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Investigation of Experimental Solar Chimney Output Parameters Behavior

استقصاء سلوك بارامترات خرج مدخنة شمسية تجريبية

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الملخص

تم تصميم وبناء واختبار نموذج للمدخنة الشمسية كمحطة لانتاج القدرة في مدينة طنطا بمدخنة ذات ارتفاع ٢٤ م ومجمع ذو مساحة ١٦٠٠م٢. تم قياس توزيع درجات حرارة الغطاء الشفاف والهواء داخل المجمع والسطح الماص ونقطتين في التربة على عمقين مختلفين من سطحها على طول نصف قطر المجمع وعلى ابعاد مختلفة من مركزه. وتم ايضا قياس سرعة ودرجة حرارة الهواء عند مدخل المدخنة. تتأثر درجة حرارة السطح الشفاف والهواء داخل المجمع والسطح الماص مباشرة بالاشعاع الشمسي وتصل لذروتها مع ذروة الاشعاع الشمسي بينما تصل درجة حرارة طبقة التربة العليا لذروتها مع الغروب ولا تتغير درجة حرارة طبقة التربة السفلى اثناء مدة القياس ولكن درجات الحرارة تلك لها قيم مختلفة عند المواضع المختلفة على طول نصف قطر المجمع. تزداد سرعة الهواء بازدياد فرق درجة الحرارة بين الهواء عند مدخل المدخنة و الهواء الجوي و التي تصل الى قيمة متوسطة ٥ م/ث في الفترة بين الساعة ٨ صباحا الى ٤ مساء عند متوسط فرق درجة حرارة مقداره ٢٣,٥ درجة حرارة مئوية ومتوسط اشعاع شمسي ٨١٢ وات/م٢.

Abstract

A solar chimney pilot plant as a power conversion unit has been designed, built and tested in Tanta with 24 m chimney height and 1600 m^2 collector area. Temperature distributions for transparent cover, air inside the collector, absorber surface and two points in the soil at different depth from the surface have been measured along the radius of the collector at different distances from the center of the collector. Air velocity and temperature at chimney entrance also have been measured. Temperature of transparent cover, air inside the collector and absorber surface are affected directly by solar radiation and they reach to their peak with peak of solar radiation, while temperature of soil at upper layer reaches to its peak with sunset and the temperature of soil at lower layer does not change during measuring period but these temperatures have different values at different measuring position along the radius of the collector. Air velocity increases with increasing temperature difference between air at chimney entrance and the ambient which reaches to a mean value of 5 m/s in the period between 8 AM and 4 PM at mean temperature difference of 23.5^{o}C and mean solar radiation of 812 W/m^2.

1. Introduction

Recently, the use of renewable energy finds a lot of interest due to the adverse environmental effects produced by the conventional energy sources, reducing the global energy demand from fossil fuel energy sources and preserving the provided reserves of coal, oil and gas for the next decades.

Solar energy is the most reliable alternative energy source as it is the origin of all other known types of renewable energy.

Solar energy can be used for several applications such as water heating system, solar heating and cooling in air conditioning system, drying of agricultural products, distillation of sea water and direct electrical power generation by Photovoltaic cells, solar thermal power plants and solar chimney power plants. Solar chimney power plant is simple, reliable, and accessible to the less developed countries which are sunny and have limited raw material resources. Stored heat in the ground or water filled bags can provide continuous operation all over the day. Utilizing direct and diffused solar radiation solar chimney power plants have little maintenance and do not need cooling water. Although, the low conversion efficiency is the major problem of solar chimney as determined by the thermal performance of the system. However, the conversion

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efficiency of solar chimney can be increased by increasing the chimney height. In solar chimney the incoming solar radiation is absorbed and converted into heat inside the collector and then this heat induce the air to flow by buoyancy forces resulting from greenhouse effect. Power can be generated by driving turbine with the flowing air.

The solar chimney power technology was first proposed by Cabanyes [1], and then described in a publication by Gunter [2].Schlaich again presented the technology in a congress in 1978 [3], and then together with his colleagues designed and constructed the first Solar Chimney Power Plant prototype in Manzanares, Spain during the two-year period between 1981 and 1982 [4–7]. This prototype had a chimney 194.6 m in height and 10 m in diameter, a collector 122 m in radius, and a single vertical axis single-rotor turbine configuration with four blades installed at the solar chimney base. This prototype operated with the peak power lying at about 50 kW for eight years [8, 9]. Since then, more researchers have shown strong interest in and studied the huge-potential solar chimney power technology over the world such as Zhou X. el al. [10], Kasaeian A.B. et al. [11], Buğutekin A. [12], Asnaghi A. and Ladjevardi S.M. [13].

In this paper solar chimney pilot plant is designed, constructed and investigated at Tanta city, Egypt during May 2015. A detailed analysis of the measured temperature inside the solar chimney is conducted to verify heat transfer mechanism in it. Energy storage is also investigated by measuring soil temperature at different depths at different positions.

2. Experimental Setup

2.1. Construction of solar chimney pilot plant

In order to evaluate the performance of a solar chimney power plant, a pilot plant of solar chimney is designed and has been constructed as shown in Fig. 1 at the campus of Tanta University in Egypt (30°49'30.45"N 30°59'50.45"E).

The collector has a square shape with 40 m edge and an area of 1600 m^2. A network of galvanized steel wires is manufactured and fixed between the periphery of the collector and the central reinforced concrete base that carries the chimney. The land of collector area is covered with black polyethylene sheet of $1*10^{-4}$ m thick to absorb maximum solar insolation. A transparent polyethylene sheet of $1.3*10^{-4}$m thick and with the same area of the collector is raised by the network of galvanized steel wires to height between 0.1m at the outer radius to 1.2m at the central chimney base. The soil of the collector land is natural agriculture clay soil.

The chimney with a total height of 24m, including its base, is made of 5 ducts with 4m long each of them and inside diameter of 1m. These ducts are made of spiral galvanized steel sheets with 0.001m thick. The ducts are also covered with glass wool blanket with FSK 0.05 m thick of density ρ= 24 kg/m^3 and thermal properties: coefficient of thermal conductivity λ_m=0.034 W/m.K and thermal resistance R_m=1.45 m^2.K/W which works as thermal insulation to reduce heat losses from the chimney wall. The ducts are supported with a steel structure frame combined with a conical shape steel structure from the bottom side which works as a base for steel structure frame, Fig. 2. The frame and the conical shape steel structure are supported over the central reinforced concrete base which has 4m inside diameter. The chimney is fixed with guyed wires at different levels. The essential parameters of the solar chimney pilot plant are listed in Table1.

Figure 1 Photo of the experimental solar chimney pilot plant

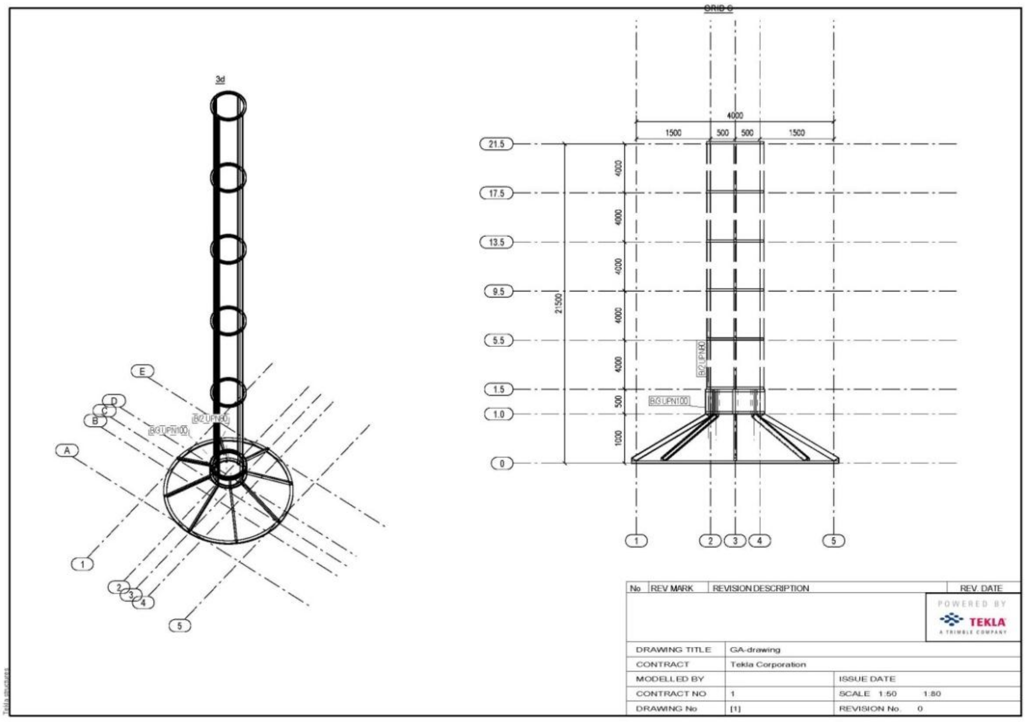

Figure 2 Shop drawing of steel structure frame with a conical shape base

Table 1 Essential parameters of the solar chimney pilot plant

Parameter	**Value**
Collector area, A_{co} (L_{co} =40 m)	**1600 m^2**
Size of the opening at the periphery, $h_{co,in}$	**0.1 m**
Height from collector outlet to ground level, $h_{co,out}$	**1.2 m**
Chimney height, H_{ch}	**24 m**
Chimney diameter, d_{ch}	**1 m**
Funnel diameter, d_f	**4 m**

2.2. Measuring procedure

Schematic diagrams of the solar chimney with the measuring positions are shown in Fig. 3. The collector is divided into 5 sections along the radius. Each section contains 5 temperature sensors distributed in vertical direction to measure the following points: first sensor measures the transparent cover inside temperature, T_{tc}, second sensor measures the temperature of air gap between the transparent cover and black absorber, T_{air}, third sensor measures the temperature of the surface of the black polyethylene layer, T_{ab}, fourth sensor measures the temperature of the soil on 0.1m depth, T_{s10}, fifth sensor measures the temperature of the soil on 0.3 m depth, T_{s30}.

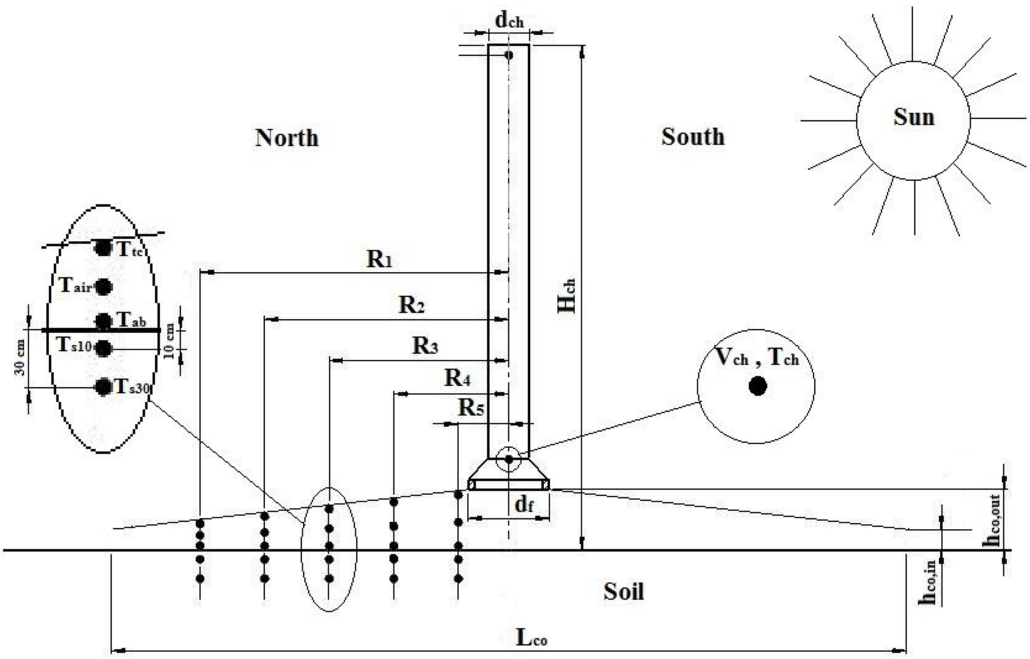

Figure 3 Schematic diagram of solar chimney with the measuring positions

Other temperature sensors are used to measure the temperature of the air at the chimney entrance T_{ch} and the ambient temperature T_a.

Global solar radiation intensity is measured with Pyranometer type "MS-802 with accuracy of ±6 W/m^2 during the day time. Digital temperature sensor type "DS18B20" is used to measure the temperatures distribution throughout the system. All the sensors are water proof type to withstand weather condition. The sensors measure temperatures from -55°C to +125°C with □0.5□C accuracy for the range -10°C to +85°C. Arduino Uno board is used as a data logger to collect data from the Pyranometer and digital temperature sensors, it's an open-source physical computing platform based on a simple microcontroller board. An anemometer type "Tenmars TM-402" is used to measure the air velocity at the chimney entrance at its center. The instrument has a range of 0.4 to 25 m/s with accuracy of ±0.2 m/s.

3. Results and discussions

Temperature variation has been conducted for different point in solar chimney experimental setup on May 17, 2015. Figure 4 shows the temperature of air at chimney inlet T_{ch} with solar radiation I, it is very clear that T_{ch} is highly effected by solar radiation variation because the absorber layer converts the radiation into heat which is divided into three parts: one part is transferred to air moving under collector by convection, another part is lost to the ambient air through transparent cover, the last part is stored into soil. After sun rise, T_{ch} increases rapidly until it reaches to the peak value of 62°C at 1:00 PM then after the noon solar radiation decreases and T_{ch} decrease too but with a slower rate and that because the soil releases a part from stored heat.

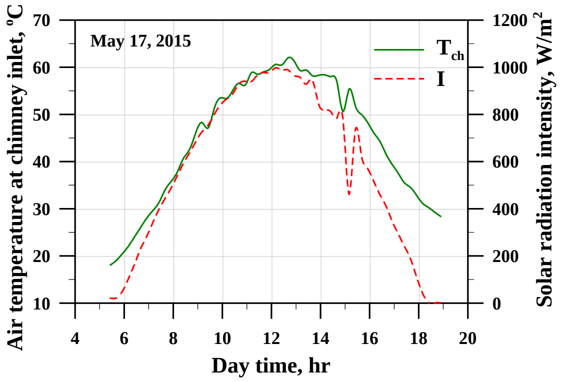

Figure 4, Air temperature at chimney inlet and solar radiation during May 17, 2015

Temperature variation during the day for transparent cover, air inside the collector, absorber surface, soil at depth of 0.1 m and soil at depth of 0.3 m is illustrated at Fig. 5 to Fig.9 at different radii. Figure 5 shows that variation at R_1= 15.3 m. The absorber temperature, T_{ab}, is the highest temperature during measuring period and reaches to 78°C as a peak value nearly with solar radiation peak. The underground temperature at 0.3 m depth, T_{s30}, is 32°C all over the day and nearly is not affected with solar radiation variation but it is affected with temperature over it and this will be illustrated in the other figure. Heat storage appears clearly in the upper underground layer at 0.1 m depth more than the deeper layer of soil. Such temperature, T_{s10} reaches its peak of 40°C at nearly before sunset and lowest value of 32°C after sunrise. Both temperature of transparent cover lower surface, T_{tc}, and air temperature inside the collector, T_{air}, have very close values and reach to their maximum value of 64°C and 62°C after the peak of solar radiation when the ambient temperature, T_a, becomes 35°C and near from its peak value.

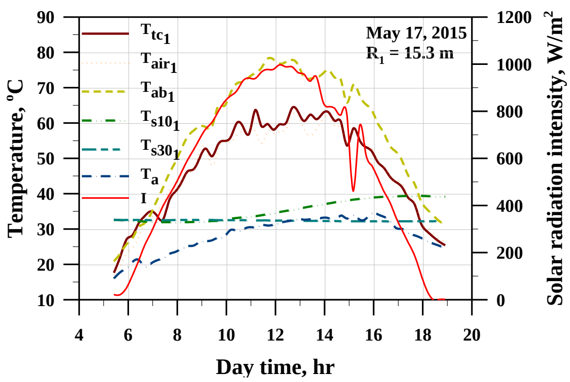

Figure 5 Temperature sensors records at R_1=15.3m on May 17, 2015

At R_2=12.1 m, the measured points become closer to the center of the collector and more heat is added to air inside the collector by convection. Figure 6 shows the variation character. And it appears clearly for all measured point at this position that all temperatures have been increased compared to the first far position.

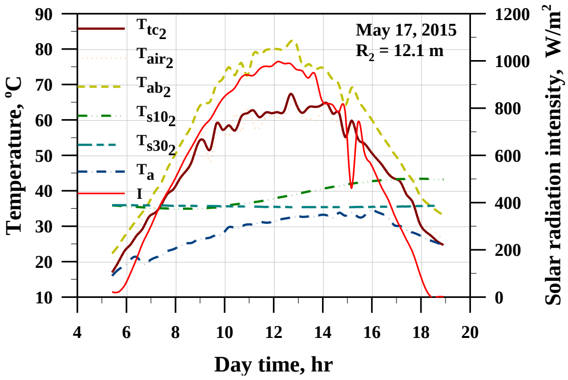

Figure 6 Temperature sensors records at R_2=12.1m on May 17, 2015

At R_3=8.9 m, the measured points become very closer to the collector center. Figure 7 shows the variation of temperatures at this position. All temperatures for all points are increased a little bit except for the temperature of absorber layer, it decreases than before and this may be declared by the increased velocity of the air over absorber layer due to the conversion of the flow area, which will increase heat transfer rate to the air inside the collector.

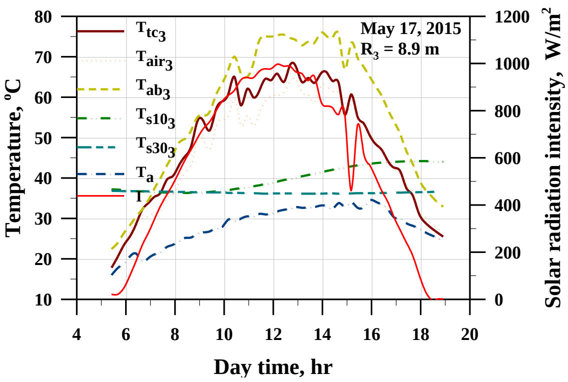

Figure 7 Temperature sensors records at R_3=8.9m on May 17, 2015

Air velocity inside the collector reaches to high values during moving from R_4= 5.7 m to R_5= 2.5 m. This speed increases heat transfer rate causing a temperature decrease to absorber layer surface and soil temperatures and a temperature increase to the moving air under the collector, Figure 8 and 9 illustrate this behavior along the collector. The sharp drop of temperature of transparent cover and absorber layer at 12:00 PM may be because the shadow effect of the chimney and its base on that position of collector because the shadow moving speed near the center become very slow. And the temperature sensors are positioned on the north of the collector.

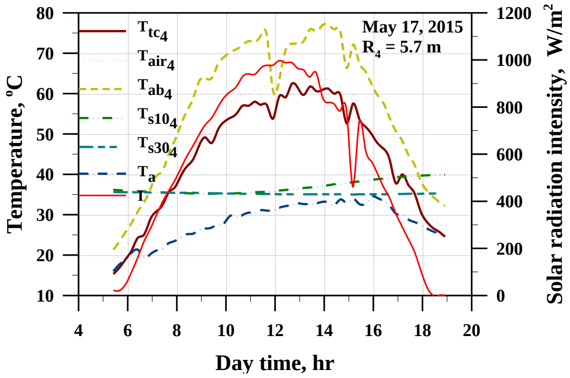

Figure 8 Temperature sensors records at R_4=5.7m on May 17, 2015

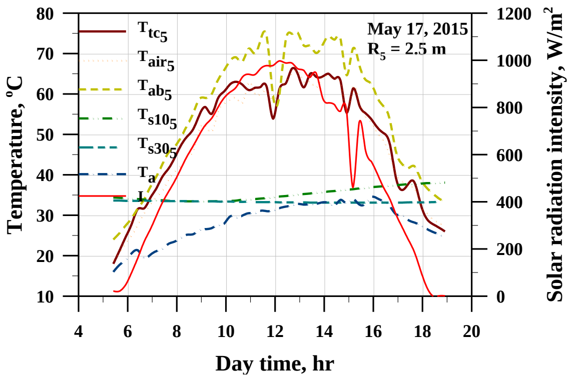

Figure 9 Temperature sensors records at R_5=2.5m on May 17, 2015

Figure 10 shows air velocity variation at chimney inlet during the day. The maximum value reaches 7 m/s just before the peak of solar radiation at maximum temperature difference of 29°C between air temperature at chimney inlet and ambient temperature.

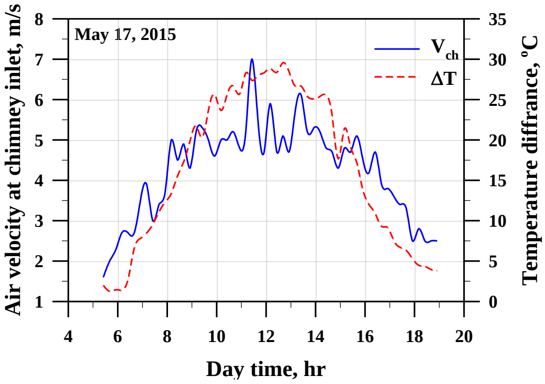

Figure 10 Air velocity at chimney inlet and temperature difference between air at chimney inlet and ambient on May 17, 2015

Figure 11 shows predicted generated electrical power from both experimentally measured parameters and mathematical model. Maximum predicted generated power is 75 Watt based on mathematical model using Eq. 1 and is produced at maximum value for ΔT. After sun set until next sun rise the value for produced power reach to value near from zero.

$$P_e = \frac{2}{3}\eta_{co} * \eta_{ch} * \eta_{gen} * A_{co} * I \quad \text{Eq.1}$$

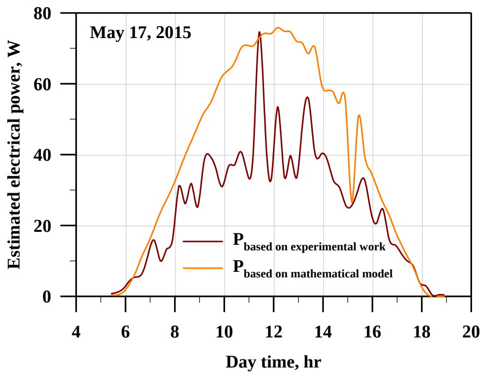

Figure 11 Predicted generated electrical power on May 17, 2015

4 Comparison with other experimental work

Table 2 shows a comparison between main parameters of small experimental solar chimney pilot plant setups that have been constructed at different countries and the present work. The main work related to the setups was to analyze the solar chimney power plant system performance by mainly testing the temperature and velocity of the air in the system.

Table 2 Main parameters of small experimental solar chimney pilot plant setups

Site	H_{ch}(m)	d_{ch}(m)	D_{co}(m)/ A_{co}(m^2)	Roof material	V_{ch}(m/s)	ΔT(°C)	year
Egypt Present Work	24	1	40x40 m^2	Plastic	7	29	2015
UAE [14]	8.25	0.24	10x10 m^2	Plastic	3.4	26.8	2011
Turkey [12]	17.15	0.8	27 m	Glass	5.5	26	2010
Iran [13]	12	0.25	10 m	Plastic	2.9	26	2010
Iraq [15]	4	0.2	6 m	Plastic	2.309	22	2009
Brazil [16]	12.3	1	25 m	Plastic	2.9	27	2003
China [10]	8.8	0.3	10 m	Glass	2.81	24.1	2002
Australia [17]	8	0.35	4.2 m	–	1	11	2002
USA [3]	7.92	2.44	18.3 m	Plastic	3.1	28.1	1997

5. Conclusions and Recommendations

In order to study solar chimney power plant, an experimental setup has been built in Tanta with chimney height and collector area of 24 m and 1600 m^2. Temperature variation at the specified points, air velocity at chimney entrance and solar radiation had been measured on May 17, 2015 from 5:00 AM to 7:00 PM. The results showed that maximum air temperature at chimney entrance was 62°C when the solar radiation was 988 W/m^2 at 12:40 PM. Maximum air velocity at chimney inlet was 7 m/s and happened for a while but mean air velocity in the period between 8:00 AM and 4:00 PM reaches 5 m/s , while mean ΔT and mean solar radiation are 23.5°C and 812 W/m^2. The average velocity during the whole measuring period is 4.2 m/s. The peak value of the estimated generated power is 75 Watt and can be increased by using increasing collector area or chimney length. The upper surface of soil is affected by temperature variation over it with noticeable rate; in the other hand deeper soil layer at 0.3 m depth was slowly affected by heat above it. It is recommended to find a way to utilize the heat stored in the soil under the collector to regulate velocity variation in solar chimney or use other heat storing material. Double layers glass panels should be used for the collector surface instead of polyethylene sheets because their temperatures reach high values causing a large amount of heat loss to the ambient through it. A new way to clean the surface of collector from dust without water should be found. Although seasonal rains cleaned the collector partly but there was dust layer that should be removed by cleaning.

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Nomenclature

dch	Chimney diameter, m
df	Funnel diameter, m
Hch	Chimney height, m
hco,in	Collector inlet height, m
hco.out	Collector exit height, m
I	Solar radiation intensity, W/m2
Lco	Collector edge length, m
Pe	Electrical power
R	Radius measured from the collector center, m
Rm	Thermal resistance of the insulating glass wool layer, m2.K/W
Ta	Temperature of ambient air, oC
Tab	Absorber upper surface temperature, oC
Tair	Air temperature inside collector, oC
Tch	Air temperature at chimney inlet, oC
Ts10	Soil temperature at 0.1 m depth, oC
Ts30	Soil temperature at 0.3 m depth, oC
Ttc	Temperature of the collector transparent cover lower surface, oC
Vch	Air velocity at chimney inlet, m/s

Greek Letters

ΔT	Temperature difference between air at chimney inlet and ambient, °C
λ_m	Coefficient of thermal conductivity of the insulating glass wool layer, W/m.K
ρ	Density of glass wool layer
η_{ch}	Chimney efficiency
η_{co}	Collector efficiency
η_{gen}	Genrator efficiency

Subscripts

ab	Absorber
air	Air inside collector
ch	Chimney
co	Collector
f	Funnel of chimney base
gen	Genrator
in	inlet
m	Measured value according manufacturer
out	outlet
tc	Transparent cover
1	Position number 1 under collector, R_1= 15.3 m
2	Position number 2 under collector, R_2= 12.1 m
3	Position number 3 under collector, R_3= 8.9 m
4	Position number 4 under collector, R_4= 5.7 m
5	Position number 5 under collector, R_5= 2.5 m

Abbreviations

FSK Foil-Scrim-Kraft
SCPP Solar chimney power plant

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