}{2} \quad (2)$$

$$KE_{air} = \frac{V_{air-base}^2}{2} \quad (3)$$

The available energy to the turbine is the power/energy in the buoyant air. The staged turbine of a SCPP converts the energy in the buoyant air into mechanical/electrical energy, thus the electrical power output of the system depends on the air power and the turbine–generator efficiency. The electrical power generated using turbine-generator in a SCPP can be expressed as Eq. 4:

$$P_{elec-out} = \eta_{turb} P_{air-tot} \quad (4)$$

The data collection from experiments when the farm has full area plants presented in Table 1.

Table 1. Data collection to SCPP in Kut farm

SCPP details	Collector Area (50×70m)	Chimney Height 20m, diameter 0.3m	Turbine Rotor diameter 0.5m, Number blades 8 plate	Ground Green plants Full area Half area without
time	Solar intensity (w/m^2)	Air velocity (m/s)	$P_{elec-out}$ (Watt)	
8:00	245	3.2	686	Full area `
10:00	644	4.56	1167	Full area
12:00	845	7.45	1945	Full area
14:00	896	16.4	2389	Full area
18:00	184	2.2	245	Full area
24:00	0	1.2	178	Full area

3. Computational Modelling

3.1. Description of the Numerical model

The numerical model of the solar chimney had a collector and chimney. The collector was a rectangle roof 70×50 m, while the absorber comprised plants inside this covered farm. The chimney was 20 m in height, 0.3 m (12.0") diameter and installed in the centre, above the farm's collector. The inlet air was passed from small holes in the farm sides.

The objective of the numerical model for SCPP was to develop a set of governing differential equations (continuity equation, momentum equations, energy equation, k-ε model) and to solve these equations using numerical techniques. Another object of this modelling was to analyse the effect of germination conditions inside the farm on the performance of a traditional solar chimney system.

Computational fluid dynamic (CFD) analysis techniques are efficient tools in engineering applications, used for representing a mechanical problem and analyzing the physical phenomena. In the present simulation, the commercial CFD software ANSYS 16.0 FLUENT with pre-processing tool, GAMBIT 12, was used to model and simulate air flow through the collector and chimney, solar chimney system geometry.

Several steps were carried out to perform the simulations. This study anticipated the possibility of using the CFD tool to analyse the properties of flow SCPP. The CFD code includes solar radiation beam as input for problem parameters and analysis of results. The three-dimensional model of the solar stoves power plant was suggested, using the pre-processor CFD program. After testing for model fragmentation cases for numbers of cells used, in one run for the program under study were 778,567 cells. Mesh refinement investigation was carried out to develop results through increasing the number of cells used. Increasing the number of cells to 815,222 and 868,555 apparently exerted no effect on the results. So, the number of cells 778,567 was selected to be the effective number of cells for use in the simulation.

3.2. Governing equation

All numerical solutions of the fundamental equations of the dynamics of fluids (continuity, momentum, energy, species and volatile equations) included in the CFD code were used. The ANSYS fluent software was used to complete this job. Navier-Stokes equations for fluid flow and analysis of physics incompressible fluids were solved, depending on pressure drop, finite volume by 3D fully implicit code. The model is used to solve a wide range of industrial problems including heat transfer (including solar radiation), fluid flow type (turbulence), and other complex phenomena.

Continuity: $$\frac{\partial}{\partial x_j}\left(\rho \overline{u_j}\right) = 0 \quad (5)$$

Momentum: $$\overline{u_j}\frac{\partial}{\partial x_j}\left(\rho \overline{u_i}\right) = B - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial z_j}\left(\mu\left(\frac{\partial \overline{u_j}}{\partial x_i} + \frac{\partial \overline{u_i}}{\partial x_j}\right) - \rho\overline{u_i^{\cdot} u_j^{\cdot}}\right) \quad (6)$$

Energy equation: $$\overline{u_j}\frac{\partial}{\partial x_j}\left(\rho c_p \bar{T}\right) = H + \frac{\partial}{\partial x_j}\left(\rho c_p \alpha \frac{\partial \bar{T}}{\partial x_j} - \rho c_p \overline{u_j^{\cdot} T^{\cdot}}\right) \quad (7)$$

The model with two new variables:

$$\overline{u_j}\frac{\partial}{\partial x_j}\left(\rho \bar{c}\right) = R + \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial \bar{c}}{\partial x_j} - \rho\overline{u_j^{\cdot} c^{\cdot}}\right) \quad (8)$$

$$\rho\frac{\partial k}{\partial t} + \rho u_j k_{1,j} = \left(\mu + \frac{\mu_t}{\sigma_k} k_{1,j}\right)_{1,j} + G + B - \rho\varepsilon \quad (9)$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho u_j \varepsilon_{1,j} = \left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \varepsilon_{1,j}\right)_{1,j} + c_1\frac{\varepsilon}{k}G + c_1(1 - c_3)\frac{\varepsilon}{k}B - c_2\rho\frac{\varepsilon^2}{k} \quad (10)$$

Where, j=1, 2, 3, which are refereeing to three axis, *ρ*- the density, *u*- flow velocity, *t*- time, *T*- temperature, *cp*- specific internal energy, *μ*- viscosity, *k*- thermal conductivity.

The boundary conditions used in the simulation are presented in Table 2.

Table 2. Conditions for the simulation of solar chimney model.

	Collector (50×70m)	Chimney 20m, 0.3m	Turbine 0.5m, 8 plate	Ground Green plants
Case-1	P_{in}= 0 Pa, T_{in}=T_{amb}	T_{wall}=constant	η= 80% [14]	Full area
Case-2	P_{in}= 0 Pa, T_{in}=T_{amb}	T_{wall}=constant	η= 80% [14]	Half area
Case-3	P_{in}= 0 Pa, T_{in}=T_{amb}	T_{wall}=constant	η= 80% [14]	without

4. Results and Discussion

The effect of the solar chimney's performance on the farm was tested, based on the experimental farm conditions (50×70 m and chimney 20 m), and analytic investigation conducted assuming the same conditions (full-area, half-area, without). The results from the simulation have been presented in terms of air velocity, temperature and system thermal efficiency.

The simulation considered 970 W/m^2 solar irradiance and prevalent ambient condition at the Kut farm location with the solar intensity between 700 W/m^2 and 990 W/m^2, which is at an average temperature of 39^{o}C. The results showed the velocity and temperature contours distribution with full-area germination in farm, which are given in Figure 3.

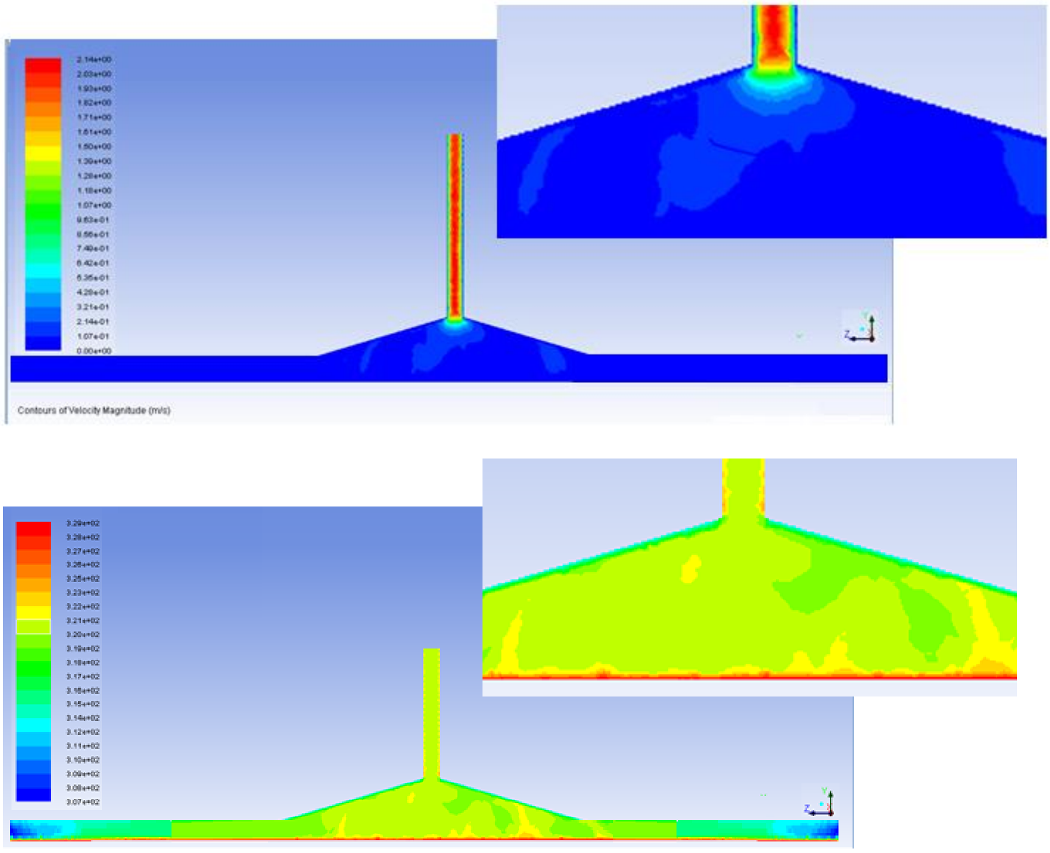

Figure 3. Air velocity and temperature contours at 50×70m dimensions; 940 W/m^2 solar irradiance.

Figure 3 shows the simulation results of air velocity and temperature in contours, for a 50×70m farm area. Air velocity has a small radial component compared to the vertical component. The radial component overrides the vertical component, because the distance from the vegetation to the farm cover is relatively large compared to the radial passage. The air flow moves mostly upwards, reaches the farm cover and accelerates toward the chimney base. Once the outer narrow passage flow reaches the central part, it may double vertical velocity component, due to the area enlargement of the configuration in the vertical direction. So, the result of the air flow direction was identified as being mainly towards the chimney base, due the overstock effect.

In Figure 4, the key parameters solar radiation intensity and updraft air velocity as an operational data are shown for a typical day in July. There are two important things to note: first, at daytime, the updraft air velocity is closely related to the solar radiation intensity of this small power plant without additional storage. Second, the system should achieve a widely range of power generation during night hours, depending on thermal energy stored, as shown in Figure 4.

Results in Figure 5 show that implementation of the solar chimney system in power generation for covered farms is viable, and such projects are capable of very reliable operation. The results suggest that solar chimney system can produce a monthly average of 1.31~2.42 kW electric power throughout the year.

Thermodynamics is one of the most important features of this system. Moreover, the possibility of operating for most of the day by developing the power generation system, especially with increasing efficiency of the turbines, was noted.

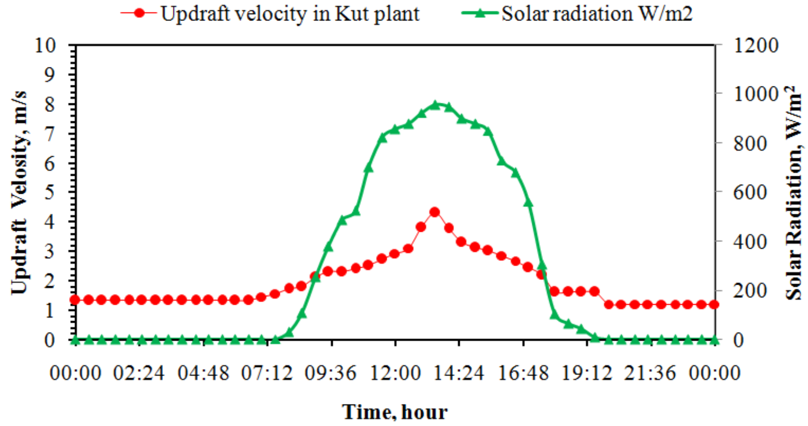

Figure 4. Analytical updraft velocity and solar intensity for a typical day.

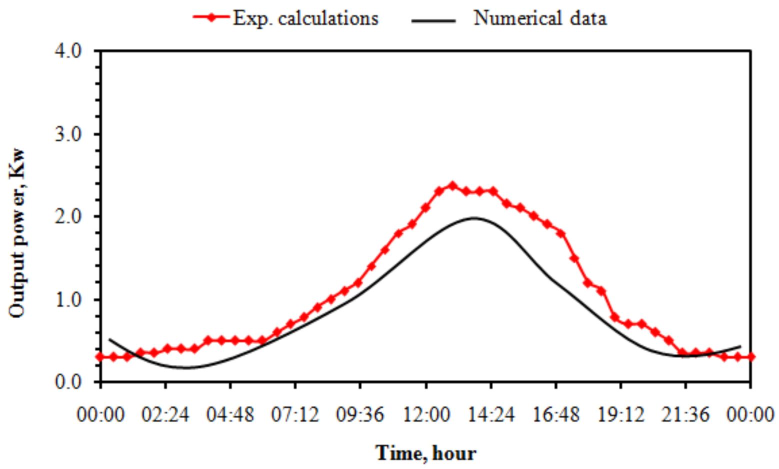

Figure 5. Analytical power results against measurement from Kut farm and numerical results for a typical day.

5. Conclusions

This study sought to to identify the requirements arising in ideal conditions for the use of a solar chimney power plant on a heat exchange collector (covered farm). Thus, innovative solutions were investigated, to model a solar chimney power plant so that the collector was a covered farm. The main objective of the research was to study the possibility of applying the solar chimney power plant in the generation of electric power, which can meet the agricultural sector's need for energy, including for lighting, running pumps and drip irrigation. The model developed in this paper addressed this issue in detail. The results showed that a solar chimney power plant, in which the chimney height and diameter are 20 m and 0.3 m, respectively, and the dimensions of green farm collector 70 m × 50 m, can produce a monthly average of 1.31~2.42 kW electric power throughout the year.

6. References

[1] Siraj M S 2012 *R. and S. Ene. Revi.* **16** 1971-1976
[2] Service R F 2005 *Science (Washington, D. C.)* **309** 548-551
[3] Armaroli N and Balzani V 2007 *Angewandte Chemie International Edition* **46** 52-66
[4] Dincer I 2000 *R. and S. Ene. Revi.* **4** 157-175
[5] Dennis C. 2006 *Nature* **443** 23-24
[6] Pasumarthi N and Sherif S 1998 *I. J. Ene. Resear.* **22** 277-288
[7] Pasumarthi N and Sherif S 1998 *I. J. Ene. Resear.* **22** 443-461
[8] Ayyappan S, Mayilsamy K and Sreenarayanan V V 2015 *Heat and Mass Transfer* 1-9
[9] Fath H E S 1998 *Renewable Energy* **14** 35-40
[10] Schlaich J, Bergermann R, Schiel W and Weinrebe G 2004 *I. J. Assoc. Brid. Struc.* **14** 225-229
[11] Aja O C, Al-Kayiem H H, and. Karim Z A A 2010 J. Applied Scienc. **11** 1877-1884
[12] Zhou X, Wang F and Ochieng R M 2010 *Renew. Sustain. Ener. Revie.* **14** 2315-2338
[13] Von Backström T W and Gannon A J 2003 *Solar Energy* **76** (1-3) 235-241
[14] Kröger D G and Burger M 2004 *International Sonnenforum* **1** 422-430
[15] Al-Kayiem H H and Aja O C 2016 *Rene. Susta. Ener. Revie.* **58** 123-131
[16] Von Backström T W, Bernhardt A and Gannon A J 2003 *J. Solar Ener. Engin.* **125** 165-169
[17] Nizetic S and Klarin B 2010 *Applied Energy* **87** 587-591

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Nomenclature

Δp_{tot} : the pressure difference, increases with chimney height. (bar)
$P_{air\text{-}tot}$: total kinetic power. (watt)
$P_{ele\text{-}out}$: electric power. (watt)
$\dot{m}_{air}$: air mass flow rate. (kg/s)
$V_{air\text{-}base}$: air velocity at chimney base. (m/s)
KE_{air} : Kinetic energy. (Joul)
η_{tur} : turbine efficiency.