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A Review of Sloped Solar Updraft Power Technology

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Abstract

The Solar Updraft Power Plant (SUPP) concept was successfully proven in the last few decades through many experimental and analytical approaches. However, the high investment cost compared to the plant efficiency and the limited height of the chimney due to the technological constraints are considered the main disadvantages of the SUPP. In order to overcome these problems, many novel concepts were proposed; One being the Sloped Solar Updraft Power Plant (SSUPP). This paper provides a comprehensive overall review for all SSUPP researches up-to-date including the principle with a description of the plant, physical process, theoretical and experimental studies.

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Keywords: Solar energy, Solar chimney, Updraft tower, Sloped solar collector;

1. Introduction

In the last few decades, the global consumption of energy has increased significantly. At the same time, continuation of utilizing fossil fuels is facing many challenges especially the global warming. These facts lead the researchers to focus more on renewable energy. Solar energy is a clean and renewable energy resource which many consider to be the future human energy resource. Electricity can be obtained from solar energy by two means, the photovoltaic effect and the solar thermal cycle. The SUPP is one of the solar thermal plants that can operate and produce electricity with very low temperature difference (starting with 10 °C [1]).

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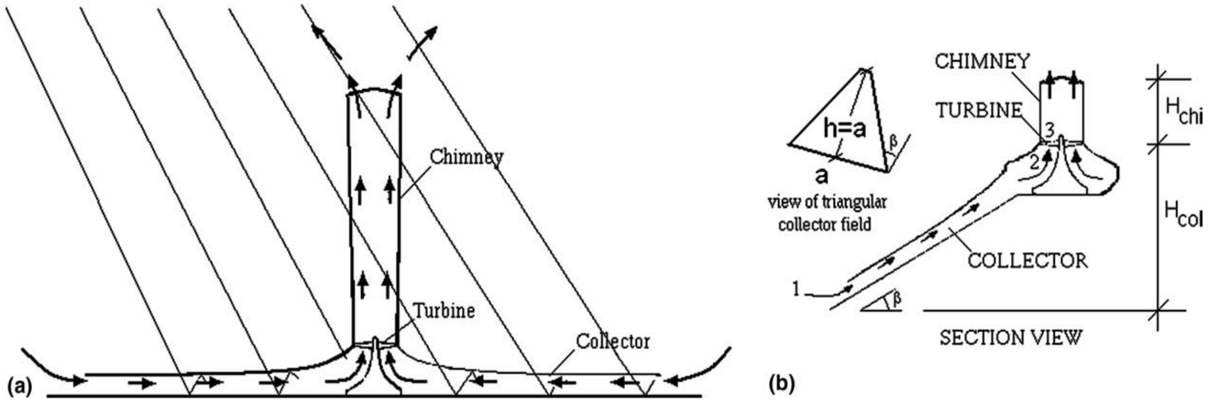

Fig. 1. Schematic of the solar chimney: (a) systems on horizontal surface at low latitudes, (b) systems in sloped surface at high latitudes [2].

As depicted in Fig. 1(a), the SUPP consists of three main components: circular solar collector, chimney, and the turbine. The circular solar collector is erected above the ground with a certain gap between the canopy and the soil. The chimney is constructed in the middle of the solar collector and last component is the turbine which is installed at the lower part of the chimney. The SUPP physical operating principle is very simple. Solar radiation heats air underneath the canopy by means of greenhouse effect. When air gets hot, the density will reduced and the air will driven naturally up to the chimney outlet under the natural buoyancy effect. This generates an updraft air velocity in the chimney that operates the turbine, which is located at the chimney base, to generate electricity. New air will enter the system through the periphery of the solar collector and it will be heated and the process will continue. The solar chimney was originally proposed by Professor J. Schlaich of Stuttgart in 1968. In the 1980s, the SUPP principle was proven through eight years of continuous operation of a 50 kW experimental plant which was built in Manzanares, Spain [1].

The SUPP has many disadvantages. The main limitation is the low efficiency which is lower than 1% .The SUPP efficiency increases as per the square root of the chimney height [1]. The chimney height, therefore, must be as high as possible. Consequently, a substantial capital cost has to be incurred for constructing the chimney. On the other hand, the chimney height is restricted because of the technological constraints and restrictions on the construction materials. There are also external limitations such as possible earthquakes, which can easily destroy super high solar chimneys. Based on these facts, many researchers developed novel designs for the SUPP to reduce capital cost and improve efficiency [1, 3].

Papageorgiou [4, 5] proposed to build higher and cheaper solar chimneys named floating solar chimneys, which can replace the conventional reinforced concrete solar chimneys. Zhou and Yang [6] proposed a novel SUPP with a floating chimney stiffened onto a mountain-side and studied the resultant power in China's deserts. Another novel design for the solar chimney was proposed and discussed by Zhou et al. [7] which consists of a design for constructing a giant solar collector surrounding a hollow space excavated in a mountain in a steady-geology region. The giant hollow space in the mountain acts as an updraft chimney.

All the above mentioned alternative designs are very limited technically and site wise. However, the SSUPP, which is proposed by Bilgen et al. [2], has more interest because of its applicability in many regions around the world were many hill and mountain sides are suitable for this kind of plants.

In this paper, the details of the Sloped Solar Updraft Power technology is described, and the up-to-date status and development of this technology reviewed, including the physical processes, experimental and theoretical studies.

2. SSUPP Technical Review

The novel Concept of the SSUPP is firstly Proposed by Bilgen and Rheault [2]. It is consisting of a sloped solar collector that has a triangular surface area with a chimney at its apex as shown in Fig. 1(b). The solar collector sides are closed and the air enters the lower side and rises as heated by ground to the apex where a short chimney is installed vertically [2]. At the chimney base, a turbine is installed to generate electricity.

Designing solar chimney collector system on sloped surface or suitable hills has two major advantages: first, if the collector slope is optimized, the solar radiation received by the collector system may be improved to a satisfactory level for a year round operation and the second, a sloped surface constitutes a natural chimney, therefore the chimney height standing above the collector height may be reduced considerably, thus reducing civil engineering problems and cost [2].

2.1. SSUPP Theoretical Study Status

In 2005, the proponents of the SSUPP technology, Bilgen and Rheault [2], developed a mathematical model following the methods for evaluating long term solar system performance using the monthly average absorbed radiation. The air density was assumed linearly changes between entrance and exit of the sloped collector. Indeed, this hypothesis is justified because ΔT between air temperature at the entrance and exit of the collector is small, about 10–15 ^{o}C.

Bilgen et al. [2] performed parametric analysis to optimize the collector slope to maximize insolation received by solar collector for three locations, Ottawa, Winnipeg, and Edmonton at high altitude, respectively, whose latitudes changed from 45.58^{o}N to 49.98^{o}N to 53.68^{o}N. The results showed that the optimum slope of collector should be 5^{o} to 7^{o} smaller than the altitude. A thermo-dynamic simulation study was conducted to determine the design parameters and operational data for 5 MW SSUPPs (See Table.1). The thermal performance of the SUPP is slightly higher than that with the conventional horizontal collector. It was found also that despite less favorable solar radiation on horizontal planes in higher latitudes, the annual electric energy production may be as high as 85% of that which would be produced in best favorable locations from the same plants with horizontal collector field. On the other hand, for a typical location, the chimney height may be reduced by almost 90%, which may result in considerable saving of initial investment as well as in elimination of civil engineering problems, which are also related to operation and maintenance cost. It was also found that the overall performance will not be penalized more than 13%, if the slope varies by 20 ^{o} to 25 ^{o} from the optimum slope [2].

Table 1. Preliminary design parameters for 5MW solar chimney power plant [2].

	Ottawa	Winnipeg	Edmonton	Schlaich [1]
Collector diameter (m)	-	-	-	1110
Collector Area (m^2)	950 000	950 000	950 000	950 000
Chimney height (m)	123	60	35	547
Collector height (m)	848	975	1024	-
Temperature rise in collector (^{o}C)	25.4	25.4	25.4	25.4
Updraught velocity (m/s)	9.1	9.1	9.1	9.1
Total pressure head (Pa)	518.3	518.3	518.3	383.3
Average efficiency				
Collector %	56.0	56.0	56.0	56.24
Chimney %	1.82	1.82	1.82	1.45
Turbine %	77.0	77.0	77.0	77.0
Whole system %	0.79	0.79	0.79	0.63

Wei et al. [8] also analyzed the slope's effect for receiving insolation based on monthly average solar radiation data and the feasibility of building SUPP in west areas of China. A simplified mathematical model was prepared and solved using MATLAB. The model was used to predict the best gradient of the sloped solar collector which was founded to be around the latitude value where the plant was located with a floating rate varied within 20%.

Cao et al. [9] designed a SSUPP provide electric power for remote villages in Northwest China, and Lanzhou City was taken as an example. The designed plant, in which the height and radius of the chimney are 252.2 m and 14 m respectively, the radius and angle of the solar collector are 607.2 m and 31° respectively, is designed to produce 5MW electric power on a monthly average all year. In the model building process, the author made some assumptions like ignoring the flow resistance losses and using boussinesq assumptions for air density. Fig.2 shows the solar chimney efficiency and system efficiency of the SSUPP during a year. It is obvious that the system efficiency and solar collector efficiency have similar curve tendencies through a year: efficiencies are both large in winter and spring days, whereas low in summer and autumn days, with the turning point in July. And, the two curves are approximately symmetrical to July. The author also gave detail expressions about the temperature increase, system pressure, airflow speed, system efficiency and solar collector efficiency.

Panse et al. [10] developed mathematical model considering the total energy balance. The factors influencing the flow of air inside the chimney (the sloped solar collector in SSUPP case) are: (i) heat losses to the surrounding, (ii) atmospheric lapse rate, (iii) frictional pressure drop and (iv) external wind near the outlet of the chimney. The complete energy balance per second of the SSUPP is given by:

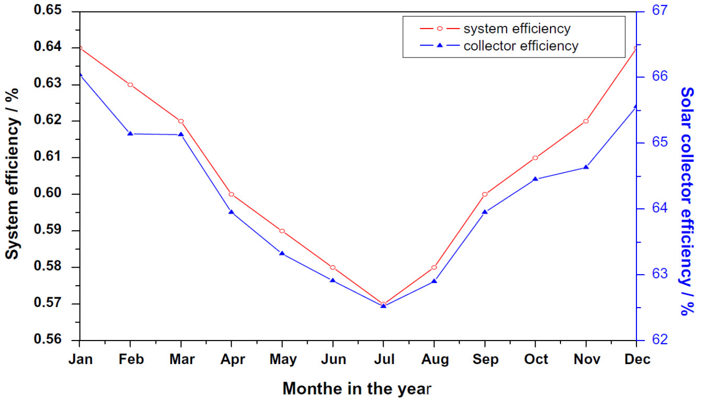

Fig. 2. Efficiency of the SSCPP in one year [9].

The amount of solar energy absorbed = Change in enthalpy of air + Heat losses to the Surroundings + Frictional energy loss + change in pressure energy + change in potential energy + change in kinetic energy.

A case study with solar collector area equal to the collector area of the Manzanares prototype was used to run the mathematical model. it was solved by the best fit method starting with a simplified base case, where all the above losses factors are treated as negligible to obtain expressions for rise in temperature, velocity of emerging air draft and hence its kinetic power. Subsequently, all the above factors are included one by one to obtain similar expressions. Based on these results, the author discussed the effect of heat losses, lapse rate, frictional pressure drop and ambient wind velocity on the power output [10].

In 2012, Koonsrisuk [11] developed a mathematical model based on the continuity, momentum, energy, and state equations for the SUPP system. Additional advantage in this model was including the dynamic pressure and the flow details within the collector. As per [12], the driving pressure in a SUPP is of the same order of magnitude as the dynamic pressure at the collector exit. Thus, neglecting the dynamic component in pressure computation can lead to a very large overall error in the predicted performance of the systems. At that time and since there is no experimental result for SSUPP published; the proposed mathematical model is validated by comparing its results with the predictions of the commercial CFD package. Comparisons shows good agreement between these two predictions with 7.6% maximum difference recorded for the mass flow rate[11]. The mathematical model is used to discuss the effect of many dimensional parameters of the SUPP. It was founded that collector inlet area to collector outlet area shall not be nearly-unity. This will create a strong wind which might carry a lot of surface dust and cause the noise pollution. Also assuming equal difference in density between the collector inlet, outlet and the chimney inlet, outlet is causing over-prediction of the pressure difference across the chimney unless the chimney height is higher than 1000 m.

Cao et al. [13] developed a heat transfer model and used it to compare the performance of a conventional SUPP and two SSUPPs with the collector oriented at 30° and 60°, respectively. To carry out the analysis of SUPP performances, Lanzhou city (103.50°E, 36.03°N) was chosen and three reference 5 MW SUPPs are considered for examples, whose baseline parameters are given based on [1, 2] which are given in Table 1 (columns two and four). Fig. 3 depicted the system efficiencies and the solar collector efficiencies for the conventional SUPP (C1), and the SSUPPs with the collector tilted angle of 30° (C2) and 60° (C3). The results show that the solar collector efficiencies of C1 are symmetrical with July and the solar collector efficiency of C2 is higher than that of C3 in summer days. In addition, C2 has the highest average solar collector efficiency of 56.43%, followed by C3 of 56.11%, and the lowest is C1 of 48.52%. In a word, the tilted collector would enlarge the solar collector efficiency[13]. Then the power generation from SUPPs at different latitudes in China is also analyzed and Results indicate that the larger solar collector angle leads to improved performance in winter but results in lower performance in summer. It is found that the optimal collector angle to achieve the maximum power in Lanzhou, China, is around 60° [13].

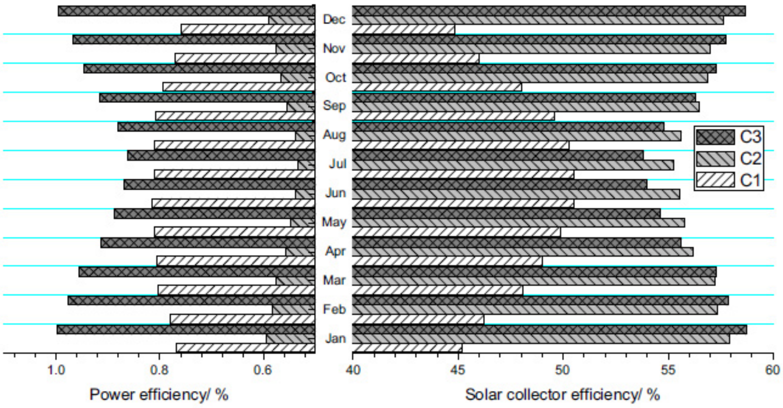

Fig. 3. Power efficiencies and solar collector efficiencies of C1, C2 and C3 throughout the year [13].

Koonsrisuk [14] compared SUPP with SSUPP using the second law of thermodynamics in order to exam the entropy generation number and second-law efficiency. The mathematical models proposed by [11, 15] were used to evaluate SSUPP and SUPP respectively. The author studied a power capacity of 5 MW and used the same design parameters used in [1, 2] which are given in Table 1 (columns one and four). As per [1], the optimal dimensions for a SUPP do not exist. however, [14] reported that for a particular SUPP, the minimum entropy generation and the maximum second-law efficiency both occur when the collector area is optimized. It was also noticed that entropy generation in SUPP is higher than that in SSUPP because temperature difference generated by the collector of the SUPP is higher than that of the SSUPP. The results also showed that the increase in chimney height for both types will result in a lower entropy generation number.

Zhou et al. [16] designed the solar collector of a SSUPP case SC1 and two SUPP cases HC1 and HC2 based on the 5 MW SSUPP proposed in Ottawa [2]. A theoretical model is developed based on essential definition of buoyancy to study the performance of SSUPP by regarding the air as a compressible fluid, as compared to conventional SUPPs. The parameters for SC1, HC1 and HC2 using essential expression of pressure potential are respectively compared with the expressions containing no integral for SC1, HC1 and HC2. The sloped collector height and width changes are carefully chosen to produce an ideal condition under which the airflow is gradually accelerated from the collector inlet to outlet. Results show that the expression containing no integral for the pressure potential of the conventional SUPP ,was developed by Kröger and Blaine [17], is accurate for conventional SUPP based on a compressible fluid model, and that the expression containing no integral of pressure potential for SSUPP based on an incompressible fluid model , was developed by Bilgen and Rheault [2], is not accurate for predicting the driving force of SSUPP, because it is neglecting the change of the atmosphere density with heights, and the change of difference of the atmospheric density and the density of the air current inside the short chimney with heights.

2.2. SSUPP experimental study status

The available publications up-to-date showed that only one experimental effort has been put on the SSUPP. Kalash et al. [18] erected a pilot SSUPP in Damascus University, Syria. The prototype has a triangular shape and is tilted at 35^o towards the south with an approximate area of 12.5 m^2. The chimney diameter is 0.31 m and it is 9 m tall. Eighteen temperature sensors were installed inside the sloped solar collector to measure glass, air, and absorption layer temperatures in different points along the collector. Experimental data were recorded every 10 min for a total of 40 consecutive days during winter from 27/01/2012 to 06/03/2012 to investigate the temperature changes in the sloped collector. Fig.4 shows the SSUPP prototype after erection.

Fig. 4. SSUPP prototype in Damascus University, Syria [18].

The daily variations of air temperature and velocity are investigated and depicted in Fig.5. The study shows that solar radiation has direct impact on the chimney inlet temperature and the absorption layer, which was comprised of mountain soil to simulate real mountains' conditions in Syria, stored enough thermal energy to control the chimney inlet temperature and keep it almost constant for about three hours during noon period when solar radiation starts to decrease [18].

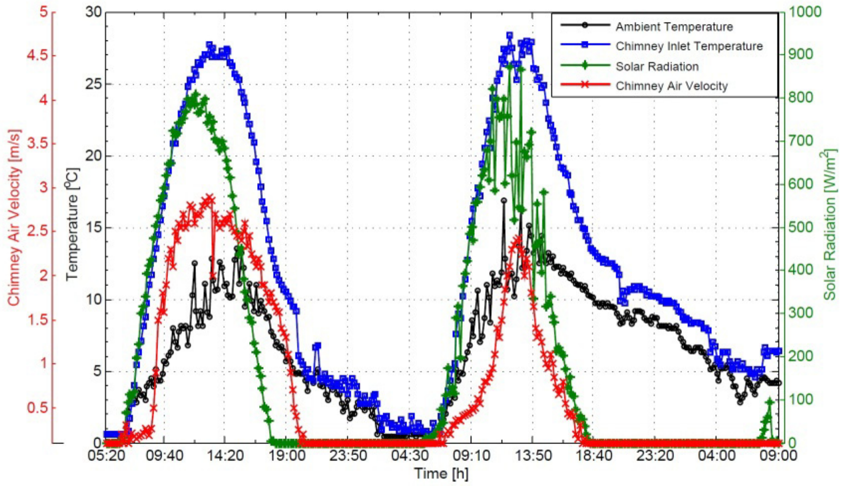

Fig. 5. Daily variations in solar radiation, chimney inlet temperature, chimney air velocity, and ambient temperature [18].

3. Conclusion

The Sloped Solar Updraft Power technology is a promising solution to improve the solar updraft tower plant performance and has attracted the attention of many researchers since firstly proposed by [2] in 2005. A comprehensive overall review for the SSUPP components, principle and the theoretical and experimental studies up to date are summarized. More investigations to optimize the SSUPP dimensional parameters, especially by using finite element technology, are recommended and accurate economical studies should be performed also to compare between the conventional SUPPs and the SSUPPs.

References

[1] J. Schlaich, The Solar Chimney: Electricity from the Sun, Axel Menges, 1995.
[2] E. Bilgen, J. Rheault, Solar chimney power plants for high latitudes, SoEn, 79 (2005) 449-458.
[3] X. Zhou, F. Wang, R.M. Ochieng, A review of solar chimney power technology, Renewable and Sustainable Energy Reviews, 14 (2010) 2315-2338.
[4] C.D. Papageorgiou, Optimum design for solar power stations with floating solar chimneys, In: Proceedings of the 32nd national heat transfer conference Kwangju, Korea, (2004) P. 763-772.
[5] C.D. Papageorgiou, turbine power stations with floating solar chimneys, In: IASTED proceedings of power and energy systems, EuroPES 2004, conference,Rhodes Greece, (2004) p. 157-158.
[6] X. Zhou, J. Yang, A Novel Solar Thermal Power Plant with Floating Chimney Stiffened onto a Mountainside and Potential of the Power Generation in China's Deserts, HTrEn, 30 (2009) 400-407.
[7] X. Zhou, J. Yang, J. Wang, B. Xiao, Novel concept for producing energy integrating a solar collector with a man made mountain hollow, Energy Conversion and Management, 50 (2009) 847-854.
[8] W. Jing, W. Fenghao, Z. Liang, Research on the Best Slope Gradient of Slope Solar Induced Convective Flows Power Generation System, in: D.Y. Goswami, Y. Zhao (Eds.) Proceedings of ISES World Congress 2007 (Vol. I – Vol. V), Springer Berlin Heidelberg, 2009, pp. 1795-1799.
[9] F. Cao, L. Zhao, L. Guo, Simulation of a sloped solar chimney power plant in Lanzhou, Energy Conversion and Management, 52 (2011) 2360-2366.
[10] S.V. Panse, A.S. Jadhav, A.S. Gudekar, J.B. Joshi, Inclined solar chimney for power production, Energy Conversion and Management, 52 (2011) 3096-3102.
[11] A. Koonsrisuk, Mathematical modeling of sloped solar chimney power plants, Energy, 47 (2012) 582-589.
[12] A. Koonsrisuk, T. Chitsomboon, A single dimensionless variable for solar chimney power plant modeling, SoEn, 83 (2009) 2136-2143.
[13] F. Cao, L. Zhao, H. Li, L. Guo, Performance analysis of conventional and sloped solar chimney power plants in China, Applied Thermal Engineering, 50 (2013) 582-592.
[14] A. Koonsrisuk, Comparison of conventional solar chimney power plants and sloped solar chimney power plants using second law analysis, SoEn, 98 (2013) 78-84.
[15] A. Koonsrisuk, T. Chitsomboon, Mathematical modeling of solar chimney power plants, Energy, 51 (2013) 314-322.
[16] X. Zhou, S. Yuan, M.A.d.S. Bernardes, Sloped-collector solar updraft tower power plant performance, IJHMT, 66 (2013) 798-807.
[17] J.P. Pretorius, D.G. Kröger, Solar Chimney Power Plant Performance, Journal of Solar Energy Engineering, 128 (2006) 302-311.
[18] S. Kalash, W. Naimeh, S. Ajib, Experimental investigation of the solar collector temperature field of a sloped solar updraft power plant prototype, SoEn, 98, Part A (2013) 70-77.