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Experimental Investigation of a Pilot Sloped Solar Updraft Power Plant Prototype Performance Throughout a Year

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Abstract

The solar updraft power plant is a promising technology for harnessing the solar energy and many researchers developed the plant design to improve its low efficiency. Using a sloped solar collector is one of the novel techniques that improves the plant efficiency in higher latitudes and reduce its capital cost. In this paper, a pilot Sloped Solar Updraft Power Plant (SSUPP) is constructed in the campus of mechanical engineering department of Damascus University in Syria. Thermometers were installed in the sloped solar collector to measure glass, air, and absorption layer temperatures along the collector. Solar radiation, ambient air temperature as well as air velocity inside the chimney were also recorded. These data were taken every 10 minutes throughout the year 2012 to investigate the performance of the SSUPP. In this paper, the effect of the average monthly recorded values of solar radiation and ambient temperature on the prototype performance were analyzed in all weather conditions and the changes in sloped solar collector outlet temperatures were investigated. The results show that the difference between the ambient temperature and the chimney inlet temperature is almost the same in winter and summer seasons leading to a conclusion of the advantage of having an inclined solar collector in the SSUPP.

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

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1. Introduction

As shown in Fig. 1(a), the Conventional Solar Chimney Power Plant (CSCPP) consists mainly of three components: the solar collector, the chimney, and the turbine. The solar collector is composed of a transparent roof material that allows the solar radiation to penetrate to the absorber (the soil in this case) and it is circular in shape, horizontally fixed allowing a gap between the canopy and the soil for the air movement underneath it; The chimney is constructed in the center of the collector; the turbine is installed at the chimney inlet. The CSCPP principle is simple, solar radiation penetrates through the canopy and heats the absorber. The air layer close to the absorber will heat up by natural convection then the hot air will flow under the collector and rise to the chimney outlet. The updraft in the chimney will rotate the turbine and deliver mechanical energy to its shaft. An attached generator to the turbine shaft will generate electricity. The CSCPP was originally proposed by Professor J. Schlaich of Stuttgart in 1968. In the 1980s, the principle was proven through eight years of continuous operation of a 50 kW experimental plant which was built in Manzanares, Spain. This experiment proved the feasibility and reliability of this novel technology [1].

The main limitation of the CSCPP is its low efficiency which is lower than 1%. Normally the efficiency is directly proportional with 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. The chimney height is also restricted by the technological constraints and restrictions on the construction materials. There are also the possibility of natural hazards such as earthquakes, which can easily destroy super high solar chimneys. Based on these facts, many researchers developed novel designs for the CSCPP to reduce capital cost and improve efficiency [1, 2].

Papageorgiou [3, 4] proposed to build higher and cheaper solar chimneys named floating solar chimneys, which can replace the conventional reinforced concrete solar chimneys. Zhou and Yang [5] proposed a novel solar chimney plant 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. [6] 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.

On the other hand, Bilegn et al. proposed a new design for the CSCPP for high latitude locations. As shown in Fig. 1(b), designing a 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. 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 [7]. This new design is called the Sloped Solar Updraft Power Plant (SSUPP).

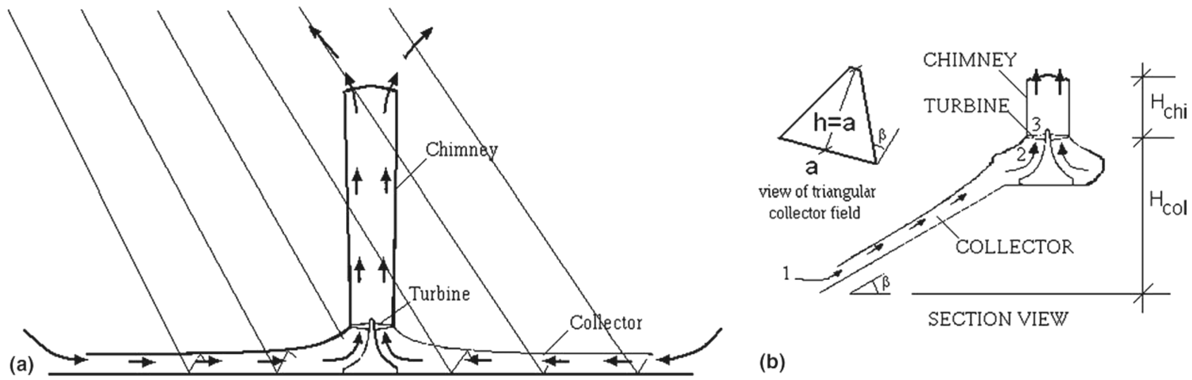

Fig. 1. Schematic of the solar chimney: (a) systems on horizontal surface at low latitudes; (b) systems in sloped surface at high latitudes [7].

Cao et al. discussed the use of SSUPP for providing electricity to remote villages in northwestern China and focus was on system and solar collector efficiencies [8]. Panse et al. developed a mathematical model that considers the total energy balance for inclined solar chimneys. In this study, the inclined face of the mountain acts like a chimney as well as a solar collector and no chimney is considered at the mountain apex [9]. In another study, Cao et al. reported a heat transfer model that is used to compare the performance of a conventional solar chimney power plant with two sloped solar chimney power plants having a collector oriented at 30° and 60°, respectively [10]. Koonsrisuk developed a mathematical model based on the continuity, momentum, energy, and state equations for the SSUPP [11]. Additional advantage in this model includes the dynamic pressure and the flow details within the collector. The same author compared the CSCPP with the 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, 12] were used for the evaluation [13]. The results also showed that the increase in chimney height for both types will result in a lower entropy generation number. Zhou et al. [14] designed the solar collector of a SSUPP case and two CSCPP cases based on the 5 MW SSUPP proposed in Ottawa [7]. Results show that the expression containing no integral for the pressure potential of the conventional CSCPP , developed by Kröger and Blaine [15], is accurate for CSCPP based on a compressible fluid model, and that the expression containing no integral of pressure potential for SSUPP based on an incompressible fluid model , developed by Bilgen and Rheault [7], is not accurate for predicting the driving force of SSUPP, because it neglects the change of the atmosphere density with heights, the change of difference of the atmospheric density, and the density of the air current inside the short chimney with heights. The first experimental research for the SSUPP appeared in 2013 when Kalash et al. [16] erected a pilot SSUPP in Damascus University, Syria and investigated the sloped solar collector performance in cold weather.

In this paper, the monthly average temperature changes along with the changes of solar radiation and ambient temperature, which are recorded for one year, will be depicted and discussed to evaluate the prototype performance and to discuss the effect of ambient parameters on the sloped collector outlet temperature.

2. SSUPP Prototype setup

A pilot experimental prototype for the SSUPP was erected in the mechanical engineering campus at Damascus University, Syria. As shown in Fig.2 (a), the erection activities included building two triangular walls to form a sloped hill between them. In order to simulate the actual conditions of the absorption layer in the mountains, soil from nearby mountains was provided to fill the empty space between the triangular walls. A small room was built at the northern side of the sloped solar collector to use its roof for supporting the chimney and to keep the data acquisition system protected inside it. The sloped solar collector is tilted about 35º and has a triangular shape with a metallic framework which was covered by 4 mm glass sheets. A metallic box was designed and fabricated to receive the air flow from the collector outlet and then direct the stream smoothly to the vertical chimney. It was insulated to reduce thermal losses to the ambient. Three PVC pipes formed the chimney with 9 m height and 0.31 m in diameter. Fig.2 (b, c) shows a view of the SSUPP prototype during data collection and the prototype schematic with main dimensions, respectively.

Eighteen platinum resistance thermometers were used to measure the ambient temperature and the temperature changes along the sloped solar collector. The sensors underneath the collector were divided into six sets with one meter distance between each set. In each position, the temperature of the absorption layer (soil), air and collector cover (glass) were measured. Solar radiation was also recorded by pyranometer “SP Lite2”. Chimney air velocity was measured by hot-wire anemometer “TES-1341”. All measured data were transferred to a data acquisition device and stored every 10 minutes for the whole day. The layout of the sensors and the data acquisition system is depicted in Fig.2 (d).

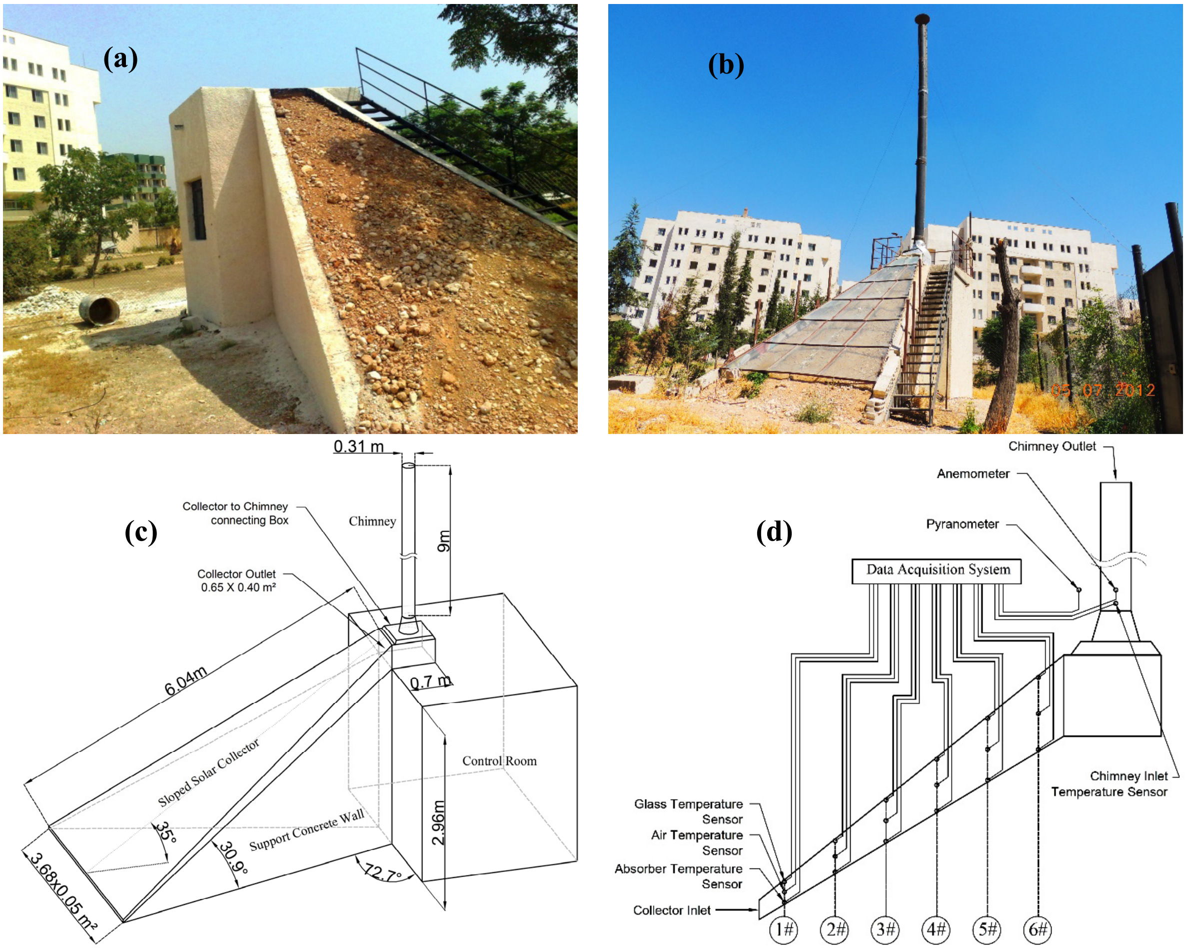

Fig. 2. (a) The SSUPP Prototype during construction; (b) The SSUPP Prototype during data collection; (c) Schematic of the prototype with dimensions; (d) Layout of the sensors and data acquisition system used in the SSUPP prototype.

3. Results and discussion

In order to study the SSUPP performance around the year, data were collected from the prototype every 10 minutes from Dec, 2011 to Nov, 2012. The monthly average values of all recorded data were calculated based on day time periods of each month. Data were taken under no load condition where the turbine had not been installed yet.

3.1. Variations of chimney inlet temperature

The monthly average value of the chimney inlet temperature was depicted in Fig.3 along with ambient temperature and solar radiation. The maximum average values of solar radiation and ambient temperature were recorded in July and there were 611 W/m^2 and 35.5 ^{o}C respectively. It is clear from the plot that curves of ambient temperature and chimney inlet temperature are parallel and the changes in solar radiation from month to month is affecting both temperatures directly. The temperature difference between the ambient temperature and the chimney inlet temperature was almost constant. From February to October, this difference was between 7.1 ^{o}C to 8.0 ^{o}C. In order to make this difference clearer, ΔT curve was also plotted and it shows clearly that the temperature difference is almost constant around the year. The prototype collector was inclined in the same angle of the site latitude, which optimized the solar collector in winter to receive maximum solar radiation and to improve the collector performance in winter season. These results are consistent with mathematical results given in [7, 8].

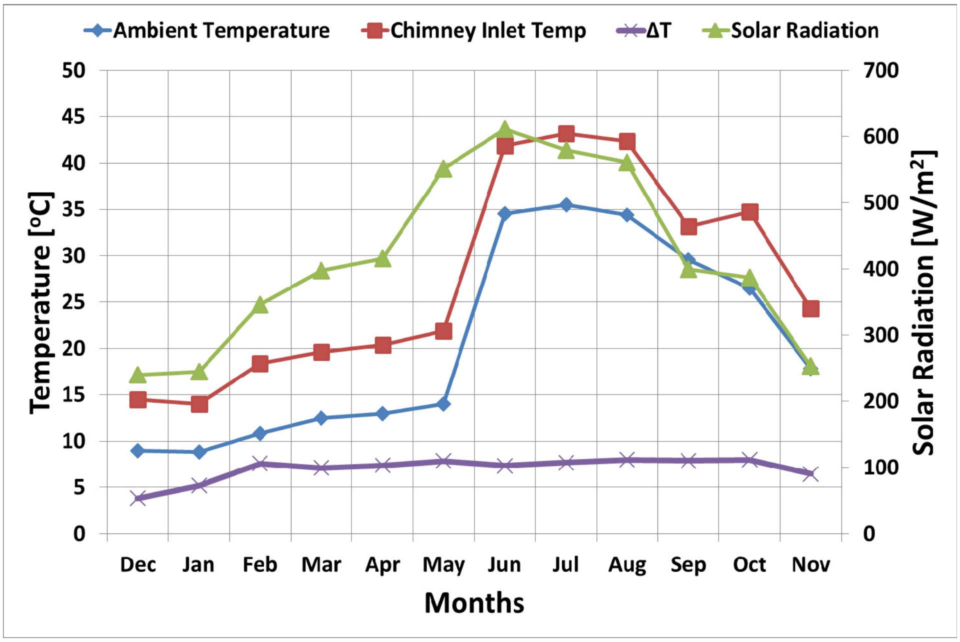

Fig. 3. The chimney inlet temperature, ambient temperature and the solar radiation changes around the year.

3.2. Variations of collector outlet temperatures

The monthly average values of the sloped solar collector outlet temperatures of the air, the glass, and the absorption layer were plotted and compared with ambient temperature as shown in Fig. 4. The absorption layer temperature was always higher than air and glass temperature around the year with a maximum value recorded in July and it was 52.4 °C while the glass and air temperatures were 49.2 °C, 47.4 °C respectively. The collector outlet temperatures were following the same changes of the ambient temperature and this reflects the impact of ambient temperature on the collector performance. The difference between collector outlet air temperature (in Fig.4) and chimney inlet temperature (in Fig.3) is due to the heat losses from the connecting box that is designed to guide the hot air from the collector outlet to move smoothly to the chimney inlet.

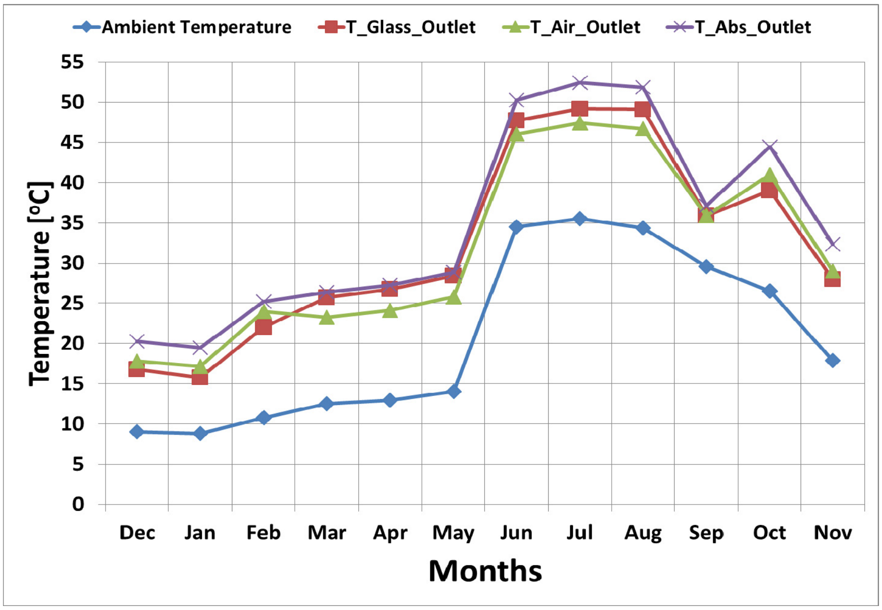

Fig. 4. The air, glass and absorption layer temperatures in the collector outlet.

4. Conclusion

A pilot SSUPP prototype has been erected in the campus of Damascus University, Syria. The data were recorded every 10 minutes 24 hours a day for 12 months. In this paper, the monthly average values of the collector outlet, chimney inlet, ambient temperature and solar radiation were recorded and plotted to investigate the prototype performance a year round. The main results are:

1) The investigations show that the temperature difference between the ambient temperature and the chimney inlet temperature is almost the same in winter and summer. This result is due to optimizing the solar collector which was inclined in the same angle of the latitude in the prototype location.
2) The results show a direct impact of both solar radiation and ambient temperature on the collector outlet air temperature.

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