Conference Paper

Performance Analysis of Solar Updraft Power Generator in Indonesia

Hadyan Hafizh, Hiromichi Shirato, and Daiki Yui

Department of Civil & Earth Resources Engineering, Kyoto University, 615-8540 Kyoto, Japan

Abstract

Solar updraft power generator (SUPG) is a renewable energy facility capable of harnessing the solar energy. The first large prototype of SUPG was built in 1980's in Manzanares, Spain to evaluate the projected performance of the facility and to serve as verification tools for future power simulator development. In this paper, the performance of a solar updraft power generator is assessed using the developed mathematical model. The model is validated by comparison with experimental data of Manzanares SUPG. The validated model is then used to calculate the amount of energy produced in seven selected locations in Indonesia. The selected cities in Indonesia exhibited a higher average monthly energy production compared to those in Manzanares. In particular a site like Kupang, would generate two times the energy of the Manzanares SUPG. The power production is sufficient for the needs of this isolated area in Indonesia and has the potential to solve the energy issue.

Keywords: Indonesia, Power Production, Renewable Energy, Solar-Induced Wind Energy

Corresponding Author: Hadyan Hafizh; email: hafizh@alumni.itb.ac.id

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1. Introduction

A solar updraft power generator consists of three main parts which are solar collector, solar tower and wind turbine. It offers compelling concepts in producing electrical power by utilizing the solar radiation to increase the airflow temperature, making it less dense than the ambient air which induces a buoyancy force in the form of an updraft flow [1]. The desired kinetic energy from the updraft flow will be extracted by one or series of wind turbine located at the center of solar collector. The energy conversion is complex, but in principle, it is not an obscure theory. The conversion process can be explained as follows. When solar radiation arrived at the surface of the solar collector, part of it is absorbed by the ground under the solar collector and most of the solar radiation is transmitted to the down layer of the ground. The ground and the solar collector will also emit radiation, making the modeling of heat transfer process more complex [2]. Furthermore, the absorbed solar radiation is then transferred in form of heat flux to the airflow via convection process and to the down layer of the ground through conduction process. These mechanisms create the differences in the properties of airflow such as pressure, density, and temperature, between the inside and the outside of SUPG system. The pressure difference conceives the inertia force while the density difference – due to temperature difference – organizes the buoyancy force. These two forces are the main driving force in the SUPG system.

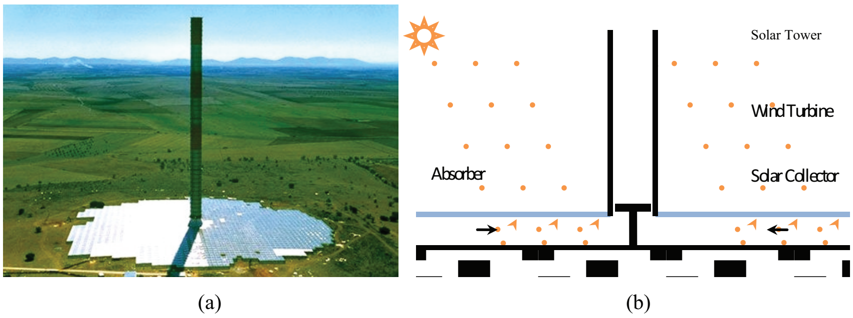


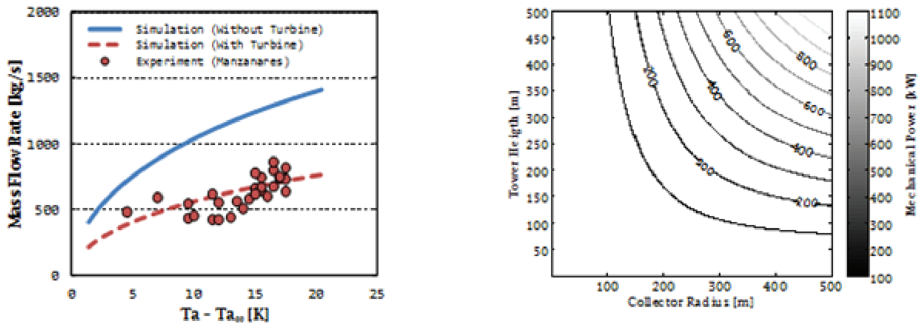
Figure 1: (a) A picture of the Manzanares SUPG in Spain, (b) Illustration of the Manzanares SUPG showing its main parts.

Although the physics behind the energy conversion process is complex, this power plant provides uncomplicated design where turbines and generators are the plant's only moving parts. Therefore, a lot of researchers have been captivated by the potential benefits that this power generator might offer for a clean power production. However, it has an inherent low efficiency compared to the other conventional power generator. Much effort have been devoted to improve its efficiency such as adding thermal storage equipment [3,4], studying the influence of geometry to the power production [5,6,7], or modifying the design of the SUPG [8,9,10]. With this reason, we investigate the performance of a solar updraft power generator expected to provide the remote regions in Indonesia with electric power. This study also presents the analysis about the influence of geometrical and physical parameters such as tower height, collector radius and temperature difference, on the power output. The physical parameters of a solar updraft power generator were determined by using the numerical simulation.

2. Mathematical Model

The performance analysis of solar updraft power generator is based on a mathematical model which has been developed in [11]. This mathematical model is derived from the mass, momentum, and energy balance equations with addition of one state equation. Several assumptions have been implemented to these equations such as inviscid, incompressible, and one dimensional axisymmetric flow. To verify the simulation assumption and procedure, the Manzanares SUPG has been considered as test case. Dimension of the Manzanares SUPG are as follows [12]: solar collector radius, 122 m; solar tower height 200 m; solar tower radius, 5.08 m; solar collector height, 2 m. A picture and illustration of the Manzanares SUPG are presented in Fig. 1.

The maximum mass flow rate inside the solar tower can be obtained by applying the momentum balance equation on a control volume in the tower. In addition, the change of airflow density can be represented by the change of airflow temperature which is known as the Boussinesq approximation [13]. The equation for mass flow rate $\dot{m}$ is then given by



(a) (b)

Figure 2: (a) Model validation, (b) Effects of tower height and collector radius to the power.

$$\dot{m} = \rho\pi {r_{tow}}^2 \sqrt{2g\frac{T_a - T_{a\infty}}{T_{a\infty}} h_{tow}} \quad (1)$$

where ρ is the airflow density, g is the gravity constant, T_a is the updraft temperature, $T_{a\infty}$ is the ambient air temperature, and r_{tow}, h_{tow} are the tower radius and tower height respectively. The mechanical power P delivered by the turbine is obtained as

$$P = \frac{\dot{m}^3 C_P}{2\rho^2\pi^2 {r_{blade}}^4} \quad (2)$$

where r_{blade} is the radius of turbine blade and C_P is the coefficient of power. The suitable value of C_P should be obtained from experimental data.

In order to validate the developed model, the simulated mass flow rate is then compared with the experimental result of the Manzanares SUPG. Simulated mass flow rate are calculated for two cases. The first case is simulation without energy extraction or without turbine configuration. This case will give the maximum amount of mass flow rate. The second case is simulation with energy extraction or with turbine configuration. The mass flow rate from the latter case will be less than the former case since part of its kinetic energy has been extracted. The results are presented in Fig. 2 (a) which shows the simulated mass flow rate for two cases together with the experimental mass flow rate from the Manzanares experiment. It is observed that the simulation result is in good agreement with the experimental data, demonstrating that the developed model is reliable and can be used for the study of power production in Indonesia.

Fig. 2 (b) shows the effect of tower height and collector radius on the generated mechanical power. The mechanical power was computed for Irradiance $I = 1000$ W/m^2. The tower height and the collector radius are varied linearly up to 500 m. It is recognized that the power production increases with the increase in the size of power generator.

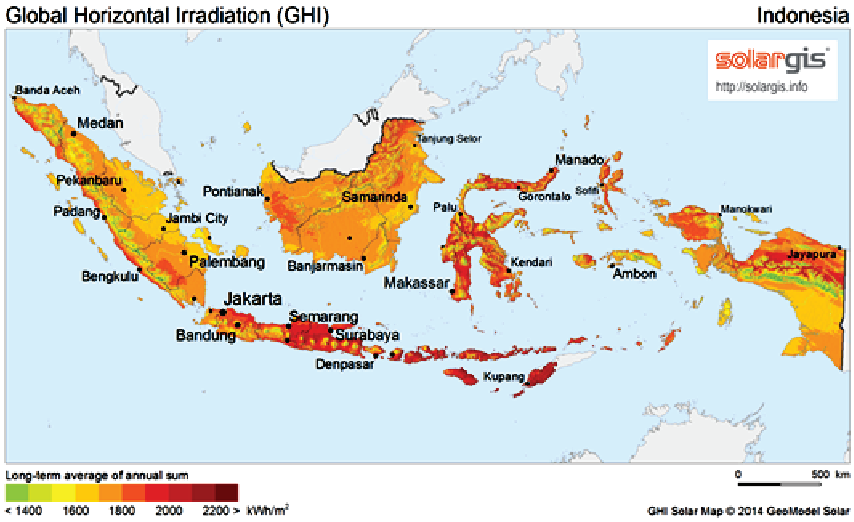


Figure 3: Solar radiation map of Indonesia [16].

3. Results and Discussion

Evaluation of solar updraft power generator performance in selected regions in Indonesia is discussed. In the current investigation, 7 regions have been selected for feasibility study of constructing a solar updraft power generator. They are: Pekanbaru in Sumatra Island, Semarang in Java Island, Pontianak in Kalimantan Island, Kupang in Nusa Tenggara Island, Makasar in Sulawesi Island, Ambon in Maluku Island, and Jayapura in Papua Island. These locations have been selected to represent regions of different major Island in Indonesia. These regions are marked with rectangle boxes in solar radiation map of Indonesia (Fig. 3). The meteorological data such as solar radiation and ambient air temperature are retrieved from [14,15]. The monthly solar radiation data were selected in the current work. These data are then used to calculate the power for each selected regions by using the developed mathematical model.

The results of simulated monthly energy production are presented in Fig.4. In this figure, the performance of a solar updraft power generator was calculated for the same geometry as the Manzanares SUPG. The energy production in Kupang is the highest among the selected regions (304.1 kWh/day in September). This is closely followed by Makassar and Semarang (270.6 kWh/day and 265.7 kWh/day, both in August). Ambon and Pekanbaru have the highest record of energy production in October and March while the other two locations are Pontianak and Jayapura, where the highest energy production is observed in August and in September respectively.

Table 1 shows a comparison between the simulated average monthly energy in Indonesia and the measured average monthly energy in Manzanares, Spain. The energy outputs are presented in kWh/month in order to estimate how many houses could be powered. With assumption that the average electricity consumption for a household is 250 kWh/month where the consumption is mainly for lighting, TV, fans, iron, rice cooker, and water pump, thus a solar updraft power generator could provide the electricity for about 20 to 30 houses in isolated area in Indonesia.

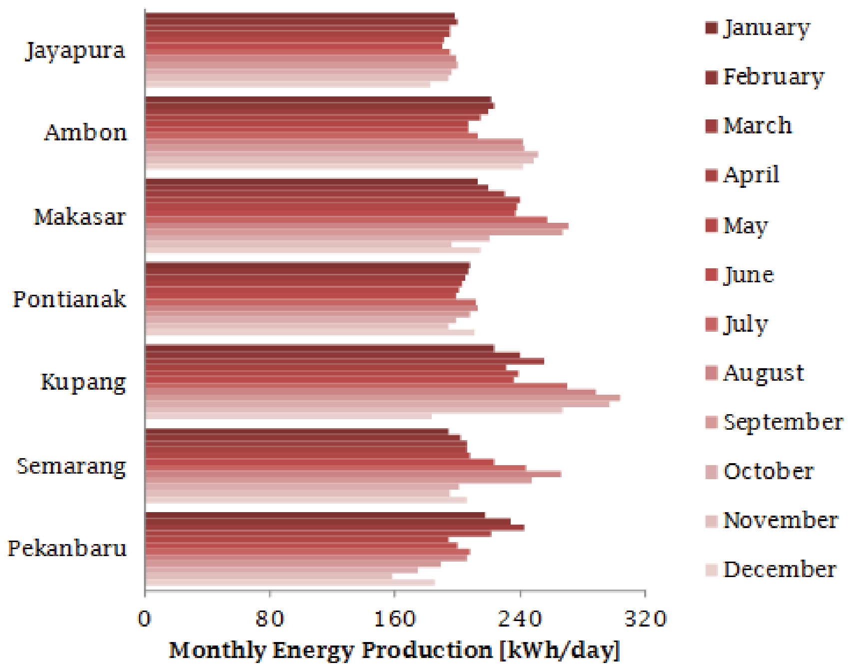


Figure 4: Calculated energy production in selected locations in Indonesia.

Selected Locations	Average Monthly Energy [kWh/month]
Pekanbaru	6081.66
Semarang	6493.24
Kupang	7583.55
Pontianak	6147.07
Makassar	7003.19
Ambon	6834.48
Jayapura	5844.31
Manzanares	3682.50

Table 1: Average Monthly Energy in Selected Locations.

Furthermore, the monthly energy production in all selected locations in Indonesia showed a higher value compared to those in Manzanares, Spain. A site like Kupang, where it has the highest energy production per month among the selected locations, would generate two times the energy of the Manzanares SUPG.

4. Summary

The performance of a solar updraft power generator in selected locations in Indonesia has been assessed to evaluate its feasibility. The assessment is conducted by using a developed model which has been validated by comparing the simulated results with the experimental data where a good agreement has been obtained [11]. The result shows that a solar updraft power generator in sunny areas of Indonesia, such as Kupang, would generate twice the energy than an identical one in areas such as

Manzanares, Spain. In addition, the energy outputs could potentially provide 20 to 30 household's electrical needs for a month in remote area in Indonesia.

References

[1] W. Haaf, K. Friedrich, G. Mayr, J. Schlaich, and I. Solar Chimneys Part, Principle and Construction of the Pilot Plant in Manzanares, Int, *J. Sol Energy*, **2**, 3–20, (1983).

[2] M. A. S. Bernardes, T. W. Von Backström, and D. G. Kröger, Analysis of some available heat transfer coefficients applicable to solar chimney power plant collectors, *Sol Energy*, **83**, 264–275, (2009).

[3] M. A. S. Bernardes and X. Zhou, On the heat storage in solar updraft tower collectors – Water bags, *Sol Energy*, **91**, 22–31, (2013).

[4] M. A. S. Bernardes, On the heat storage in solar updraft tower collectors – Influence of soil thermal properties, *Sol Energy*, **98**, 49–57, (2013).

[5] M. A. S. Bernardes, et al., Thermal and technical analyses of solar chimneys, *Sol Energy*, **75**, 511–524, (2003).

[6] J. Li, P. Guo, and Y. Wang, Effects of collector radius and chimney height on power output of a solar chimney power plant with turbines, *Renew Energy*, **47**, 21–28, (2012).

[7] M. Ghalamchi, A. Kasaeian, and M. Ghalamchi, Experimental study of geometrical and climate effects on the performance of a small solar chimney, *Renew Sustain Energy Rev*, **43**, 425–431, (2015).

[8] M. Zhang, X. Luo, T. Li, L. Zhang, X. Meng, K. Kase, S. Wada, C. W. Yu, and Z. Gu, From dust devil to sustainable swirling wind energy, *Sci Rep*, **5**, p. 8322, (2015).

[9] L. M. Michaud, Vortex process for capturing mechanical energy during updward heat-convection in the atmosphere, *Appl Energy*, **62**, 241–251, (1999).

[10] M. W. Simpson, A. J. Pearlstein, and A. Glezer, Electric power generation using buoyancy-induced vortices, ICREPQ 13-Spain, (2013) ISSN 2172-038 X, no. 11.

[11] H. Hafizh and H. Shirato, Aerothermal simulation and power potential of a solar updraft power plant, *J Struct Eng JSCE*, **61A**, 388–399, (2015).

[12] W. Haaf, Solar Chimneys Part II: Preliminary Test Results from the Manzanares Pilot Plant, Int, *J. Sol Energy*, **2**, 141–161, (1984).

[13] G. Nellis and S. Klein, in *Heat Transfer*, Cambridge University Press, New York, 2009.

[14] M. Rumbayan, A. Abudureyimu, and K. Nagasaka, Mapping of Solar Energy Potential in Indonesia using ANN and GIS, *Renew Sustain Energy Rev*, **16**, 1437–1449, (2012).

[15] `http://www.dataonline.bmkg.go.id`

[16] `http://www.solargis.info`