Experimental investigation of the effect of wind speed and wind direction on a solar chimney power plant

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Abstract

Wind has been reported to have adverse effect on the performance of traditional solar chimney power plants but no reference has been made on the wind effect on inclined solar chimneys. An experimental investigation on the effects of ambient wind speed and wind direction on the performance of a south facing inclined solar chimney power plant model is reported in this paper. The effect of ambient wind speed and direction on the system performance was analyzed and the results showed that for the south facing collector, wind speed and directions have strong effects on the plant performance. The wind speed was found to have considerable influence on the convective heat loss through the cover and the walls to the ambient. Considering the wind direction, it was found that the system performance was favoured when the wind direction is from south moving north while the performance is impaired when the wind direction is from east or west. The results also showed some performance degradation when the wind is from the north. The findings also revealed that the walls of the air flow channel of the system resist the wind from sweeping the hot air generated in the system out to the ambient. Based on the findings, the use of inlet guide vanes as wind breakers at the collector inlet of traditional solar chimney power plant can reduce the losses associated to the wind effect inside the collector. The wind breakers will channel the natural energy of the wind into the system and enhance the system performance.
Keywords: convective heat losses, open-solar-air collector, solar chimney power plant, solar energy, wind speed, wind direction, air velocity, system performance.

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1 Introduction

In 2011, BP [1] reported the global energy need has been mitigated with about 86.91% fossil fuels (oil, gas and coal), 4.91% nuclear energy, 6.5% hydropower, while only about 1.68% was supplied from other renewable energy sources (Geothermal, Solar, Wind, Wood and Waste). A recent report from BP [2] showed that the global energy consumption for 2012 increased by 2.06% of the energy consumed in 2011 and the total energy consumed was supplied from 86.94% fossil fuels (oil, gas and coal), 4.50% nuclear energy, 6.66% hydropower, and 1.90% renewable energy sources. The report from BP [2] also indicated that depletion in the non renewable energy resources reserves. It is important to point out that the use of the non renewable emery resources (fossil fuels and nuclear) as fuel endanger the environment through emission of greenhouse gases (Al-Ghandoor *et al.* [3]). In the quest to sustain our environment for future generation, a more environmental friendly energy use is pertinent. Renewable energy is globally been promoted which solar energy conversion systems have received high promotions. One of the interesting solar energy technologies that can be used for commercial electricity generation is the solar chimney power plants (SCPP) (Pasumarthi and Sherif [4]).

The SCPP is a solar thermal electricity generation plant which converts the solar energy into electrical power in a complex heat transfer and fluid flow processes. A traditional solar chimney power plant consists of a circular transparent canopy raised a certain height above the ground with a chimney at its centre as shown in Figure 1. The chimney at the centre houses one or more turbine(s) located at its base. Radiation from the sun penetrates through the transparent canopy/roof and strikes the ground surface. The ground absorbs the solar energy and in turns transfers the thermal energy gained to the adjacent air. The warm air inside the greenhouse becomes less dense, rises and flows toward the central chimney. The kinetic energy in the air is converted to electrical energy using the wind turbine(s) and generators.

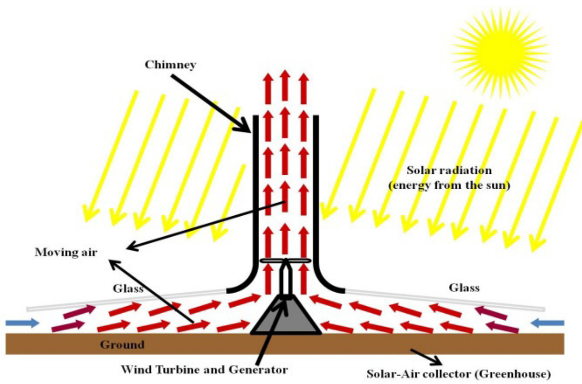

Figure 1: Schematic view of the solar chimney power plant.

The SCPP operational principles are based on three technologies: greenhouse, chimney and turbine technologies (Schlaich [5]). This technology was first demonstrated by Prof Schlaich when he and his colleagues constructed a SCPP prototype in Manzanares, Spain. The prototype was experimented from 1982 to 1989 for about 15,000 hours and generated about 50 KW of energy (Schlaich *et al*. [6]). The design model of the Manzanares SCPP prototype was presented in Haaf *et al.* [7] and the experimental results of the prototype was reported by Haaf [8]. Since the successful prove of the SCPP technology using the Manzanares prototype, several investigations on performance enhancement, designs, reduction of energy losses, integration of the SCPP with other process etc has been conducted by different researchers.

To enhance the power production during night times, Kreetz [9] investigated the use of water bags as heat storage medium. Pretorius [10] introduced the use of intermediate secondary roof to enhance heat storage in the soil of the collector. Pasumarthi and Sherif [4, 11] integrated collector with black canvas and black painted plate to improve the plant performance. Alrobaei [12] proposed the use of geothermal hot water pumped through pipes embedded in to the collector for thermal enhancement. Bilgen and Rheault [13] and Cao *et al.* [14, 15] investigated the use of mountain slope as collector/chimney. Davey [16] proposed hybrid solar pond and SCPP to enhance the system performance. Aja *et al*. [17–19] introduced and investigated hybrid process of SCPP with flue gas waste heat.

At the SCPP collector, the plant is faced with over 30% convective and conductive heat losses to the cover and ground respectively, Bernardes [20]. Convective heat loss impairs the performance of SCPP because the loss is completely irrecoverable while the conduction heat lost to the ground is stored and some percentage of the stored energy can be recovered and used for the night operation. Energy generated from SCPP wind turbine is dependent on the mass flow rate of the buoyant air which depends to a great extent on the air velocity at the collector inlet [21]. Ambient wind is the major cause of convective heat loss in SCPP [22, 23]. Investigation by Serag-Eldin [22] reveals that the wind velocity degrades the SCPP performance as a result of the wind sweeping the air in the system off the collector. Serag-Eldin [23] introduced the concept of controllable flaps to reduce the proportion of hot that is swept off the stack of SCPP by wind but did not consider the wind effect on the collector. Pretorius and Kröger [24, 25] investigated the effect of ambient environment on the performance of SCPP and the result inferred that the prevailing ambient winds at the location have considerable influence on the system and reduces the annual plant output by approximately 10% compared to the same plant under no wind conditions throughout the year. Similarly Pretorius [26] analyzed the effect of wind on a proposed SCPP in South Africa and reported that wind adversely affect the system performance. VanReken and Nenes [27] in their investigation inferred that cloud would probably form as a result of downwind thus causing shade over the collector area and reduce performance. Ming *et al*. [28] numerically simulated the effect of cross wind on the performance of SCPP and the results reveal two ways influence which inferred that when the wind is comparably weak (below 15m/s), the system performance deteriorates while strong wind (above 15 m/s) will increase the mass flow rate and output power of the system. Du Preez and Kröger [29, 30] used turbulence numerical model to investigate the effect of wind on a cooling tower and it was found that the flows inside at on the inlet of the tower was affected by wind thus in order to minimize the wind effect, they introduced windbreak walls. Zhou *et al.* [31] mathematically correlated atmospheric crosswind and the air inside a SCPP with the assumption of the inflow air to be compressible. Their results inferred that strong wind velocity increases the air velocity in the system with large collector area; the system performance is reduced with wind effect. Recently, Ming *et al.* [32] numerical simulated SCPP with blockage surrounding the collector area giving some distance away from the collector inlet. Their investigation showed improvement and reduction in the effect of wind on the system. But the use of blockage in real practice will drastically increase the investment cost of the plant for commercial purposes. Similarly, if the distance between the collector inlet and the wall is not enough, it may also reduce the available supply of air to the system.

All the investigations on the wind effect were conducted numerically using the traditional SCPP geometry which the air inlet is open round the collector periphery with no consideration of the wind direction. This paper presents an experimental study on the effect of ambient wind on the performance of a south facing sloped SCPP which has its air inlet in one direction (facing due south).

2 Experimental setup, instrumentation and procedure

To experimentally study the effect of the ambient wind on the system performance, an experimental sloped SCPP was use. The sloped SCPP is a south facing SCPP which is composed of open solar air collector, air-chimney and turbine as shown in Figure 2. The open solar-air collector of the sloped SCPP is the greenhouse/heat exchanger of the plant where the energy from the sun is converted into thermal energy. The top surface of the open solar-air collector is made of transparent cover (acrylic glass) to allow the solar radiation to penetrate to the absorber plate. The system has two side-walls made of acrylic glass to allow solar radiation in to the channel even at sunrise and sunset (low elevation angle). The walls for the greenhouse support and hold the transparent cover over the absorber plate. The bottom of the open solar-air collector is the absorber plate (heat exchanger) where the solar radiation is absorbed and the heat energy gained is transferred to the working fluid (air). The absorber plate is made of aluminium sheet painted with flat black oil paint to increase the solar absorption of the surface. The open solar-air collector is designed to absorb the optimum available solar radiation at the location where the experiment was conducted (4.39°N and 100.98°E) and also to enhance buoyancy and guide the air to the chimney. The collector has a total area of 3 m^2 (width 1 m and length 3m).

The chimney acts as pressure tube through which the buoyant hot air generated in the solar air collector exits the system to the atmosphere. It is situated at the exit of the absorber plate, unlike the traditional SCPP which has

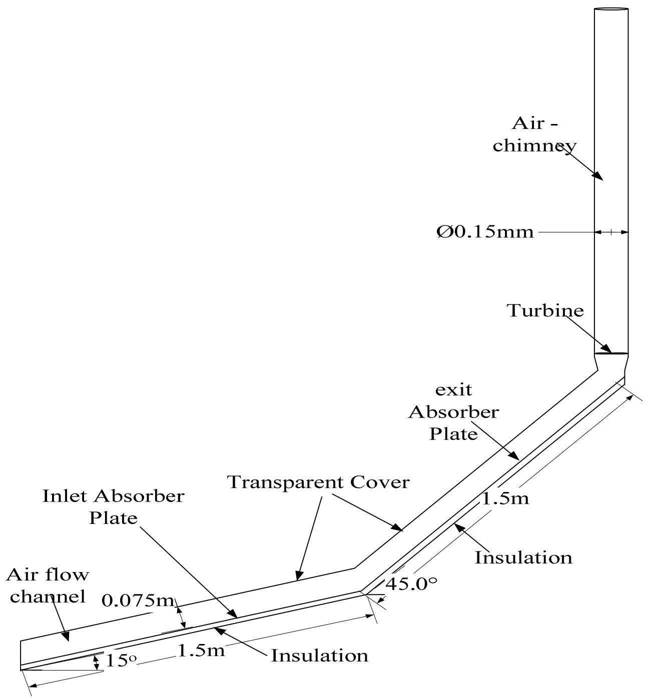

Figure 2: Schematic diagram of slope SCPP experimental test-rig.

its chimney at the centre of the solar air collector. The chimney of the experimental prototype was made of PVC pipe with internal diameter, 0.15m. The chimney height considered in the experimental investigation was 6m. At the base of the chimney is situated the wind turbine to convert the energy in the air into mechanical/electrical energy.

To prevent heat loss through the back of the system, the back was insulated with asbestos and plywood. The insulation was protected from weather effect using thing aluminium sheet (external). The thickness of the asbestos was 0.03 m while the plywood was 0.02m thick.

To measure the parameters for the analysis of the system, the transparent cover was instrumented with 10 numbers of type K surface thermocouples to measure the temperature of the cover at different points from the inlet to the chimney connection point. The absorber plate was also instrumented with 11 numbers of type K surface thermocouples to measure the surface temperature. At the air flow channel 2 numbers of type K probe thermocouples were installed to measure the air temperature at the 15° and 45° tilted absorber plates. The chimney was instrumented with an air flow sensor to measure the air velocity at the chimney base and also a type K probe thermocouple to measure the temperature of air before the turbine location. Above the position of the turbine in the chimney, the air temperature is measured using 4 numbers of type K probe thermocouples. The back insulation was instrumented with 6 numbers of type K surface thermocouples to measure the back temperature. The thermocouples wires where extended to lengthen the wire to the data logging point.

Figure 3: The experimental test rig Instrumentation.

The velocity of air at the chimney base was measured with the SCHMIDT air flow sensor – SS 20.260 (Figure 4). The air flow sensor was directly connected to data logger to measure capture the data per minute.

Figure 4: SCHMIDT air flow sensor – SS 20.260.

Two data loggers where used for the data collection, Graphtec 800 with 20 sensor connection slots and Fluke Hydra series II data logger with 20 sensor connection slots. The Graphtec 800 data logger was used to connect the SCHMIDT air flow sensor – SS 20.260 and some of the thermocouples and the data collected.

Figure 5: Data logging and sensor connections.

3 Results analysis and discussions

To be certain with the result of the investigation, the plant was investigated for 14 day using 6m chimney attached at the collector exit. The ambient wind speed and wind directions were measured. At the location of study, it was found that during the month when the investigation was conducted, the wind directions were from north (0°) through east to south (180°). The temperature difference between the air in the system and the ambient air was found to be the driving force that produced the buoyancy effect and generated the velocity.

Considering the performance of the system under no wind condition, Figure 6 shows the average air velocity at the chimney base. It shows that the air velocity depend on the temperature difference.

Figure 8 shows the average angular wind direction for a whole day of investigation and the relationship to the effect of wind speed on the plant performance.

Looking at the result of Figure 8, it can be seen that when the wind direction is below 100°, the system experience a lot of losses which resulted in the drop in velocity of the system. This is because the wind sweeps over the transparent cover thereby causing loss of energy from the system to the ambient. This negative effect of the wind on the plant performance is in line with the reports of Pretorius [24] and Ming *et al.* [28, 32].

When the wind direction exceeds 110°, the wind velocities positively affect the plant performance. Some of the moving wind finds their way into the greenhouse. This is mostly experienced in the night. It can be inferred that for a walled solar air collector which opens at the base, for air inlet, wind velocity coming from the direction where the collector faces will receive enhancement as

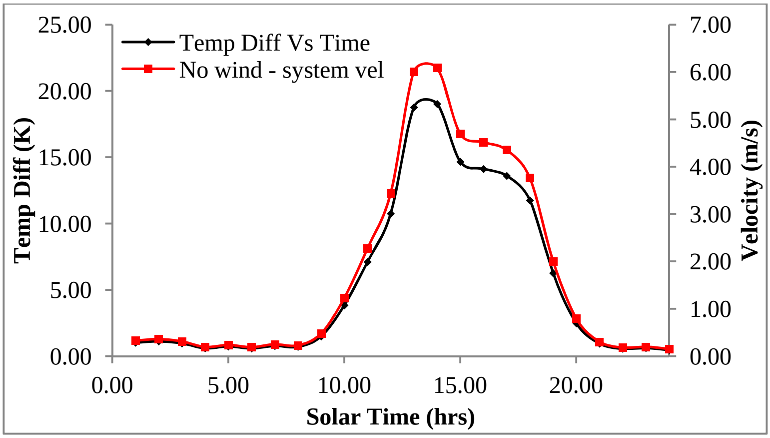

Figure 6: Temperature difference and system air velocity under no wind condition.

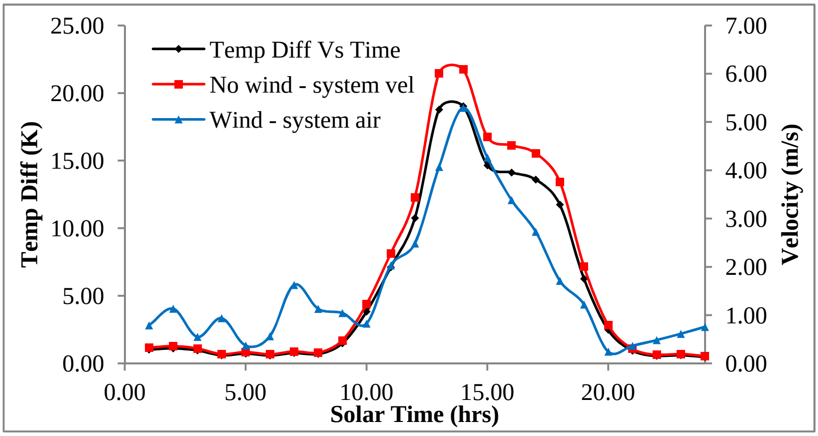

Figure 7: Temperature difference and system air velocity under no wind and windy conditions.

a result of the wind speed but when the wind comes 0°, 90° or 270° from the inlet, the wind negatively affects the performance. In relation to the traditional solar chimney which is open round the periphery, as reported by Ming *et al.* [32], the wind negatively affect the system performance due to sweep of the hot air in the system out by the wind; they suggested the use of blockage round the power plant area which is considered very high cost. From the above results, the system performance can be improved by creating guide vanes that can guide the wind into the collector centre instead of the wind sweeping off the hot air; it will then enhance the air velocity and also the mass flow rate of the air in the system.

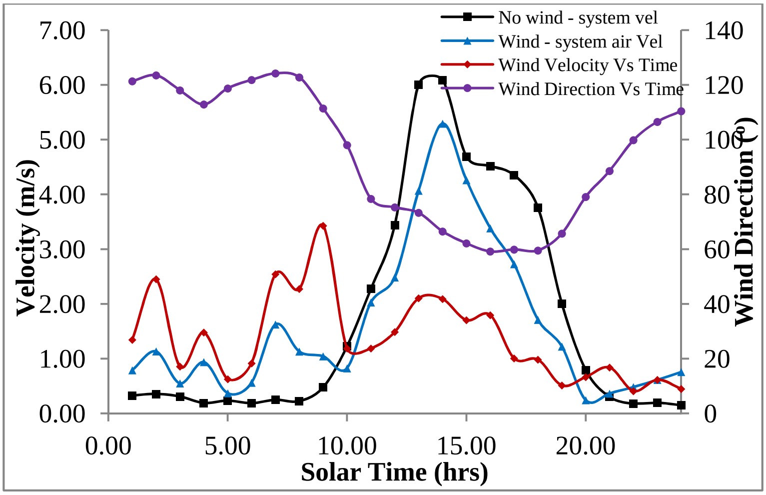

Figure 8: The effect of wind direction on the system air velocity.

4 Conclusions

The performance of a solar chimney power plant is affected by the wind velocity at the location. The wind direction is one important factor that has not been investigated on its effect on the plant performance. This work investigated the influence of wind speed and wind direction on the system air velocity. The system air velocity and mass flow rate are the major factors that controls the power output of a SCPP. With respect to the wind velocity, it was found that the wind velocity generally cause energy loss through the cover but for a south facing collector, it was found that the loss is higher when the wind direction is from the north, east or west but when the wind direction is from the south going north, the system performance is favoured due to flow of the wind into the collector. Based on this finding, the work suggest the use of inlet guide vanes at the periphery of traditional SCPP to reduce the heat loss from the collector as a result of the wind sweeping off the hot air in the collector

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