Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by
Center for Solar Energy Research and Studies

Experimental and Theoretical Investigation of Performance of a Solar Chimney Model, Part I: Experimental Investigation

Essaied M. Shuia[1], Bashir H. Arebi[2], and Ibrahim A. abuashe[3]

[1,3]Faculty of engineering, Zawia University, Zawia - Libya.

[2]Faculty of engineering, Tripoli University - Libya

[1]e-mail: essaied_shuia@yahoo.com,

[2]e-mail: arebi_bashir@yahoo.co.uk, [3]e-mail: ae.ibabdullah@zu.edu.ly

الملخص: تعرض هذه الورقة القياسات والبيانات التجريبية التي تم تجميعها من مدخنة شمسية تجريبية صغيرة. هذه القياسات التجريبية يمكن استخدامها جنبا إلى جنب مع الظروف المحيطة في تقييم أداء ودراسة سلوك المدخنة الشمسية. وسيتم استخدام هذه البيانات في تطوير نموذج نظري في ورقة أخرى (الجزء الثاني). المدخنة الشمسية التجريبية صممت وبنيت في كلية الهندسة في صبراته – ليبيا. وقد جمعت البيانات على مدى عدة أيام من شهر يونيو 2011. منظومة المدخنة الشمسية تتكون من عنصرين رئيسيين هما المجمع الشمسي والمدخنة الشمسية. أما المجمع الشمسي فله شكل دائري مساحته حوالي 126 م^2 والمدخنة عبارة عن أنبوب من PVC قطره الداخلي 0.2 م وارتفاع المدخنة الكلي يساوي 9.8 م. البيانات التي تم جمعها تشمل شدة الإشعاع الشمسي داخل وخارج المجمع الشمسي وكذلك درجة حرارة الهواء وسرعته في مدخل المدخنة ، ودرجة حرارة الهواء وسرعته خارج المجمع الشمسي ، كما تم قياس درجات الحرارة لأرضية المجمع ودرجات الحرارة للهواء في نقاط محددة وعند مستويات مختلفة داخل أرجاء المجمع الشمسي. شدة الإشعاع الشمسي كان لها تأثير مباشر على تغير درجات الحرارة داخل المجمع وبالتالي على سرعة الهواء خلال المدخنة الشمسية. سرعة الرياح خارج المجمع الشمسي كان لها تأثير صغير على سرعة الهواء داخل المدخنة وتميل إلى تغييرها بنسبة ضئيلة ويمكن إهمال تأثيرها على أداء المنظومة. كما سجلت النتائج التجريبية فروقا بين درجة حرارة الهواء عند مدخل المدخنة الشمسية ودرجة حرارة الجو خارج المجمع الشمسي تتراوح بين 30 إلى 45 ^{0}م وذلك عند منتصف النهار خلال فترة التجارب في شهر يونيو، وكانت أعلى درجة حرارة للهواء سجلت عند مدخل المدخنة الشمسية هي 73.4 ^{0}م عند منتصف النهار في يوم 9 يونيو، كما سجلت في نفس اليوم أعلى سرعة للهواء عند مدخل المدخنة مقدارها 3.6 م/ث. النتائج التجريبية تبين أن هذا النوع من النظم يمكنه حبس مقدار كاف من الإشعاع الشمسي الذي يرفع درجة حرارة الهواء داخل المجمع الشمسي تمكنه من التمدد والتدفق بكميات كافية خلال المدخنة قادرة على تدوير تربين لإنتاج الكهرباء. هذا يعني أن نظام المدخنة الشمسية لإنتاج الكهرباء يمكن أن يعمل في الجزء الشمالي الغربي من ليبيا في فترة الصيف على الأقل.

***Abstract*:** This paper presents the experimental data that was collected from small pilot solar chimney. The experimental data together with ambient conditions are used to

Solar Energy and Sustainable Development, Volume (3) № (1) 2014

evaluate the performance and study the behavior of the solar chimney; this data will be used for comparison with theoretical models in another paper (part II). The solar chimney prototype was designed and constructed at the Subrata Faculty of Engineering-Libya. The data were collected over several days of June 2011. The solar chimney system contains two main components; the solar collector and the solar chimney. The solar collector roof has a circular area of 126 m^2, the solar chimney is a PVC tube with internal diameter of 0.2 m and the total height of chimney is 9.8 m. The measurements include the intensity of solar radiation inside/outside the collector, temperature and velocity of air at the entrance of the chimney, temperature and speed of wind outside the collector, temperature of the ground inside collector and temperature measurements of air at specific points at different levels throughout the collector. Solar irradiance was found to affect the chimney temperature and subsequently affects chimney air velocity. The experimental results showed that temperature differences of (30 – 45°C) were recorded between the ambient temperature and that of air inside the chimney in the middle of the day, where the highest air temperature of 73.4°C was recorded at the entrance of the solar chimney. The maximum air velocity of 3.6 m/s was recorded inside the solar chimney at noon on 9 June. Wind speed outside the collector had a small effect on the speed of the air inside the chimney and tends to change slightly, hence, can neglect influence of wind speed on the performance of the system. Also the experimental results indicate that such type of system can trap a sufficient amount of solar radiation, which elevates the air temperature to a sufficient value able to generate enough air flow to operate a wind turbine to produce electricity; this means the solar chimney system for electricity production can work in the north-western part of Libya in the summer time at least.

Keywords: Solar energy, solar chimney, Buoyancy effect, Draft tower, Renewable energy.

1. INTRODUCTION

Solar chimney power plant (SCPP) is a relative novel technology for electricity production from solar energy. The SCPP consists of a greenhouse roof collector and updraft chimney that is located at the center of the greenhouse roof collector. The greenhouse roof collector is usually made of plastic sheet or glass plate which traps the solar energy and elevates the air temperature. The chimney is used to direct and vent the hot air through the wind turbine. The wind turbine is used to convert the air kinetic energy into mechanical work. No full scale solar chimney power plant has been operated to date, however many proposals have been investigated in different parts of the world. The feasibility of SCPP was evaluated by different experimental studies. The first outstanding action for the solar chimney power plant (SCPP) development was the prototype erection in 1982 in Manzanares, Ciudad Real, 150 km south of Madrid, Spain. The chimney height was 195 m and its diameter 10 m. The collector area was 46,000 m^2 [1]. 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 about 50 kW. In 1997, a small scale solar chimney was established by Pasurmarthi and Sherif [2], [3] in Florida. That system includes a collector diameter of 9.15 m and the tower height is equal to 7.92 m and its diameter gradually decreases from 2.44 m at base to 0.61 m at the chimney top. The study was conducted to evaluate the performance characteristics of solar chimneys both theoretically and experimentally. A pilot experimental solar chimney setup was built in HUST- China by Zhou, et al. [4]; the experimental model consists of 5 m radius air collector and a chimney 8 m height. The size of the opening at the periphery of the collector was chosen as 0.05 m. Standard PVC drain-pipes 0.3 m in diameter were used as a chimney. The temperature distribution in the solar chimney was measured and the temperature difference between the collector outlet and that of ambient, can usually reach 24.1°C, which generates the driving force of airflow in the chimney. A pilot experimental solar chimney was built in Adıyaman University by Buğutekin [5]. The collector of 27 m diameter and the chimney of 17 m height were used to investigate the effect of environmental temperature, chimney height, the collector diameter, the value of solar radiation, etc. on the performance of solar chimney system. It was found that solar radiation and environmental temperature had a considerable impact on the system and temperature difference between the environment temperature and the air temperature inside the chimney was (21-26 °C). Moreover, it was found that the environmental air velocity had no affect on the system. In order to evaluate the solar chimney model, a prototype was constructed in Alain, United Arab Emirates (UAE) [6] which consists of a 10m x10m collector and a chimney of 8.25 m height. The study [6] reported the effect of internal collector dynamic temperature, the amount of solar energy trapped within the collector. This paper presents the experimental data that were collected from small scale solar chimney to evaluate and study the behavior and the performance of the solar chimney.

2. DESCRIPTION AND SETUP OF THE SOLAR CHIMNEY PROTOTYPE

In order to perform an investigation on the performance of a solar chimney system, a small scale solar chimney system was designed and built at Subrata Faculty of Engineering in north-west of Libya (Latitude 32° 48′ 28.63″ N - Longitude 12° 27′ 36.84″ E). A schematic diagram of the system is shown in Figure 1 and a number of Photographs of the solar chimney prototype are shown in Figure 2.

2.1 Chimney design and choice of dimensions

According to previous studies, the chimney height has very strong effect on the efficiency and total power harvested. The chimney diameter has small effect except for very small chimney diameter where friction becomes a dominating factor.

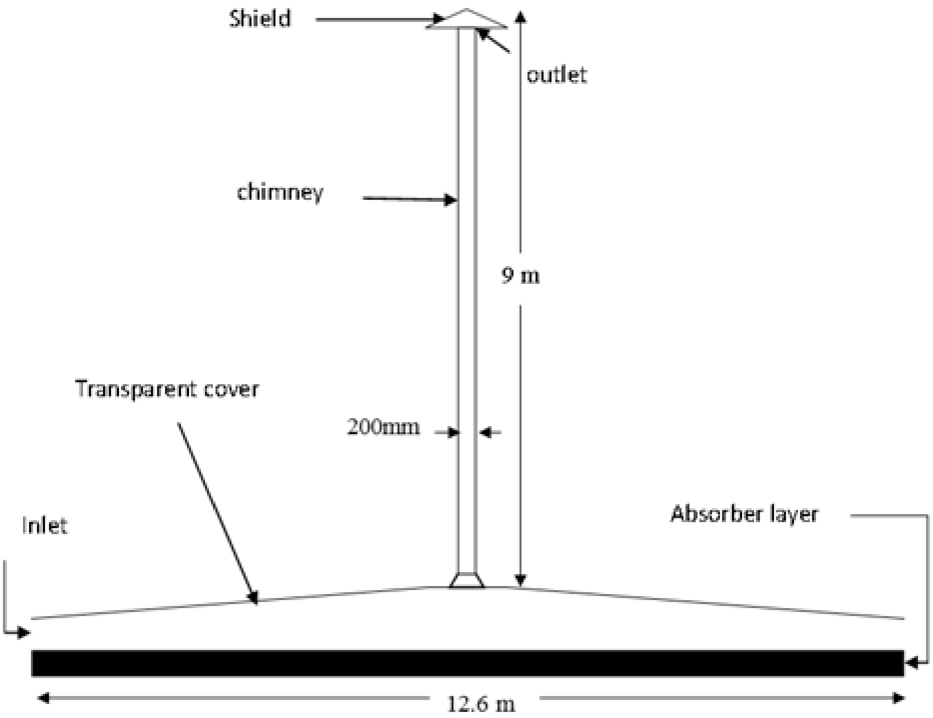

Figure (1). Schematic arrangement of the solar chimney system.

The collector diameter has very small effect on the efficiency since the friction losses were minimized by the wide inlet area and low average velocity inside the collector but it has strong effect on harvested energy. The previous works of several researchers [1,2,3,4,5] conclude that the ratio of the chimney height to the solar collector diameter determines the solar chimney dimensions.

The ratio of the collector diameter to the chimney height was found to have a wide range of acceptable values ranging from 0.8 to 5. The prototype at Manzanares [1] has been considered when designing the solar chimney model in this study by taking the same ratio of the collector diameter to the chimney height. However, the appropriate chimney diameter is chosen according to what is available on the local market, taking into account the appropriate diameter which provides flow with less friction. The tested solar chimney prototype contains two main components; solar collector and chimney.

2.2 Solar collector

The solar collector is a circular shape that has a floor of 126 m^2 area. This area is covered with transparent plastic of 0.2 mm thick. The plastic cover is raised by a steel framework from height of 0.3 m at the outer radius to 0.8 m at the center of the collector just under the chimney entrance. In order to allow the air to flow into the system, several holes were made around the outer edge of the collector. A central base is attached to eight hinges which are distributed uniformly around the base. These hinges were assembled with a rectangular structural tube (0.5 m x 0.35 m x 6 m, with 2 mm thick). The rectangular tubes were supported by two radial tubes to avoid the deflection on a steel framework. The steel framework is shown in Figure 2- a. The floor of the collector was made of two layers. The upper layer is about 6 cm thick of fine crushed black stones and works as an absorber, and the second layer is a fine wood (sawdust wood) works as insulator. A plastic film was placed between the two layers to allow changing the absorber layer when ever needed. The layers of crushed stones and sawdust wood were spread evenly over the floor; the thermo-physical properties of the materials used in the solar chimney system components are shown in Table 1.

(a) (b) (c) (d)

Figure (2). Pictures of solar chimney prototype in Subrata faculty of engineering, Libya (a) steel frame work, (b,c) from out side (d) under the plastic cover collector.

The central base of the solar chimney is supported by a concrete stand to ensure the stability of the system.

2.3 Chimney

The chimney is constructed from PVC pipes with an inside diameter of 192 mm and a height of 9 m. These pipes are covered with glass wool blanket (10 mm thick and thermal conductivity k = 0.05 W/m K) which works as a thermal insulator to reduce heat losses from the chimney wall. The thermal insulator is covered with aluminum foil to prevent the insulation from wetness; also the chimney outlet was covered by a cap to avoid the rain to go into the chimney. The chimney is connected to a conical nozzle which works as a base for the chimney. To sustain the chimney, two coupling rings were fixed around the chimney; each ring was connected to four galvanized steel wires and attached to the concrete foundations.

Table (1). Properties of the tested solar chimney system components, [7-8]

Properties / component	Density (kg/m^3)	Thermal conductivity (W/m.°K)	Specific heat (kJ/kg. °K)	absorptivity	transmissivity	emissivity
Insulator (sawdust wood)	150	0.06	1. 9	-	-	-
absorber (sandstone)	2160	1.83	0.71	0.9	-	0.9
Collector roof (Polyethylene)	918	0.33	2.3	0.0	0.89	0.15

2.4 Manufacturing and construction processes

Manufacturing processes were done by using the CNC machines. The experimental rig of solar chimney system was constructed in the site at Faculty of Subrata. Figure 2 shows a number of photographs of the solar chimney prototype.

2.5 Measuring Instruments

The experiments were carried out during the summer 2013. The temperature distribution throughout the solar chimney system, solar radiation, air velocity through the chimney, wind speed and the ambient temperature were measured hourly for fifteen hours daily.

The instrumentations used in the experiment include the following:

- A pyranometer with data-logger to measure solar radiation. The instrument has a range of 0 to 4000 W/m^2 with accuracy of ±0.1 %.
- Two anemometers type (AR836) to measure air velocity at the chimney entrance and the wind speed outside the collector, the instrument has a range of 0 to 25 m/s with an accuracy of ± 0.05 m/s.
- Forty thermocouples to measure temperature distribution throughout the system. All the thermocouples are Ni-cv/Ni-Al type K, the thermocouples were connected to digital thermometers (DT-612). The thermocouples together with the digital thermometers were calibrated with an accuracy of ± 0.2 °C.

Because the temperature measurement is taken directly from the digital thermometer, the uncertainty of the temperature measurement is assumed to be defined by the calibration accuracy which is equal to ± 0.2 °C.

Schematic diagrams of the measuring positions are shown in Figure 3. The collector is divided into ten sections; each section consists of four measuring nodes distributed in vertical direction as follows:

- Ten nodes under the insulation layer.
- Ten nodes at absorber layer.
- Ten nodes in the middle of the air gap.
- Ten nodes under a transparent cover.
- The measurements were taken hourly (7am to 9pm) on 9th, 11th, 12th, 13th of June 2013.

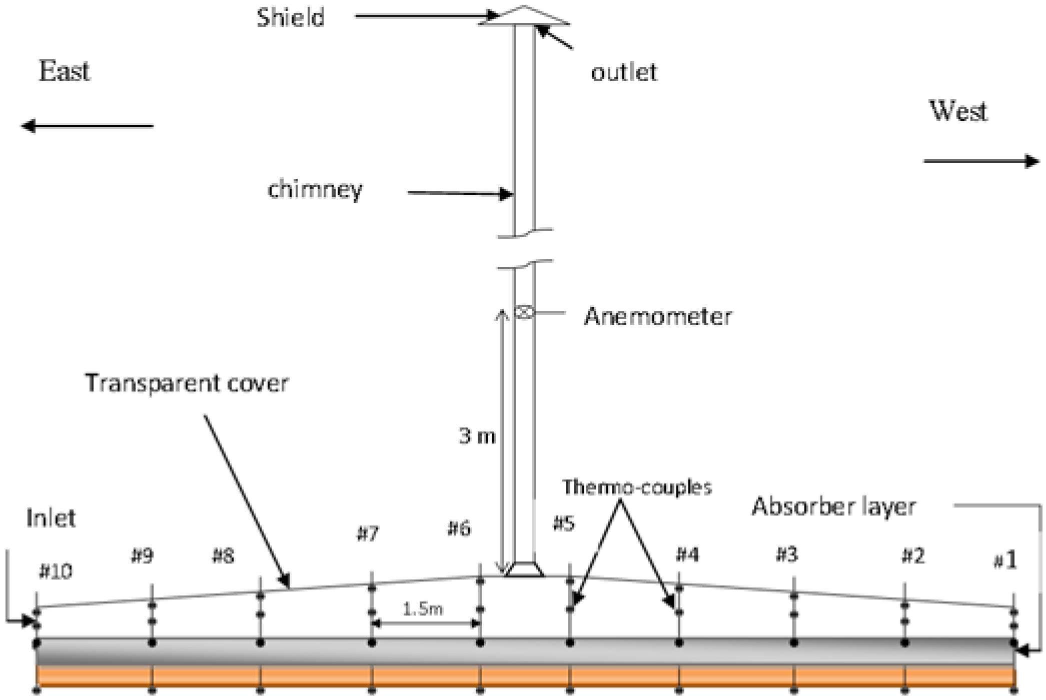

Figure (3). Schematic diagram of the measuring positions.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A number of tests were carried out to illustrate the behavior of the solar chimney system. The tests and the measurements cover: 1- Solar radiation intensity during the day time. 2- Temperatures distribution at specified points inside the collector and chimney inlet. 3- Velocity of air through the chimney. 4- Wind speed and ambient temperature.

The data from the tests are illustrated in Figures 4 to 7. Figures 4 to 6 show chimney velocities, temperatures and irradiance, against time in one hour intervals.

Figure 4 shows that the increase in the intensity of solar radiation leads to an increase in the temperature of the absorber, which in sequence leads to an increase in air temperature inside the collector, and as a result of that, the air expands and increases its speed within the solar chimney. The figure indicates that the temperature differences between collector exit and the ambient reached its maximum value about 44.6 °C at noon on the day 11 of June. Figure 5 shows the variation of air velocity versus the solar radiation. The figure shows that the increase in the intensity of solar radiation leads to an increase in the air temperature inside the collector, and as a result, the air expands and increases its speed within the solar chimney. Since air is heated, it starts to rise up and move towards the chimney's entrance and gains higher velocity as the solar radiation intensity increases, it reaches its maximum velocity about 3.6 m/s after noon when the temperature of the absorber reaches its maximum value.

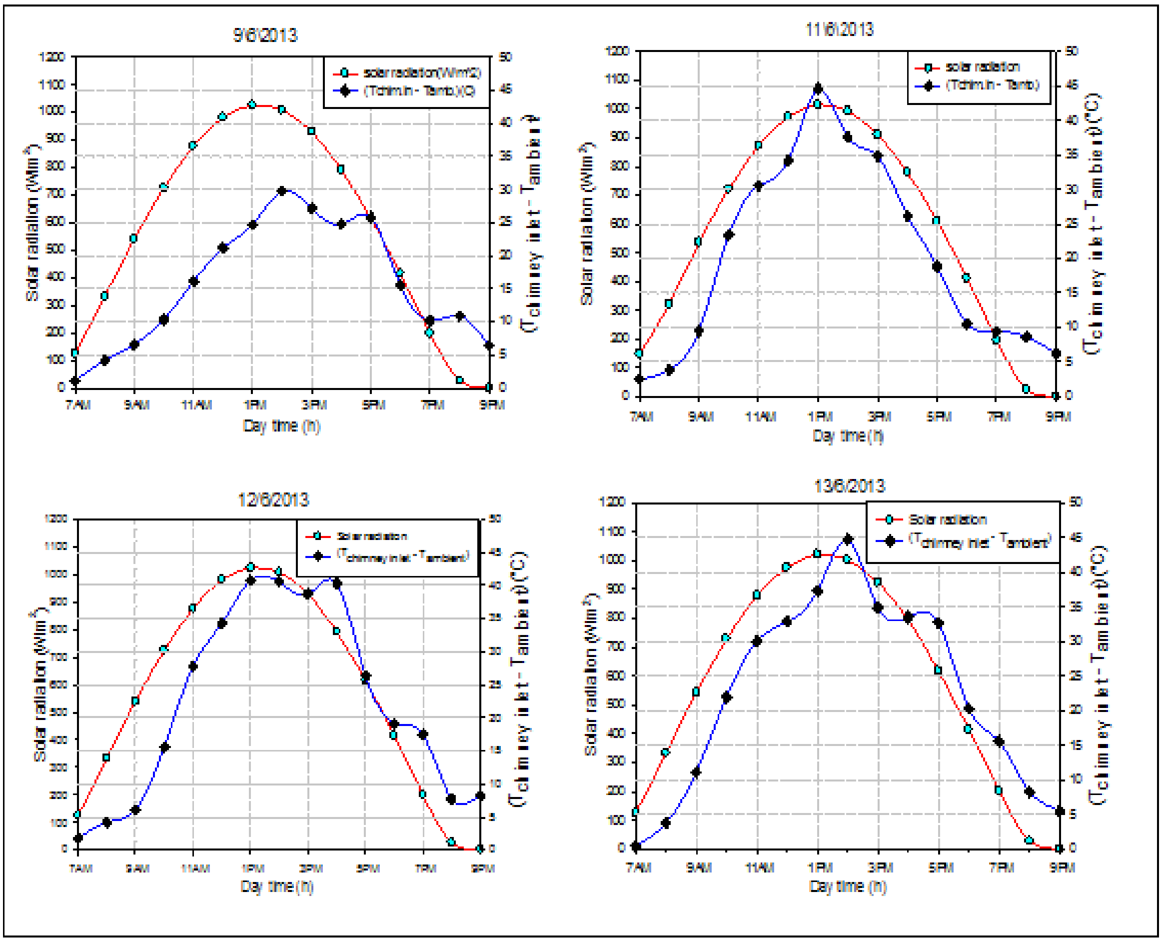

Figure (4). Air temperature differences ($T_{ch.\ inlet}$-$T_{amb.}$) variation with solar radiation.

Also Figure 5 shows that the heated air continues to flow into the solar chimney after sunset; this is because of the thermal storage by the floor of the solar collector (absorber) which continues to provide heat to the air even after sunset. Therefore, the absorber with high thermal capacity is important to absorb more heat during the day and releases it during the night. This allows continuous flow of air through the chimney at night and thus electricity can be produced even after sunset. Also the effect of wind speed on the air velocity at the chimney entrance is shown in Figure 5.

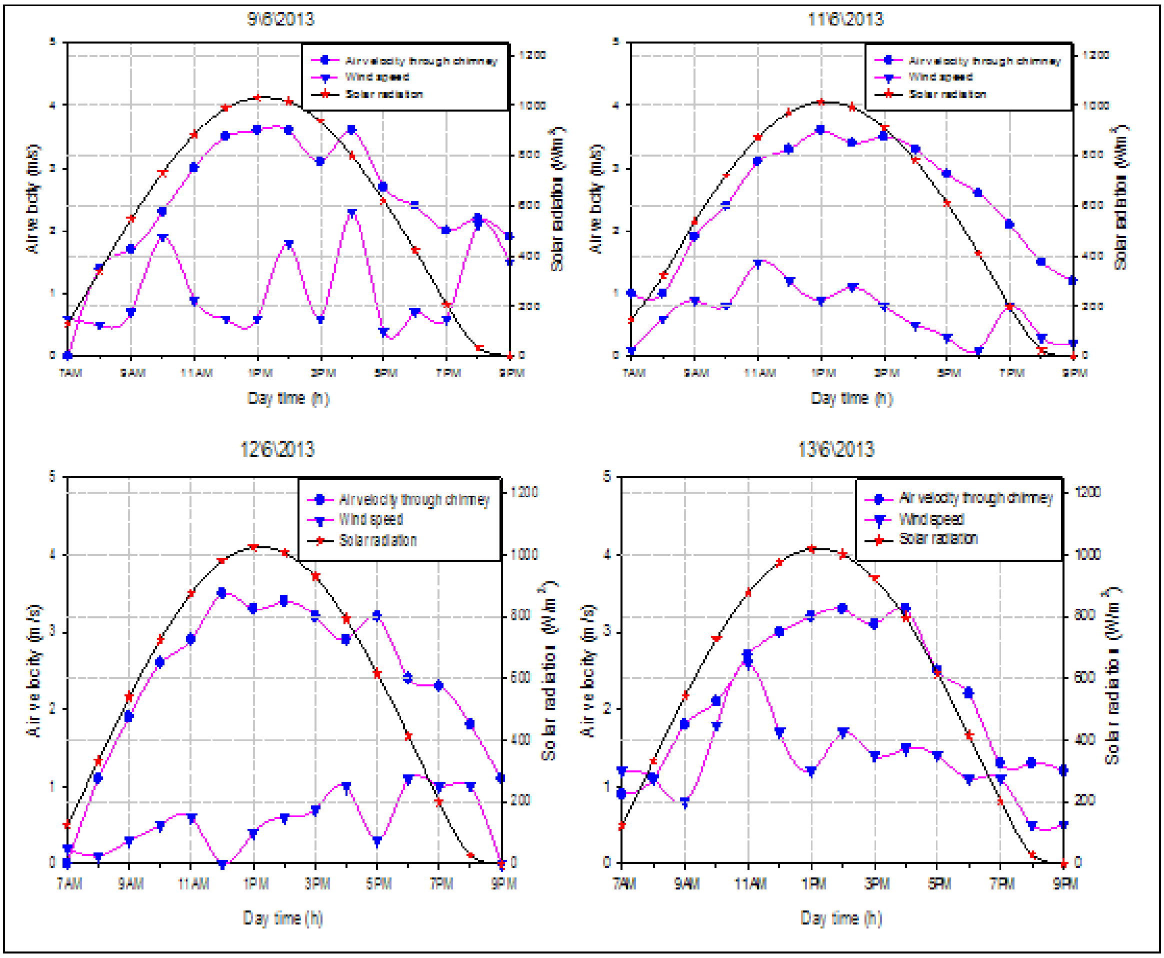

Figure (5). The effect of solar radiation and wind speed on the air velocity at the chimney entrance during the day time.

The figure indicates that any variation in the wind speed outside the solar collector leads to a small change in the air velocity inside the solar chimney; therefore the effect of the wind speed on the performance of the solar chimney system can be neglected.

The temperatures at specified points at the middle of the solar collector were measured and presented in Figure 6. The figure shows that ground temperature under the absorber during the day stayed nearly constant; this is due to a very small heat loss to the ground. In the morning, the absorber temperature is less than air temperature, this leads to heat transfer from the air to the absorber, while in the evening the temperature of the absorber is greater than the air temperature even after sunset; this is because of the thermal storage by the floor of the solar collector (absorber) which continues to provide heat to the air even after sunset.

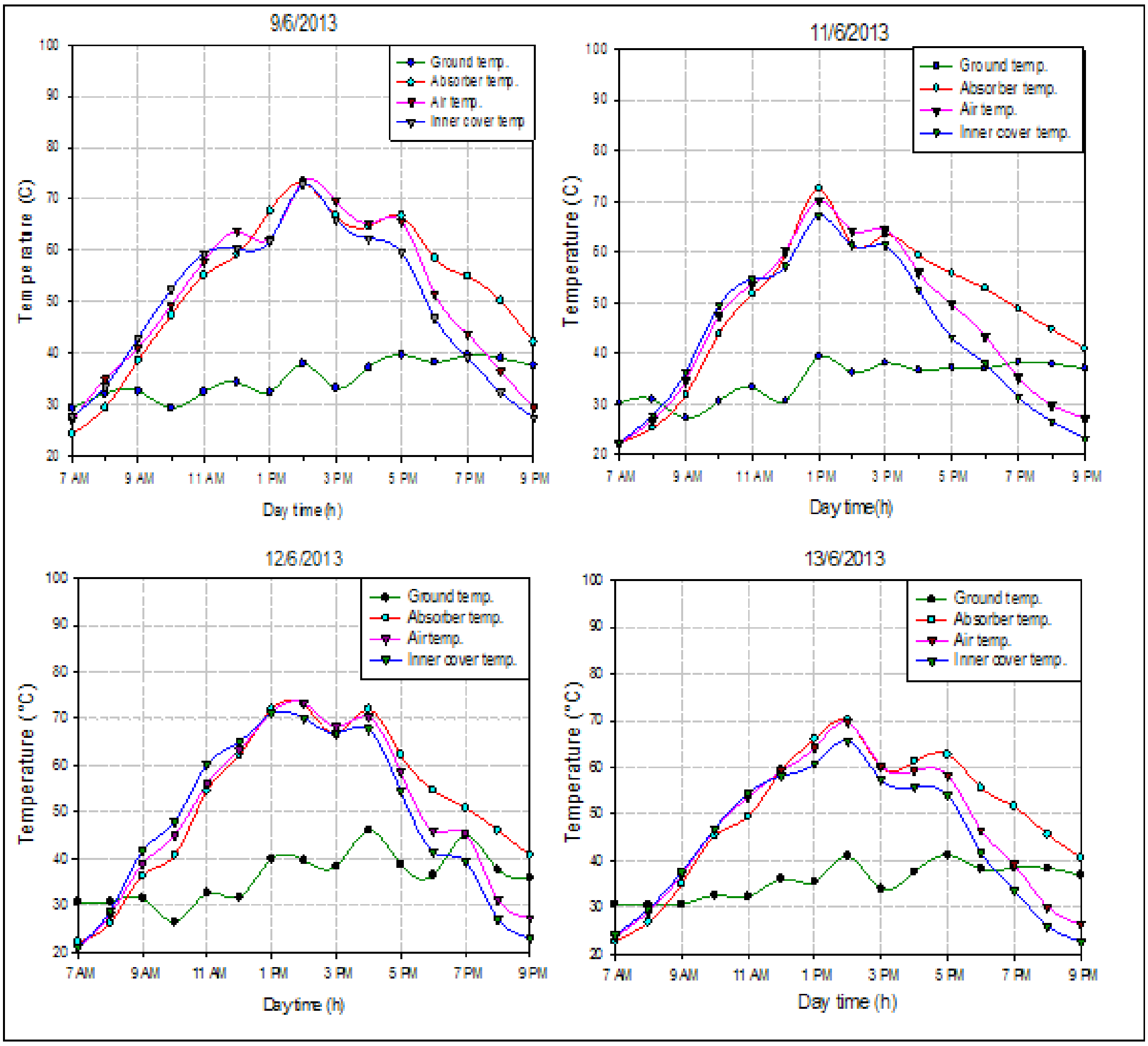

Figure (6). Temperatures at specified points at the middle of the collector during the day

The graphs of Figure 7 show the air temperature distribution at different sections throughout the collector. The minimum values of the temperatures were recorded at the morning and the maximum values reached at noon when the solar irradiance reached its maximum value. The figure also indicates the maximum values of air temperature in the middle of the collector at the chimney entrance.

4. CONCLUSIONS

From the experimental results, a number of conclusions may be drawn as follows:

- The highest temperature of 73.4°C was recorded at the entrance of the chimney at noon on the day of June 9, and the velocity of 3.6 m/s was measured at chimney entrance. The air speed peak is directly related to the temperature difference between the collector internal temperature and the ambient temperature. Temperature difference between the collector air outlet and the ambient can reach 45 °C during summer time, which can generate a driving force of airflow in the setup, this means that a solar chimney system may be operated to produce electricity in the northern-west part of Libya.

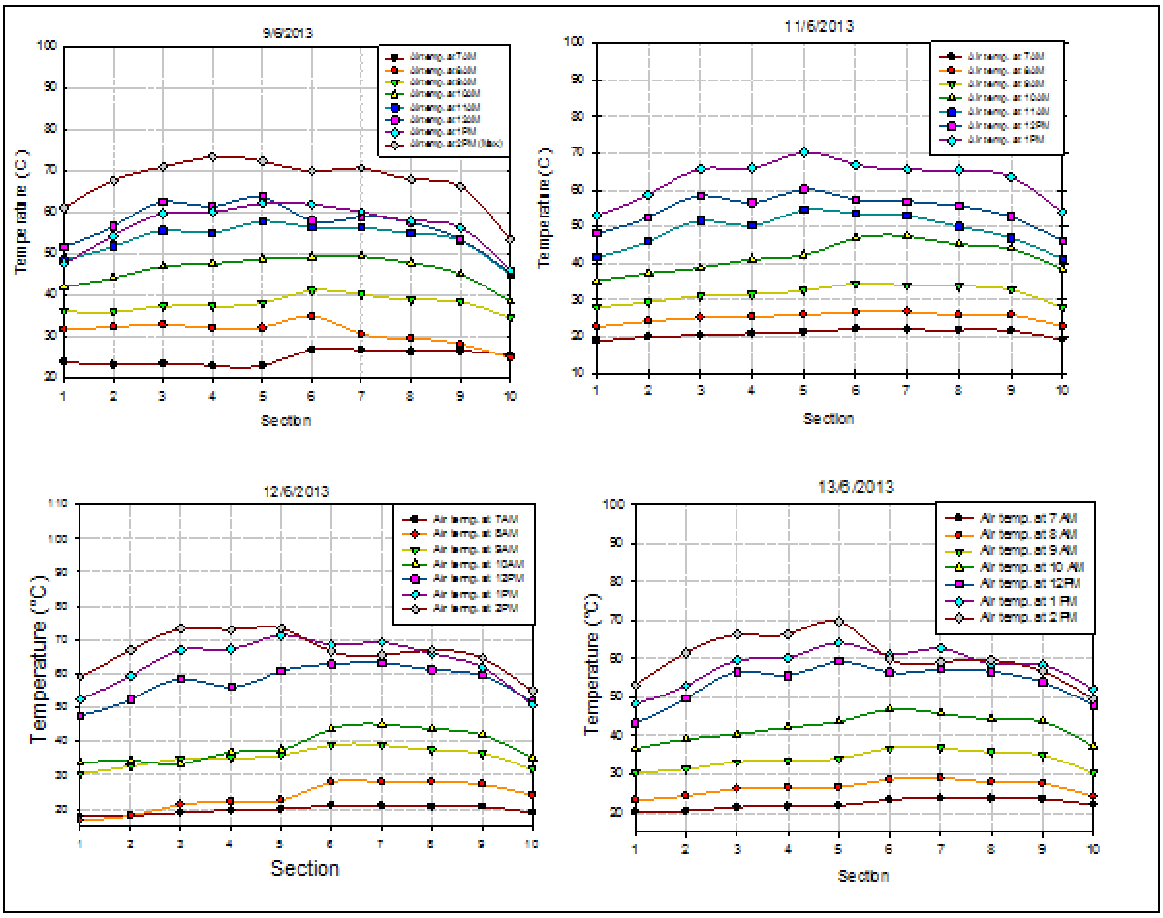

Figure (7). Air temperature distribution inside the collector at different sections and times

- The performance of the solar chimney at noon hours is higher than that in the morning and evening hours.
- The floor of solar collector stores part of the thermal energy during the day and releases it during the night; therefore, using absorbers with high thermal capacity in solar chimney power plants is important to produce electricity after sunset.
- Wind speed outside the collector has a negligible effect on the solar chimney performance.

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