Review of Solar Chimney Power Technology and Its Potentials in Semi-Arid Region of Nigeria

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Abstract: *Solar chimney (SC) is a natural draft device which uses solar radiation to provide upward momentum to the in-flowing air, thereby converting the thermal energy into kinetic energy. It uses a combination of three established technologies, namely, the greenhouse, the chimney, and the wind turbine. In this study the details of SC power technologies are described, and the status and development of this technology reviewed including the experimental and theoretical study status, as well as the economics for SC power technology. There are also potentials of citing this technology in Nigeria especially in the semi-arid region with solar sunshine hours of up to 9 hours, solar radiation of 7kW/m^2/day and enormous flat land.*

Keywords; Solar chimney (SC), Power plant (PP), Experimental model, Theoretical model, Green house, Wind turbine, Power conversion unit (PCU).

I. Introduction

Increasing in energy demand and large use of fossil fuels have generated great environmental concerns, solar chimney power plant (SCPP) offers interesting opportunities to use pollution free resources of energy. It is a natural power generator that uses solar radiation to increase the internal energy of flowing air. The air mechanical energy can be transformed into electric power through suitable wind turbine (Salah et al, 2010).A solar chimney is a combination of three established technologies, namely, the greenhouse, the chimney, and the wind turbine. The chimney, which is a long tubular structure, is placed in the centre of the circular greenhouse, while the wind turbine is mounted inside the chimney. This unique combination accomplishes the task of converting solar energy into electrical energy. Solar-to-electric conversion involves two intermediate stages; in the first stage, conversion of solar energy into thermal energy is accomplished in the greenhouse (also known as the collector) by means of the greenhouse effect, while in the second stage, the chimney converts the generated thermal energy into kinetic and ultimately into electric energy by using a combination of a wind turbine and generator (Pasumarthi and Sherif, 1998).

The SCPP has notable advantages in comparison with other power production technologies. These include the following: the collector in solar chimney power plant uses both direct and diffuse radiation;the ground provides a natural heat storage; the low number of rotating parts ensure its reliability; no cooling water is necessary for its operation; and simple materials and known technologies are used in its construction (Schlaich, 1995). The objective of this work is to review the concept development and recent advances in the field of solar chimney power technology and to assess its potentiality in semi-arid regions of Nigeria.

II. Solar chimney concept development

One of the earliest descriptions of a solar chimney power station was written in 1903 by Isidoro Cabanyes, a Spanish artillery colonel. He made public the proposition “Proyec to de motor solar” (solar engine project) introducing an apparatus consisting of an air heater attached to a house with a chimney. In the house interior, a kind of wind propeller was placed with the purpose of electricity production, (Cabanyes, 1903).In 1926 Prof. Bernard Dubos proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of the high height mountain,(Günther, 1931). The author claims that an ascending air speed of 50 m/s can be reached in the chimney, whose enormous amount of energy can be extracted by wind turbine.

In the face of the original concepts, the first outstanding action for the SCPP development was the prototype erection in 1982 in Manzanares, The 50 kW plant prototype built in Manzanares (Fig.1), is 194.6 m high, 0.00125 m-thickness metallic wall SC guyed and aPVC roof-covered collector 122 m in radius. Regardless of its dimensions, this prototype was considered as a small-scale experimental model. As the model was not intended for power generation, the peak power output was 50 kW. Haaf(1984) divulged preliminary test results including energy balances, collector efficiency values, pressure losses due to friction and losses in the turbine section,

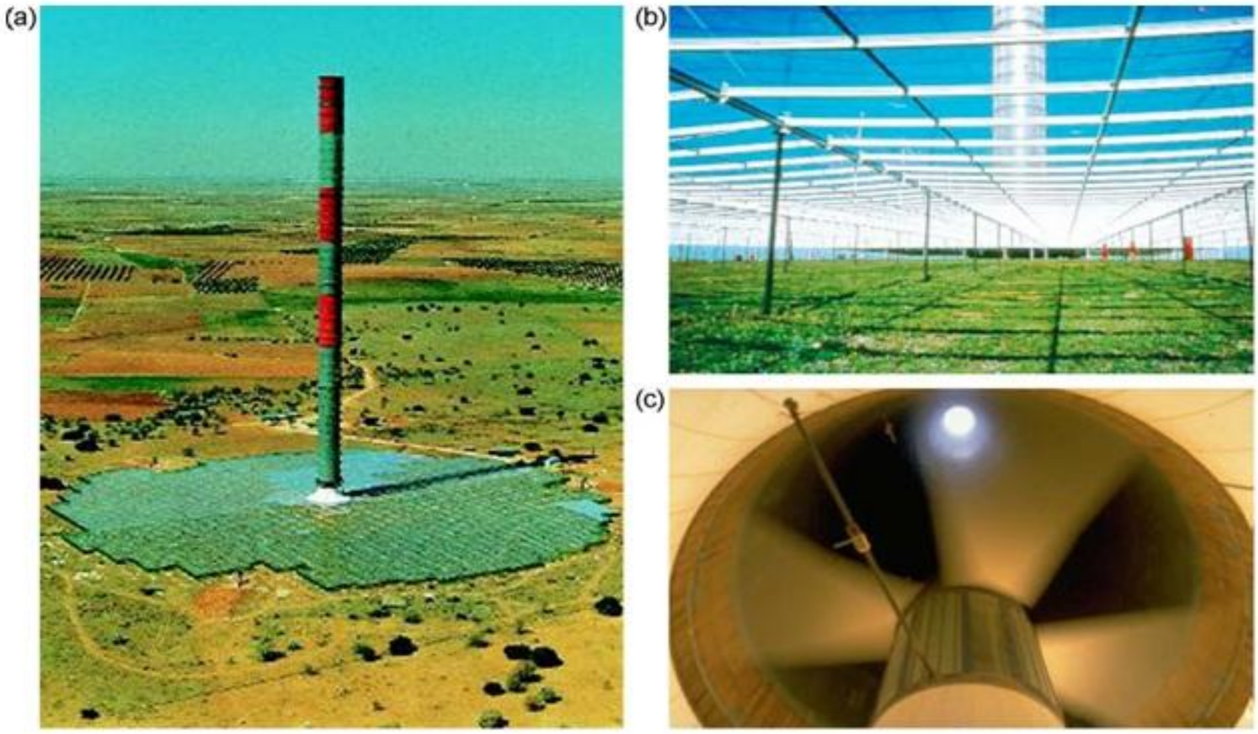

FIG: 1Pictures of Manzanares plant prototype: (a) whole plant; (b) collector; (c) turbine (Schlaich et al 2005)

Castillo (1984) suggested a new "soft" structure approach to the chimney building instead of the conventional "rigid" one. Several other studies were conducted after the construction and testing of the Manzanares prototype, these include transient and steady state fluid dynamic and thermal models, as well as, structural analysis for chimney, collector (including the ground natural heat storage capability) and turbine setups.

III. Study status and advances in solar chimney technology

1. Experiment studies

In the past decades, several experimental models of solar chimney were successively designed, built up, and tested. The Manzanaresplant has been operating for eight years from 1982 to 1989 (Schlaich, 1995). The power output profile correlates closely with solarinsolation profile during day time for this prototype plant without additional storage system, while, there is still an updraft during night time due to thermal storage capacity of natural soil which can be used to produce power during some hours of the night (Haaf, 1984).Krisst(1983), built a courtyard SC power setup with 10W power output. The collector base diameter and SC height were 6 m and 10 m respectively. In 1985, a micro-scale model with a SC 2 m high and 7 cmin diameter and a 9 m^2 collector was built by Kulunkin Turkey (Kulunk, 1985).

In 1997, a SC power setup was built by Pasurmarthi and Sherif in Florida, which had a Lexan roof covered collector of 9.15 m in diameter and a 7.92 m high SC with its diameter gradually decreasing from 2.44 m at the inlet to 0.61 m at the top (Pasurmarthi and Sherif,1998 and Sherif et al, 1995). Type I configuration has an aluminum plate absorber laid down on the ground under the collector roof. Two enhancements were tried on the Type I configuration collector to increase the power output. The Type I configuration collector base was extended18.3 m in diameter to form Type II configuration. Black visqueen and clear visqueen with transparency of about 60% were respectively used as the absorber and the roof for the extended parts of Type II configuration collector. An intermediate canvas absorber was introduced between the roof and the aluminum plate absorber inside the Type II configuration collector to improve the conversion efficiency of the collector and formType III configuration collector. The Type I configuration collector air temperature rise was about 15^{o}C, whereas the Type II and Type III collectors were able to raise the temperature by 25^{o}C and 28^{o}C, respectively. These showed the Type I configuration collector was not as effective, as type II and type III. In the Type II and Type III collectors the temperature variation in the extended section was almost the same, whereas in the Lexan roof covered collector section there was a marginal improvement in the Type III collector compared to the Type II collector. In the Type III collector, air flowed on either side of the extended canvas absorber, thus inducing an increase in mass flow rate, and hence power output (Pasurmarthi and Sherif, 1998).

A pilot SC setup consisting of an air collector 10 m in diameter and an 8 mhigh SC was built in Wuhan, China in 2002 and re-built several times (Zhou et al 2007a, 2007b and 2008). For up-to-date structure, collector roof and the SC were made of glass 4.8 mm in thickness and PVC, respectively. Temperature difference between the collector outlet and the ambient usually could reach 24.1^{o}C. An interesting phenomenon was found that air temperature inversion appeared in the latter SC after sunrise both on a cool day and on a warm day. The air temperature inversion was formed by the increasing process of insolation from the minimum and cleared up some time later when the absorber bed was heated to a high enough temperature to let airflow break through the temperature inversion layer and normally flow out from the SC outlet.

Based on the need for plans for long-term energy strategies, Botswana's Ministry of Science and Technology designed and built a pilot SC power setup for research (Ketlogetswe, 2008). SC was manufactured from glass reinforced polyester material, which had an inner diameter of 2 m and a height of 22 m. The collector roof was made of a 5 mm thick clear glass supported by a steel framework. The collection area reached at approximately 160 m^2. The absorber under the roof was made of two layers of compacted soil approximately 10 mm thick and a layer of crushed stones. The layer of crushed stones was spread on the top surface of the compacted soil layer. A SC power setup was built with a SC 11 m high and 1 m in diameter on the campus of Universidade Federal de Minas Gerais, in Belo Horizonte, Brazil (Ferreira et al, 2008 and Maia et al, 2009a and 2009b). The SC structure was manufactured in five wood modules of 2.2 m high each, which was covered internally and externally with glass fiber. A SC power setup was also built up on the campus of Suleyman Demirel University, in Isparta, Turkey, which had 15 m high SC 1.2 m in diameter and a glass covered collector 16 m in diameter.

A small prototype demonstrating the combination of an experimental solar pond of approximately 4.2m diameter and 1.85m dept with a SC 8m high and 0.35m in diameter was constructed by Golder in the campus of RMIT University, in Bundoora, Australia in 2002 (Akbarzadeh,2009and Golder,2003). The water to air heat exchanger was equipped at the SC base. The SC was manufactured from flexible circular ducting which was insulated with60mmthick fiberglass and supported by the structure of a small experimental aero generator with in a fewmeters of the solar pond. Hot brine was extracted from the solar pond at a rate of 1.21 liter per minute through a diffuser placed at approximately 0.5mabove the bottom of the pond and was pumped through the heat exchanger. After delivering its heat to the air which passed through the heat exchanger and SC, the cooler brinewas returned to the bottom of the pond through a second diffuser. The measurements showed that for a solar pond temperature of 45°C, the temperatures of the brine entering and exiting the heat exchanger could reach 37°C and 25 °C, and the air entering through the heat exchanger was raised from the outside ambient temperature of 17°C to an exit temperature of about 28 °C. An air flow velocity in the SC was measured at 1 m/s (Akbarzadeh, 2009and Golder, 2003).

2. Theoretical studies

Schlaich's pioneered the first work on the SC concept to harness solar energy, after that many researchers, such as;Haaf et al.(1983), Lautenschlaqer et al. (1985), Louis (1985), Mullett(1987), Padki and Sherif(1989a and b,1992 and 1999), Yan et al.(1991), Lodhi(1999), Bernardes et al.(1999), Schlaich et al. (2005,1995,2004), von Backstromet al, (2000,2002, 2003,2004 and 2006,), Bernardes et al. (2003), Dai et al. (2003), Zhou et al. (2006,2007b,2008,2009 and 2010), Ninic (2006),Nizetic and Klarin (2010), Pastohr et al. (2004), Ming et al. (2006,2007, 2008a and b), Danzomo (2008), Koonsrisuk and Chitsomboon (2007,2009a,b and c,2010), Roozbeh et al (2011), provided theoretical modeling investigations for large-scale SCPP. Pretorius (2004 and 2007), Guoliang et al (2011) performed the comprehensive studies on air flow and heat transfer in large-scale SCPP.

Two typical effective methods of controlling and enhancing power output from SCPP include introducing intermediate secondary roof under the first collector roof and additional closed water-filled thermal storage system on the ground. The results showed that intermediate secondary roof gave a much more uniform daily output profile compared to a plant with single roof. The incorporation of additional closed water-filled systemhas also proved to be a good mechanism for a power output controlling and enhancing, which gave a much more uniform daily output profile compared to a plant without such closed water-filled system (Schlaich et al, 2005).

3. Floating SC power technology

The conventional SC used for power generation is constructed by reinforced concrete. Although having a long service life, the reinforced concrete SC, whose height is required to be as high as possible in order to improve the efficiency of SCPP, has some disadvantages. The disadvantages include high construction cost and limited height 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 SCs. Based on these facts, Papageorgiou (2004 and 2006) proposed a floating solar chimney (FSC) concept instead of reinforced concrete SC to be used for SCPP. FSC consists of three parts: main body, heavy base and folding lower part. The main body is composed of buoyant gases-filled cylindrical balloon rings tied up to each other with the help of supporting rings. The main body is fastened to the seat of the heavy base and the folding lower part is fastened to the lower part of the heavy base, which can withstand the exterior winds by letting the air enter and come out freely from its rings so that FSC can receive any suitable declination exposed to wind.

Papageorgiou (2004 and 2006) designed the FSC structure, and performed some work on FSC power plant, including investigation of external wind effect and optimum design of SCPP. Zhou et al. (2009c) performed economic analysis of FSC power plant using an economic model. Later, they proposed a novel solar thermal power plant with FSC stiffened onto a mountain-side, segment by segment and estimated the potential of the power generation of the system in China's deserts (Zhou and Yang, 2009).

IV. Potentials of solar chimney in semi arid region of Nigeria

Nigeria which is located between longitude 3°and 14°East of Greenwich and latitude 4°and 14°north of equator has about 160 million people and a total land area of 923,768 km^2.Nigeria lies within a high sunshine belt and thus has enormous solar energy potentials, according toBala et al (2000), Nigeria is endowed with an annual Average daily sunshine of 6.25 hours, ranging between about 3.5 hours at the coastal areas and 9.0 hours at the far northern boundary (semi-arid region).

Similarly, it has an annual average daily solar radiation of about 5.25 KW/m^2/day, varying between about 3.5 kW/m^2/day at the coastal Area and 7.0kW/m^2/dayat the northern boundary (semi-arid region). Nigeria receives about 4.851x 10^{12} KWh of energy per day from the sun. This is equivalent to about 1.082 million tonnes of oil Equivalent (mtoe) per day, and is about 4 thousand times the current daily crude oil production, and about 13 thousand times that of natural gas daily production based on energy unit. The country is also characterized with some cold and dusty atmosphere during the harmattan, in its northern part, for a period of about four months (November-February) annually. The dust has an attenuating effect on the solar radiation intensity, but this has little or no effect on SCPP since the collector uses both direct and diffuse radiation. The specific potentials of the semi-arid regions can be characterized by the availability of flat land in the northern Nigeria couple with the high intensity of solar radiation, such as 5.714kWh/m^2/day in Bauchi, 6.003kW/m^2/day in Kano,5.673kW/m^2/day in Kaduna,6.176kW/m^2/day in Maiduguri and 5.920kW/m^2/day in Sokoto. The average sunshine hour in the arid region is about 9 hours (UNIDO,2003).With this potentiality, the SC technology as an appropriate technology for power generation in semi-arid region of Nigeria cannot be overemphasized.

V. Economics

1. Economics for power generation

In order to assess the economics and competitiveness of SCPP, economic analyses were performed by several researchers (Schlaich (1995), Schlaich et al. (2004) and Bernardes (2004)). Schlaich (1995) estimated the costs for all plant components for various plant sizes.He also evaluated the levelised electricity cost (LEC) and performed the sensitivity analysis of LEC to the interest rate and the length of the depreciation period. Schlaich et al. (2004) presented the component costs and the LEC for various plants for fixed economic parameters. Bernardes (2004) also estimated the component costs and LEC of various-size SCPP, and performed the sensitivity analysis of LEC to the economic parameters. In addition to that, he derived a parametric cost model for the main plant components, i.e., collector, SC and PCU. Fluri et al. (2009) presented a more detailed cost model, including a first detailed cost model for the PCU, where the impact of carbon credits on LEC was also considered, and compared the results to Schlaich et al. (2004) and Bernardes (2004). For the purpose of comparison, two reference SCPPs with similar sizes as the 100MW plants respectively proposed by Schlaich et al. (2004) and Bernardes et al. (2004) were selected. In the detailed cost model, the SC cost includes the material cost, construction cost, hoisting cost, and transport cost, the collector cost includes the material cost, construction cost, and transport cost, and the PCU cost includes the cost of balance of station, generators, turbines, ducts, power electronics, central structure, controls, and supports. Fluri et al. (2009) estimated the power output of the reference SCPPs using Pretorius's thermodynamic model (Pretorius, 2007). The simulation results showed a lower peak power output of 66MW for Schlaich et al.'s reference plant, and 62MW for Bernardes's reference plant, instead of 100 MW. LEC for the Schlaich et al.'s 100MW plant therefore reached at a higher value of €0.270/kWh than Schlaich et al.'s at €0.1/kWh with the same economic parameters (i.e., interest rate = 6%, inflation rate = 3.5%, and depreciation period = 30 years). LEC for the Bernardes's 100MW plant at €0.43/kWh is far larger than the value at €0.125/kWh re-calculated using Bernardes's model with the same economic parameters (i.e., interest rate = 8%, inflation rate = 3.25%, depreciation period = 30 years, and construction period = 2 years). (Fluri et al. (2009) thought a very low LEC at€0.037/kWh actually quoted by Bernardes (2004) was caused by an error in calculation).

During operating period, the SCPP avoids the CO_2 emissions from coal-fired power plant, which typically emits 0.95 kg of CO_2 per kWh power output. Large amount of carbon credits was therefore obtained for SCPP. The fact that SCPP construction will need to consume fossil fuels is neglected because the coal-fired power plant construction also needs to consume fossil fuels, and long service life of reinforced concrete SC corresponds to the total of service life of two to three coal-fired power plant. When the potential impact of carbon credits on LEC is included in this model, the LEC decreases a little, for example, the LEC of Schlaich et al.'s 100MW plant decreases to €0.232/kWh. In usual, the reinforced concrete SC could use for more than 80 years, which would lead to further reduction in SCPP LEC.

2. Additional revenues

A great concern with all solar technologies is extensive use of lands because of low energy concentration of sunlight. The investment of large-scale SCPP is large, and the solar collector is the main cost factor of SCPP.

The best additional use of a solar collector would be for growing vegetables or fruits as a greenhouse for possible additional revenues. The ground under the collector roof requires to be irrigated with fresh water. However, fresh water could be scarce in the potential construction sites of SCPPs, which are often selected in deserts, where land is cheap and sunlight is abundant. In order to grow vegetables or fruit, some lands are selected for the locations of SCPP, which aren't yet deserts but are threatened to become a desert if the climate change goes on, or which has recently become a desert. With pleasure, a wet cultivated ground is often darker than a dry flat one, so that this albedo effect generates a synergy among agricultural and power productions. However, solar heating of an irrigated ground would generate much evaporation, i.e., convert parts of solar heat to latent heat, thus reducing power output largely. According to this principle, since 1998, South African researchers have designed and performed experimental and theoretical study on a mixed project of a SCPP and a large, possibly profitable greenhouse for additional agricultural use (http://www.greentower.net). In the greenhouse, some black 'shadowing nets' were used, whose purpose might be multiple. During day time, these black shadowing nets will absorb solar radiation, and provide the main source of sensible heat to the moving air, which will be hotter than the agricultural greenhouse air. So, quite no convection will drive both airs to switch their places. During night time, the ground is hotter than the black shadowing nets. This will drive air convection from the ground to the black shadowing nets. Black shadowing nets can be the thermal contact point between cold collector operating air and the agricultural greenhouse mild warm air. When evaporated water coming from the ground is recondensed at the colder lower surface, the heat exchange would produce some dew, which will fall back to the humus. The 'shadowing nets' prevent steam from escaping into the SC, without wasting the fresh water and the latent heat.

Such a structure with 'shadowing nets' will give the whole system a very dark albedo. Of course, shadowing a greenhouse could slow down the photosynthesis, but, in very sunny regions, temperature and hygrometry regulations are an asset, especially if these shadowing nets can be adapted to the light conditions all the day.

In addition to use for heating collector operating air, at the same time, additional use of the outer 2/3 of solar collector area as greenhouse can increase production of a highly productive agricultural area from 100% to at least 270%, adding a virtual 170% to the existing land. Furthermore, vegetation in the collector also could increase heat and power production. These conclusions are mainly drawn based on Prof. Kroger's experimental and theoretical studies in 2000 (http://www.greentower.net.).

VI. Conclusion

Solar chimney (SC) power technology is a simple solar thermal power technology, which includes three familiar technologies: solar collector, SC, and PCU, e.g., turbine generators. The details of SC power technology are described, potentials of citing this power plant in Nigeria and the status and development of this technology reviewed, including, experimental and theoretical study status, and economics for this SC power technology. In addition the descriptions of other types of SC power technology are also done, however the average sunshine hour and solar radiation are 9 hours, and $7kW/m^2$/day respectively. With this potentiality, the SC technology as an appropriate technology for power generation in semi-arid region of Nigeria cannot be overemphasized.

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