Experimental and Theoretical Performance of Mini Solar Chimney Power Plant

T. Mekhail, A. Rekaby, M. Fathy, M. Bassily, and R. Harte

***Abstract*—Electricity production generated by sufficient amount is a critical issue over the entire world. The global warming is another critical issue. Currently, renewable energy sources are ones of the most important solutions to deal with these two issues. Aswan city is one of the hottest and sunniest cities in the world. This climate conditions makes the city an ideal place for Solar Chimney Power Plant (S.C.P.P) to produce electrical energy. In this study, a very small model of chimney height of 6m, collector diameter of 6m and chimney diameter of 0.15m is installed. The mathematical model which is based on the thermodynamic analysis of the flow inside the SCPP, is used to predict its performance .The experimental performance and the theoretical one–calculated from the mathematical model- are found to be in a good agreement. This model is used to predict the output power of a bigger model of 20m chimney height, 30 m squared collector and 1m chimney diameter which is still under construction. The results show that the bigger model can produce a theoretical power of about 600 hundreds times the smaller one. This study helps in selecting the generator power for the bigger model.**

***Index Terms*—Solar chimney, axial turbine, collector.**

I. Introduction

In Egypt, fossil fuel resources mainly dominate electricity production. However, high solar radiation and large desert area are available. These two main factors encourage the full development of solar power plants for thermal and electrical energy productions.

Herein, the solar thermal power plants have many advantages, the priorities of consistent power output and the ability to incorporate storage. One of the options that will help in global electricity production is the Solar Chimney Power Plant (SCPP). The SCPP is a natural driven power generating system. It can convert solar energy first into thermal energy then into kinetic energy finally into electrical power. It combines the concept of solar air collectors and a central updraft chimney to generate a solar induced convective flow which drives turbines to generate electricity. The SCPP consists of a greenhouse roof collector and updraft chimney that is located at the center of the greenhouse roof collector. The SCPP has been proposed as a device to economically generate electricity from solar energy in commercial-scale in the future.

In 1982, the first pilot plant of the S.C.P.P was built in Spain, since then many prototypes of the S.C.P.P had been built by experts in various countries. Australian intends to construct the largest SCPP in the world at present with the generation capacity reaching up to 200 MW in New South Wales of Australia. A chimney in the plant will be 1000m in height and the collector is 7 km in diameter, the system would cover a ground area of 38 km^2 [1]. Experimental work and numerical calculation method can be used to study on the performance of the S.C.P.P, but the large scale system is hard to establish. However, with the development of computer technology and commercial software techniques, both temperature and pressure distribution in the large system can easily be obtained by numerical calculation method [2]. More analytical models to predict the performance of solar chimney power plants have been proposed since the early 1980s. Haaf *et al.* [3] presented a simple model, which they used for the design of the pilot plant in Manzanares. Pasumarthi and Sherif [4] showed a more detailed model, which they verify against their own experimental results and results of the Manzanares pilot plant (Pasumarthi and Sherif) [5]. Gannon and Von Backström [6] adapted the standard gas turbine cycle to define a standard solar chimney cycle. Bernardes *et al*. [7] have developed recent comprehensive models, and Pretorius and Kröger [8] presented some techniques to predict the SCPP performance. Koonsrisuk and Chitsomboon [9] predicted the performance characteristics of large-scale commercial solar chimneys, indicating that the plant size, the factor of pressure drop at the turbine, and solar heat flux were important parameters for a performance enhancement. The collector radius and chimney height of 200 m and 400 m, respectively, were built. Furthermore, the optimum ratio between the turbine extraction pressure is shown and the available driving pressure for the proposed plant is approximately 0.84. A simple method to evaluate the turbine power output for solar chimney systems was also proposed in the study using dimensional analysis.

Backström and Gannon [10] presented analytical equations in terms of turbine flow and load coefficient and degree of reaction, to express the influence of each coefficient on turbine efficiency. Characteristics measured on a 720 mm diameter turbine model confirm the validity of the analytical model. Application to a proposed large solar chimney plant indicates that a peak turbine total-to-total efficiency of around 90 % is attainable, but not necessarily over the full range of plant operating points.

The present study aims to measure and predict the performance characteristics of a small S.C.P.P of a collector diameter of 6 m and chimney height of 6m from which a

Manuscript received January 27, 2016; revised May 26, 2016. This work is a part of joint project supported by STDF (Egypt) and BMBF (Germany).

T. Meakhail, A. Rekaby and M. Fathy are with the Faculty of Energy Engineering, Aswan, Egypt (e-mail: mina_tarek@hotmail.com, ahrk60@yahoo.com, mfsadik@yahoo.com).

M. Bassily is with the Department of Mechanical Power Engineering, Faculty of Engineering, Minia University, Minia, Egypt (e-mail: bassily1@yahoo.com).

R. Harte is with the Faculty of Architecture and Civil Engineering, University of Wuppertal, Germany (e-mail: eharte@uni-wuppertal.de).

doi: 10.18178/jocet.2017.5.4.386

bigger model of 20 m chimney height and 30m squared collector -under construction- can be predicted to select the generator power.

II. Mathematical Model

The thermal analysis of the S.C.P.P depends on parameters such as the ambient conditions and structural dimensions of the system. The former includes quantities such as the solar radiation and ambient temperature, whereas the latter includes the height and radius of both the chimney and collector. The mathematical model of Koonsrisuk and Chitsomboon [9] is used with modification of calculating the mass flow rate entering the chimney instead of assuming it. With the stations numbered as in Fig. 1, the temperature rise can be estimated from the energy equation across the roof portion:

$$\dot{m}C_P(T_2 - T_1) + \frac{1}{2}\dot{m}(V_2^2 - V_1^2) = q_{\text{added}}A_r \tag{1}$$

where T_2 and T_1 are the outlet and inlet temperatures respectively for the collector, V_2 is the velocity nearly at the chimney inlet, V_1 is the velocity at the inlet of the solar collector, q_{added} denotes the heat added to the collector according to its area A_r.

For simplicity, the kinetic energy term has been ignored because the flow is in the very low Mach number regime, therefore;

$$q_{\text{added}}A_r = \dot{m}C_P\Delta T \tag{2}$$

where $\dot{m}$ is the mass flow rate, C_P is specific heat (kJ/kg.C), ΔT refer to the temperature differences between inlet and outlet from the solar collector.

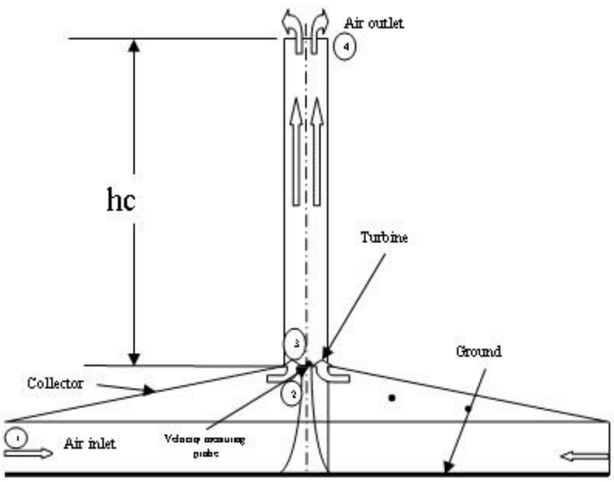

Fig. 1. Schematic layout of SCPP.

Instead of assuming the flow rate in Ref. [9], it can be calculated from the following equation [11];

$$\dot{m}_{ch} = \dot{m}_{\text{collector}} = \rho_{\text{air}}A_{ch}\sqrt{2gh_c(T_2 - T_4)/(T_0 + (T_2 - T_4))} \tag{3}$$

where ρ_{air} the is density at the inlet of the chimney refer by point 2, A_{ch} is the chimney area, h_c denotes to the chimney high, g is the gravity acceleration, T_4 is the temperature at outlet of the chimney and T_0 is the ambient temperature.

The heat added can be represented by:

$$q_{\text{added}}A_r = I(\alpha_g) - U_t(T_2 - T_1) \tag{4}$$

α_g is the collector absorption coefficient, I denotes to solar radiation, U_t is the overall heat transfer coefficient.

By synthesizing equations for continuity, momentum and energy of the flow under the roof it is proposed that:

$$p_2 = p_1 + \frac{\dot{m}q_{added}}{2\pi h_r^2 \rho_1 C_p T_1} In\frac{r_r}{r_c} - \frac{\dot{m}^2}{2\rho_1}\left(\frac{1}{A_2^2} - \frac{1}{A_1^2}\right) \tag{5}$$

where p_1, ρ_1 and T_1 are approximated as p_∞, ρ_∞ and T_∞. p_2 and p_1 are the pressure at the outlet and inlet of the solar collector respectively, h_r is solar collector height refer to the distance from the ground to the solar collector cover, ρ_1 is the density of air at the inlet of the solar collector, r_r is the collector radius, r_c is the chimney radius, A_2 and A_1 efer to the area of the solar collector at outlet and inlet respectively.

If the work extraction process at the turbine is assumed to be an isentropic process, then;

$$T_3 = T_2\left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} \tag{6}$$

where T_3 and p_3 refer to the temperature and pressure after the turbine- generator unit.

Furthermore, by rearranging the momentum and continuity equations for the flow through a constant area vertical tower of height, h_c, p_3 can be considered as follow;

$$p_3 = p_4 + 0.5(\rho_3 + \rho_4).g.h_c + \left(\frac{\dot{m}}{A_c}\right)^2\left(\frac{1}{\rho_4} - \frac{1}{\rho_3}\right) \tag{7}$$

p_4 is the pressure at the outlet of the chimney, ρ_4 and ρ_3 are the densities at the chimney outlet and at the location after the turbine respectively, h_c is the chimney height.

Assuming that the air obeys the ideal gas equation of state, p_4 is represented by:

$$p_4 = p_3\left(1 - \frac{g}{T_3C_p}l_{ch}\right)^{\frac{C_p}{R}} \tag{8}$$

The air moves in and out of the solar chimney system continuously, driven by the pressure difference between the inside and outside. This pressure difference is called the "available driving pressure" and symbolized as dptot. Neglecting friction losses, dptot can be subdivided into a turbine extraction component representing the pressure extracted at the turbine, and a dynamic component describing the kinetic energy of the airflow:

$$\Delta p_{\text{tot}} = \Delta p_{\text{turb}} + \Delta p_{\text{dyn}} \tag{9}$$

where Δp_{tot} and Δp_{turb} are the pressure differences on the turbine and overall pressure differences for the system respectively.

The ratio $p_{\text{turb}}/p_{\text{tot}}$ can be defined as x, so that

$$\Delta p_{\text{turb}} = x \Delta p_{\text{tot}} \tag{10}$$

The result for the optimal pressure ratio is;

$$x = \frac{2}{3} \tag{11}$$

The theoretical turbine power extracted by the turbine can be determined from the energy equation:

$$P = \dot{m} \int v dp \approx \frac{\dot{m}}{\rho_{\text{turb}}} \Delta p_{\text{turb.}} \tag{12}$$

Accordingly, the available turbine power is computed using the following expression:

$$P = \frac{\dot{m}}{(\rho_2 + \rho_3)/2} (p_2 - p_3) \tag{13}$$

III. Experimental Test RIG and Measurements

The experimental test rig used in the present work to evaluate the S.C.P.P is shown in Fig. 2 [11]. The small test rig consists of a solar collector of thin sheets of plastics (instead of glass), chimney, turbine and measuring instruments. Its main dimensions are: the collector diameter is 6.0 m, the chimney is constructed from PVC pipe with diameter of 0.15 m and height of 6.0m, the collector is constructed using steel beams with wooden wired network to support the plastic cover. The collector surface is designed with inclination; its height from the ground is 0.25 m at the outer rim and 0.5 m at the inner core. A single stage turbine, Fig. 3, with vertical axis is designed and manufactured with hub diameter is 0.02 m and the tip diameter is 0.14 m. Fig. 4 shows the bigger SCPP which is 20m chimney height and 1m diameter and 30m squared collector, which is still under construction.

Measurements of temperature are carried out at locations 1, 2, 3 and 4, shown in Fig. 1 by K-type thermocouple.

Fig. 2. Small SCPP with a zoomed collector.

Fig. 3. Axial turbine.

Fig. 4. Bigger SCPP.

The solar radiation is measured using Protective Glass Dome and Solar Shield (pyranometer) with an uncertainty of ±0.1 W/m^2. The rotational speed of the turbine rotor is measured using Extech 461895 Combination Contact/Photo Tachometer that has an accuracy of 0.05% rdg +1 digit. Electric power is measured using a multimeter.

IV. Results And Discussions

Series of test runs have been carried out in ten days of May and June 2015 with different conditions to test the performance of the S.C.P.P in terms of the outlet collector temperatures, chimney temperature and heat added. Moreover, comparisons between present work and theoretical results are carried out.

Fig. 5 shows hourly variations of the measured solar radiation I over time for the ten days shown in the figure. The maximum solar radiation is found at 6th of June at noon and recorded a value of 1200 W/m^2. Fig. 6 illustrates the hourly variation of ambient air temperature for all measuring days. It is shown from the figure that the day 6th of June has the highest value of temperature that reaches 48 degrees Celsius. It is also shown that the peak value of ambient temperature occurs three hours after the time of maximum solar radiation due to the heat storage.

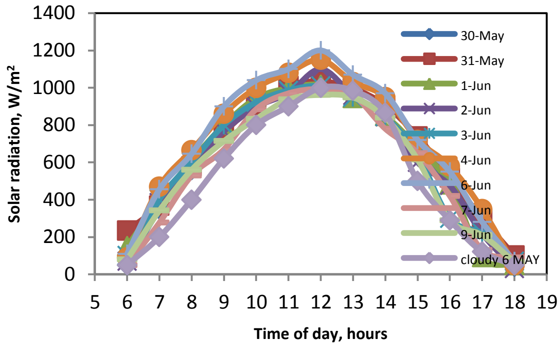

Fig. 5. Hourly variation of solar radiation.

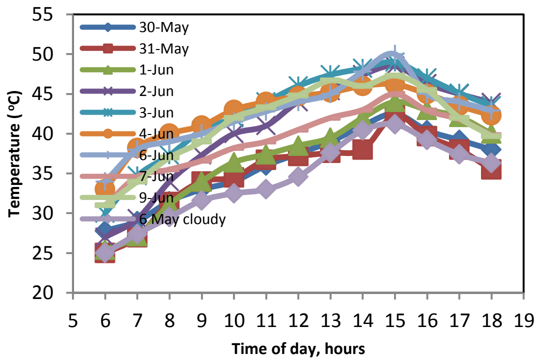

Fig. 6. Hourly variation of ambient air temperature.

Fig. 7 illustrates the electric power measured from the turbine-generator unit through all measuring days. It is observed that the curves presenting all measuring days nearly have the same trend, that is as electric power increases from the beginning of operation hour at 6:00 AM until maximum value at 2:00 PM and then decreases until the end of operation at 6:00 PM. The maximum power is recorded also at 6th of June of a value of 0.85 W at 2:00 PM. Fig. 8 shows a comparison between the measured input power (or available turbine power) and the theoretical one. A good agreement between the two curves is obtained. The available turbine power can be calculated for the bigger model (20 m chimney height). Fig. 9 shows the available turbine power for the bigger model. It is shown from the figure that increasing the chimney height (from 6 m to 20 m) increases the maximum theoretical power from 3 W to 2 kW approximately.

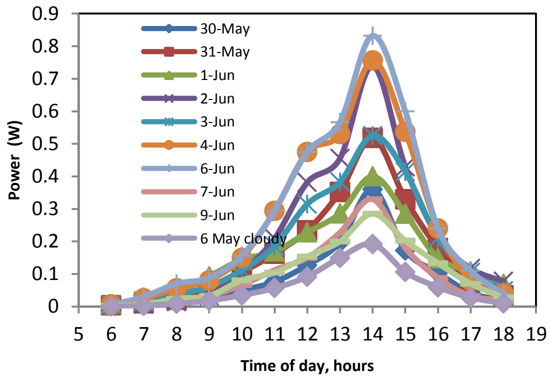

Fig. 7. Variation of exit power from the turbine-generator unit.

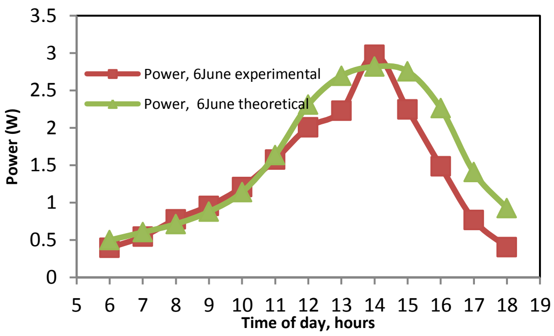

Fig. 8. Comparison between experimental and theoretical available turbine power.

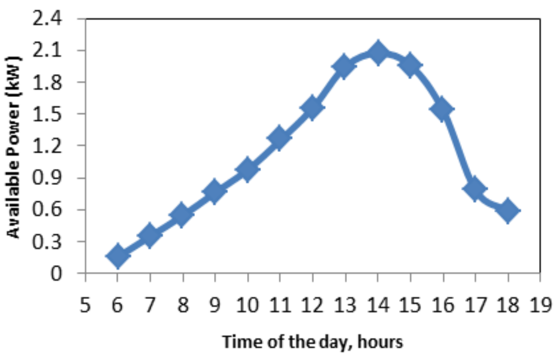

Fig. 9. Available power for the bigger model.

V. Conclusion

A very low cost and very small SCPP is installed to verify the theoretical model used for predicting its performance. The mathematical model of Koonsrisuk and Chitsomboon [9] with some improvements is used. Performance measurements of SCPP are carried out. The results show that the solar intensity has a major effect on the ambient temperature and the power generated. The comparison between the theoretical and experimental power is fairly good. The model is used to predict a bigger size SCPP which is planned in cooperation between Aswan University (Aswan, Egypt) and RUB (Bochum, Germany) and BUW (Wuppertal, Germany) [12]. The bigger model is currently under construction.

Acknowledgment

This work is part of a joint project funded by the Science and Technology Development Fund (STDF)(Project ID:5054) of Egypt and the Federal Ministry of Education and Research (BMBF) of Germany.

References

[1] F. Lu, H. Zhang, X. P. Yao *et al*., "Review of key technologies for solar chimney power generation," East China Electric Power, 2006.

[2] H. Huang, H. Zhang, Y. Huang, and F. Lu, "Simulation calculation on solar chimney power plant system," in *Proc. International Conference on Power Engineering*, Hangzhou, China, 2007.

[3] W. Haaf, K. Friedrich, G. Mayr, and J. Schlaich, "Solar chimneys; Part I: Principle and construction of the pilot plant in Manzanares," *International Journal of Solar Energy*, no. 2, pp. 3–20, 1983.

[4] N. Pasumarthi and S. Sherif, "Experimental and theoretical performance of a demonstration solar chimney model – Part I: Mathematical model development," *International Journal of Energy Research*, no. 22, pp. 277–288, 1998.

[5] N. Pasumarthi and S. Sherif, "Experimental and theoretical performance of a demonstration solar chimney model – Part II: Experimental and theoretical results and economic analysis," *International Journal of Energy Research*, no. 22, pp. 443–461, 1998.

[6] A. Gannon and T. Von Backström, "Solar chimney cycle analysis with system loss and solar collector performance," *Journal of Solar Energy Engineering*, no. 122, pp. 133–137, 2000.

[7] M. Bernardes, A. Voss, and G. Weinrebe, "Thermal and technical analyses of solar chimneys," *Solar Energy*, no. 75, pp. 511–524, 2003.

[8] J. Pretorius and D. Kröger, "Solar chimney power plant performance," *Journal of Solar Energy Engineering*, vol. 3, no. 128, pp. 302–311, 2006.

[9] A. Koonsrisuk and T. Chitsomboon, "Mathematical modeling of solar chimney power plants," *Energy*, no. 51, pp. 314-322, 2013.

[10] T. V. Backström and A. Gannon, "Solar chimney turbine characteristics," University of Stellenbosch, South Africa, 2002.

[11] A. Rekaby, "An experimental investigation and CFD analysis of solar chimney power plant," Ph.D. dissertation, Minia University, Egypt 2016.

[12] R. Harte *et al*., "Solar updraft power plants: Engineering structures for sustainable energy generation," *Engineering Structures*, no. 56, pp. 1698-1706, 2013.

Tarek Mekhail is a professor of mechanical engineering, with the Faculty of Energy Engineering, Aswan University. He got his PhD degree from Shanghai Jiao Tong University, China. His research interests are Turbo machinery, computational fluid dynamics. He is currently the manager of Integrated Technical Cluster, Educational Development Fund, Cabinet of Minister.

Magdy Bassily is an Emirate professor of Turbo machinery, with the Mechanical Power Engineering and Energy Department, Faculty of Engineering, Minia University, Minia, Egypt.

Reinhard Harte received his MSc and PhD degrees in civil engineering and expert on structural safety & fire design, approved by the German Authorities. As a co-founder and CEO of Krätzig & Partner GmbH, he worked in this company for 15 years, becoming an experienced civil engineer and a world-renowned expert for large RC shell structures. Since 1997 he is a full professor at University of Wuppertal, the head of the Institute of Statics and Dynamics of Structures. He is a member of various committees including member of Scientific Board for "Chimneys and Cooling Towers" at VGB Essen; head of Working Group 3 "Cooling and Solar Updraft Towers" of IASS; member of DIBt-Board on "Wind Turbines"; member of Editorial Board of Acta Polytechnica of CTU Prague as well as honorary expert of DFG, DAAD, GACR (Czech Republic) and NRF (South Africa).

Ahmed Rekaby is an assistance lecturer at the Department of Mechanical Power Engineering, Faculty of Energy Engineering, Aswan University, Aswan, Egypt. His research interest is applications of the solar energy especially in the solar chimney power plants.

Mohamed Fathy has received a B.Sc. degree in mechanical power engineering from Assuit University, Egypt in 1991, a M.Sc. degree from Cairo University, Egypt in 2000, then continued his education at the Graduate School of Natural Science and Technology, Okayama University, Japan where he earned him a PhD degree in 2010. He initiated his professional work in the academic sector, starting as a demonstrator at the Mechanical Power Engineering Department since 1993, and later working as an assistant professor at the Mechanical Power Engineering Department, Faculty of Energy Engineering, Aswan University, Egypt. His research interest includes two phase flow and renewable energy. Since December 2014, he has been a researcher in the research project of Solar Chimney Power Generation – Case of Aswan, Egypt, founded through STDF of Arab Republic of Egypt and BMBF federal republic of Germany.