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EXPERIMENTAL STUDY OF TEMPERATURE FIELD IN A SOLAR CHIMNEY PLANT IN ADIYAMAN

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Abstract:The solar chimney is a simple renewable energy source consisting of three main components, a solar collector, chimney and turbine. Air is heated by the greenhouse effect under the glass collector. This hot air, less dense than the surroundings, rises up the chimney at the center of the collector. At the base of the chimney an electricity generating turbine is driven by the rising air. This study investigates the temperature field in a solar chimney plant. The experimental system, designed and constructed in Adıyaman, is used to study the environmental temperature, distribution of the temperature, ground temperature and air velocity determined at the specified points and heights in the solar chimney system. It is found that solar radiation and environmental temperature has a huge impact on the system and temperature difference of the environment temperature and the output air temperature of the collector is approximately 21-26 °C. Moreover, it is seen that the environmental air velocity has not affect over the system. Also, temperature and air velocity at the point where the turbine assembly to be made is measured as maximum value of the system. In addition, measurements has shown that the temperature distribution in the southern part of the solar chimney is little more than in the northern part.
Keywords: Solar chimney plant, Collector, Temperature field.

ADIYAMAN'DA BİR GÜNEŞ BACA TESİSİNDE SICAKLIK ALANIN DENEYSEL OLARAK İNCELENMESİ

Özet: Güneş bacası üç ana bileşenden, bir güneş kolektörü, baca ve türbin den oluşan basit bir yenilenebilir enerji kaynağıdır. Hava cam toplayıcı altında sera etkisi ile ısıtılır. Çevre yoğunluğundan daha az olan bu sıcak hava, kolektör merkezinde baca doğru yükselir. Baca dibinde bir elektrik üreten türbin yükselen hava ile tahrik edilir. Bu çalışma güneş bacası tesisi alan sıcaklığını araştırmaktadır. Tasarlanan ve Adıyaman'da kurulan bu deneysel sistem, güneş bacası tesisinde belirlenen özel nokta ve yüksekliklerde çevresel sıcaklık, sıcaklık dağılımı, zemin sıcaklığı ve hava hızı incelemek için kullanılmıştır. Güneş ışınımı ve çevre sıcaklığı sistem üzerinde büyük bir etkisi olduğu ve farklı çevre sıcaklıklarının ve kolektörün çıkışındaki hava sıcaklığının yaklaşık olarak 21-26 °C olduğu saptanmıştır. Ayrıca, çevre hava hızı, sistem üzerinde etkisinin olmadığı görülmektedir. Ayrıca, türbin montajının yapılacağı yerdeki notada, sıcaklık ve hava hızı değerleri maksimum değerleri ölçüldü. Buna ek olarak, ölçümler güneş bacasının güney kesiminde sıcaklık dağılımı, kuzey kesiminde biraz daha fazla olduğunu göstermiştir.
Anahtar kelimeler: Güneş bacası sistemi, Kolektör, Sıcaklık alanı.

NOMENCLATURE

A_c Cross-sectional area of solar chimney [m^2]
A_{coll} Solar collector area [m^2]
C_p Specific heat of air [kJ/kg°C]
g Acceleration of gravity [m/s^2]
G Solar irradiance [W/m^2]
H_{sc} Solar chimney height [m]
$\dot{m}$ Mass flow rate of air [kg/s]
P_{tot} Useful energy contained in the airflow [kW]
$\dot{Q}$ Heat gain of air in the collector [kW]
T_0 Ambient temperature [°C]
V_c Inlet air velocity of solar chimney [m/s]

Greek letters

$(\tau\alpha)$ Effective product of transmittance and absorbance
β Heat loss coefficient [W/m^{2}K]
η_{coll} Solar collector efficiency
η_{sc} Solar chimney efficiency
ρ Air density [kg/m^3]
ΔP_{tot} Pressure difference produced between chimney base and the surroundings [Pa]
ΔT Temperature rise between collector inflow and outflow,°C

INTRODUCTION

Global warming is boosting the need for clean energy sources day by day. In the meantime, using alternative energy sources becomes a new trend by the impact of global energy crisis. One of these alternative energy sources is solar energy. Solar power is safe, environmental friendly and cost effective. Electricity is produced from solar energy in many different ways. There are two ways in the production of electrical energy by utilizing solar energy. First way is transforming directly solar energy into electrical energy by means of photovoltaic batteries (Selbaş *et al.*, 2003). Second way to produce the electrical energy is to use solar energy to heat water or air to gain back the energy from steam or hot air (Solar Chimney Plant).

Hot air has a lower density than cold air. Therefore, it ascends. The opposite is also true for cold air. Solar chimney plant applications use this physical phenomenon and guide the air rising through a hollow tower. The hollow tower also accelerates the air. The harvested energy from the rising air is captured by wind turbines or hydro turbines that are more familiar with (Zaslavsky, 1997). To create an ascending airflow, a large area is over-roofed with glass or plastic frames. The short wave radiation from the sun goes through the frames and reaches the surface as transformed into a long wave heat radiation which can not pass frames. By building the frames with a little incline in the field hot air is forced to move in the direction of the tower. A high tower that speeds up the hot air creates a strong draft. By placing a wind turbine to the beginning of the tower, the energy in the air can be harvested A micro-scale model chimney with a radius of 3.5 cm, 2 m in height and 9 m^2 in area was built in İzmit (Kulunk, 1985). Haaf et al. described the operation and Schlaich presented results for a prototype solar chimney power plant built in Manzanares, Spain, in 1982. (Haaf *et al.*, 1983; Haaf, 1984 and Schlaich, 1994). A solar chimney thermal power generating facility courtyard with an output power of 10 W built in America had a diameter of 6 m. Its collector and the chimney was 10 m tall (Krrist, 1983). A solar chimney thermal power generating demonstration model was built and modified on the campus of the University of Florida and both theoretical and experimental investigation was carried out on their performances (Pasurmarthi and Sherif, 1997). A case study of the SC power plants in Northwestern regions of China, concluded that a SC power plant is able to produce 110-190 kW of electric power with a chimney height of 200 m and diameter of 10 m, and with a cover of collector 196.270 m^2 through the use of a sloped collector fields in Mathematical models and code for MATLAB (Dai *et al.*, 2003). This study developed an analysis for the solar chimneys, particularly aimed at a comprehensive analytical and numerical model to estimate the power output of solar chimneys as well as to examine the effect of ambient various conditions on the power output and structural dimensions. Another study shows that the height of the chimney, the factor of pressure drop at the turbine, the diameter and the optical properties of the collector are important parameters for the design of solar chimneys (Bernardes, 2003). Pretorius *et al.* developed a numerical model simulating the performance of their study, a large-scale solar chimney power plant reference, indicating that greater power production is possible by optimizing the collector roof shape and height (Pretorius *et al.*, 2004). A good overview of the technology and theoretical principles-including the governing its design has been provided by Schlaich *et al.* . The main parts of the plant are the collector roof solar chimney and machinery space, which includes turbines and generators for electric power production (Schlaich *et al.*, 2005). The working potential of the power source is the heated air, defined and analyzed in the study of Ninic (2006). The dependence of the work potential on the air flowing into the air collector from the heat gained inside the collector, air humidity and atmospheric pressure as a function of elevation are determined (Ninic, 2006). The potential applications of the SC power plant in rural areas were studied and the appropriateness of a solar chimney considered rural villages and to highlight some of such a power generating plant in features. The calculations of the temperature ratio of the difference between the collector surface temperature at the turbine and the temperature, mass difference between the air temperature under the roof and the collector surface temperature (Frederick *et al.*, 2006). Pretorius and Kröger evaluates the influence of a convective heat transfer equation developed recently, more accurate turbine inlet loss coefficient, quality collector roof glass and various types of soil on the performance of a large scale solar chimney power plant (Pretorius *et al.*, 2006). A simulation study was carried out to investigate the performance of the power generating system based on developed mathematical models. Steady state power outputs were simulated in the global solar radiation obtained for different intensity, collector area and chimney height (Xinping *et al.*, 2007). They compared the methods used to calculate the heat fluxes in the collector, and their effects on performance of solar chimney. Reasons for the discrepancies between the predictions of the two models are given (Bernardes *et al.*, 2009). Chimney 10 m diameter and 8 m tall solar chimney was built for in the measured temperature distribution. That they find different between the collector outlet and the temperature 24.1 °C with ambient usually, which generates the driving force of the airflow in the setup. (Xinping *et al.*, 2007). A study aimed to wash while dynamic similarity models for a protoype using the same and its solar heat flux (Atit *et al.*, 2009). A study is to investigate the effect of the collector diameters on air flow rate and temperature in the chimney by using mathematical theories. For this purpose at certain times of the day, air flow rate and temperature in the chimney, ambient temperature, and ambient air velocity, surface temperature of collector and solar radiation values of Adıyaman are measured and evaluated for collectors having different diameters. As a result, collector having large diameter means more solar energy. As the collector area grows, the ground temperature increases %35-55 with respect to ambient temperature and at further studies, it is observed that temperature and air flow rate at the point turbine placed (C_2) increase quickly as diameter of collector increases (Bugutekin, 2011).

Solar Chimney Plant system has many parameters that affect the efficiency. One of them is the temperature under the collector. This is one of the reasons to install the system in Adıyaman University campus area in the Southeastern Anatolia Region where solar radiation levels are high. In 2003, a similar study has done in China (Xinping Z. et al., 2007). Production of the system in this study started in March 2009 and has completed in June 2010. Ambient temperature, ambient air velocity, temperature and air velocity distribution at specified points and heights under the collector according to the solar radiation air conditions of Adıyaman, temperature and air velocity distribution at point F_2 within the turbine assembly to be made are investigated. The experimental system and the results obtained will be given at following pages.

THEORETICAL MODEL

The height of the solar chimney, solar collectors, or stone materials such as soil beneath the structure of the solar tower can affect performance. The temperature changes and air flow inside the solar chimney can be evaluated using CFD software programs (Dai *et al.*, 2003, Gannon *et al.*, 2000 and Backstrom *et al.*, 2000).

Solar Collector

Soil coated with glass or other transparent material is a layer of self-temperature-absorption material. The height (periphery) around collector and the energy balance equation of the chimney in the middle of collector (Dai *et al.*, 2003);

$$\dot{Q} = \dot{m} C_p \Delta T = (\tau\alpha) A_{coll} G - \beta \Delta T_a A_{coll} = \eta_{coll} A_{coll} G \quad (1)$$

where $\dot{m}$ mass rate of hot air, flow through solar chimney, and can be calculated by below equation.

$$\dot{m} = \rho_{coll} A_c V_c \quad (2)$$

The air velocity at outlet of the solar collector is expressed by,

$$V_c = \frac{(\tau\alpha) A_{coll} G - \beta \Delta T_a A_{coll}}{\rho_{coll} A_c C_p \Delta T} \quad (3)$$

and the efficiency of the solar collector is given below.

$$\eta_{coll} = (\tau\alpha) - \frac{\beta \Delta T_a}{G} \quad (4)$$

where ΔT_a is the difference between heat-absorbing layer and the environment air temperature (the temperature of heat absorbing layer was considered equal to the average air temperature), ρ is the air density at the outlet of solar collector, β heat loss coefficient of solar collector, the A_C is cross-sectional area of solar chimney, A_{coll} solar radiation field area, G the standard solar radiation, τα is absorption and permeability of the material which solar collector is made of. ΔT is the difference between outlet of the collector and the ambient air temperature. If air temperature of the collector rise, air flow in a linear direction along collector. ΔT can be estimated as proposed at reference (Dai *et al.*, 2003, Zhang, 1992).

$$\Delta T = \frac{2Q}{A_{coll} \beta F_R}(1 - F') \quad (5)$$

where, the heat removal factor, F_R, can be approximately estimated by,

$$F_R = \frac{1}{\dfrac{1}{F'} + \dfrac{A_{coll}\beta}{2\dot{m}C_p}} \quad (6)$$

F' is the efficiency factor of the solar collector, F'' is the flow factor and is given as,

$$F' = \frac{F_R}{F''} \quad (7)$$

Furthermore, ΔT_a can be expressed below, under the assumptions given above.

$$\Delta T_a = \frac{1}{2}\Delta T \quad (8)$$

Solar Chimney

Chimney itself is a real thermal motor. It is a pressure tube having small friction losses. Efficiency of chimney depends on the conversion of air temperature, rising under collector, to kinetic energy. In fact, air temperature at ground level and height of chimney determines efficiency.

The chimney efficiency (Dai *et al.*, 2003, Schlaich, 1995) is expressed as follows:

$$\eta_{sc} = \frac{T_{tot}}{Q} = \frac{gH_{sc}}{C_p T_0} \quad (9)$$

where, H_{sc} is the height of the chimney, P_{tot} is the power contained in the flow, which can be written as,

$$P_{tot} = \eta_{sc} Q = \frac{gH_{sc}}{T_0} \rho_{coll} V_c \Delta T A_c \quad (10)$$

The pressure difference, ΔP_{tot}, which is produced between the chimney base and the surroundings, is calculated by,

$$\Delta P_{tot} = \rho_{coll} g H_{sc} \frac{\Delta T}{T_0} \quad (11)$$

Equations (1-11) are available in the study of Dai *et al.*, 2003.

EXPERIMENTAL PROCEDURE

A collector, covered with 0.004 m thick glass and having 6° slope (greenhouse) (with respect to solar inclination angle of Adıyaman), 27 m in diameter, on sun along all hours of a day and in an open field, has been manufactured in Adıyaman university campus area. 17.15 m high, 0.8 m in diameter chimney were produced from 0.07 m thick metal plate. Chimney, covered with 0.05 m thick aluminum foil and glass wool, was placed in the middle of the floor to keep inside temperatures low. The air inlet portion (periphery), 0.05-0.35 m height adjustable (Figure 1 and Table 1), is produced with 0.04 x 0.04, 0.04 x 0.08 and 0.02 x 0.02 metal square and rectangular profiles (metal profiles are insulated to absorb surface temperature) to be resistible to wind.

To measure air and ambient temperature in the collector and chimney, 10 thermometers in the range of -50 to 150 °C with measurement sensitivity ± 0.01 °C and to measure soil temperature 5 infrared thermometers was used. To measure the air velocity in collector and chimney and ambient air flow, ± 0.01 m/s precision, the propeller diameter of 50 mm with 8 blades, 10 Homis anemometers and to measure solar radiation values daily and with 10 minutes interval and to record the data values, the CMP21 model pyranometer is used.

Ground Description

27 m diameter and 0.5 m deep pit is covered with the aluminum foil with a 0.05 m thickness of glass wool and so, heat stored daytime in the ground floor was blocked to pass. 0.10 m gravel and 0.05 m thick sand, 0.05 m (15 tons) of glass and the top surface 0.25 m asphalt paved was compressed onto glass wool (Fig. 2).

Measuring The Temperature Distribution In Solar Chimney Plant

Measurements of temperature distribution in the solar chimney system can be seen in Figure 3. The temperature distribution of the ground (asphalt) under collector by means of laser (infrared) thermometer at the points in the southern and northern fronts , seen in Figure 3.a, and at the heights (0 m) at A,B,C,D,E,F points in Figure 3.c were measured. Air temperature distribution under collector (greenhouse), at the point in the south and north fronts, seen in Figure 3.a, at the heights in Figure 3.c seen as A, B, C, D, E, F were measured. Measurements of temperature distribution within the chimney at the points and heights shown in Fig.3.b were measured.

RESULTS AND DISCUSSION

Instantaneous Measurements

The temperature distribution of solar chimney is measured before turbine system has been assembled. Temperature measurements of collector, the chimney and the ground, are taken in 26th of July on 13.00 (when the intensive solar radiation of Adıyaman occurs) (Figures 4 and 5).

Figure 4 shows the change in air temperature at the ground and under the collector. It is shown in Figure 4 that the floor absorbed solar radiation as heat in a

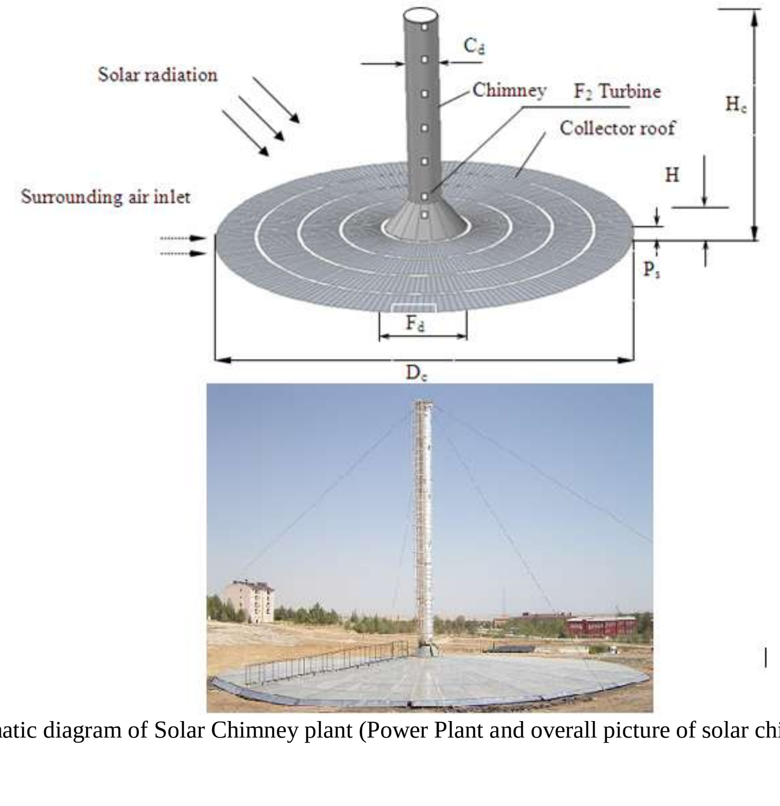

Figure 1. Schematic diagram of Solar Chimney plant (Power Plant and overall picture of solar chimney plant)

Table 1. Main parameters of the Solar Chimney plant Power Plant

Parameter	Symbol	Value/m
Collector Diameter	D_c	27
Height from collector outlet to ground level	H	1.35
Periphery (Surrounding air inlet)	Ps	0.05
Chimney diameter	C_d	0.8
Chimney height	H_c	17.15
Funnel diameter	F_d	1.6
Hight of turbine from ground	F_2	2.15

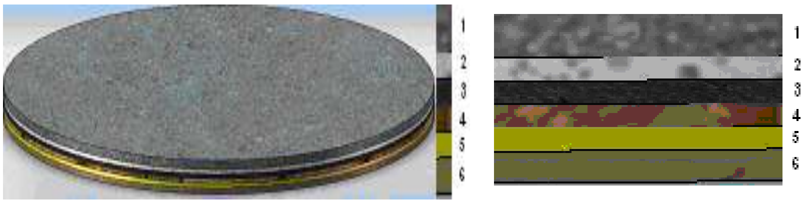

Figure 2. Ground (1.Aspalth, 2.Glass, 3.Sand 4. Gravel 5. Glass wool with aluminum folio 6. Ground floor.

wonderful way and a portion of this heat passed to the air stream comes from input part (periphery) of collector and goes on warming while proceed in through chimney. The temperature distribution of southern and northern fronts varies widely; temperature at the point. A_1-E_1 in southern front is more than temperature at the points A_2-E_2 in northern part. South side slope of collector is exposed to more solar radiation; receive more solar radiation and so more effective. The highest temperature is at the center point F_1 of collector, at point A_2 in the north side as well as for the entrance area of collector shows the lowest temperature (26^{th} of July, 13.00, ambient temperature is 41 °C). Temperature at the collector outlet point F_2 is 25.5 °C higher than environment temperature in the center and the entrance of chimney. Air currents at the point F_2, rapidly increase. As can be seen in Figure 5, temperature is decreased while air is rising in the chimney.

Daily Measurements

The temperature and air velocity distribution under collector (Figures 6 and 7), ambient temperature and air velocity (Figure 8), the ground temperature under collector (Figure 9), the temperature and air velocity (Figure 10 and 11) at the F_1 point in solar chimney, the F_2 point (turbine assembly point) and the F_3 point, solar irradiance and ambient temperature (Figure 12) tests are taken on July 28, 2010 between 8:00-18:00 hours.

The temperature distribution of collector (Figure 6) has minimum according to the values measured this summer on 8:00 at A_1 and A_2 points respectively in the morning and evening hours; the maximum value is reached noon from 12:00 to 14:00 at E_1 and E_2 points as solar irradiance, ambient temperature increases, soil temperature increases,

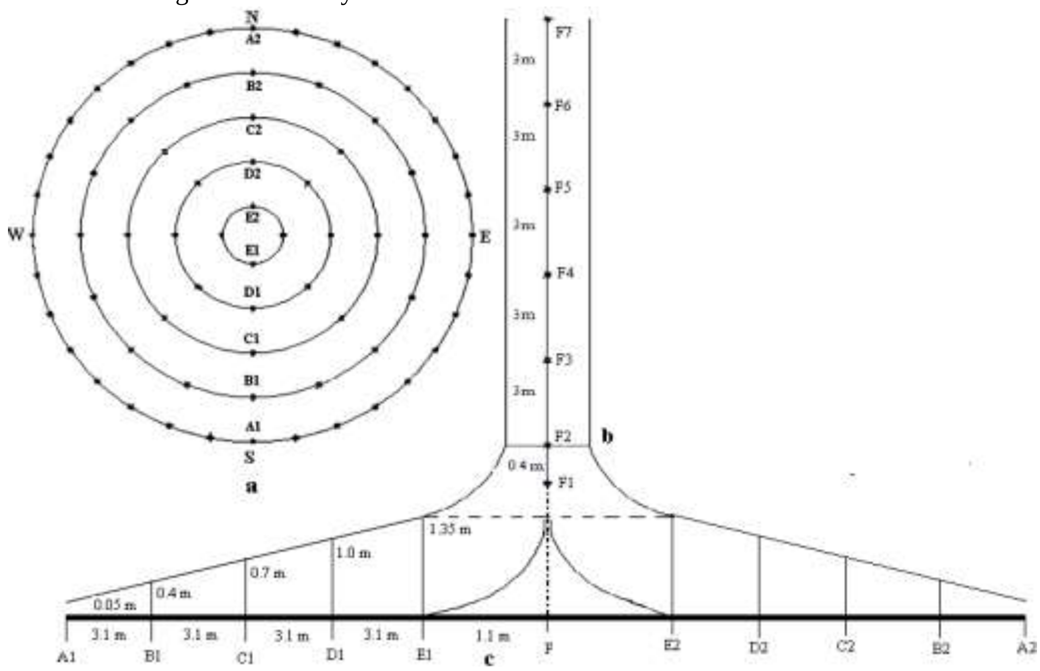

Figure 3. Air temperature measurement points in the solar chimney system, (a) measure points on ground (asphalt), (b) measure points from the center of the chimney and their heights, (c) measure points and heights under the collector.

respectively, (Figure 9 and 12),. The temperature distribution increases through the entry point of the chimney and output of collector at the E_1, E_2.

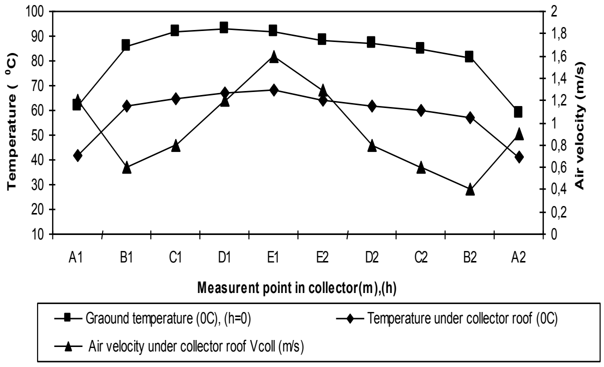

Figure 4. Temperature distribution and air velocity at certain points and heights of solar chimney system (on 13:00, ambient temperature 41 (°C), ambient air velocity 1,3 (m/s), solar radiation 830 (W/m^2))

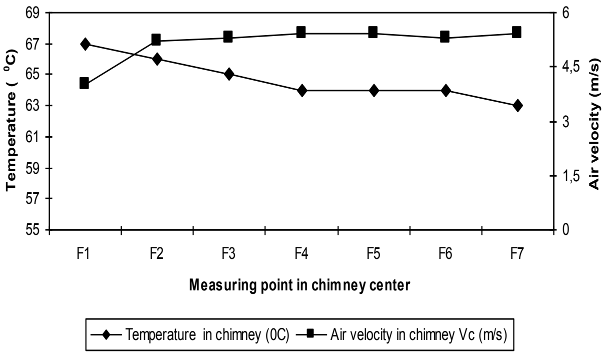

Figure 5. The air temperature distribution and air velocity in the center of chimney at the certain points and heights of solar chimney system (on 13:00, Ambient Temperature 41 °C, ambient air velocity 1.3 m/s, solar radiation, 830 W/m^2)

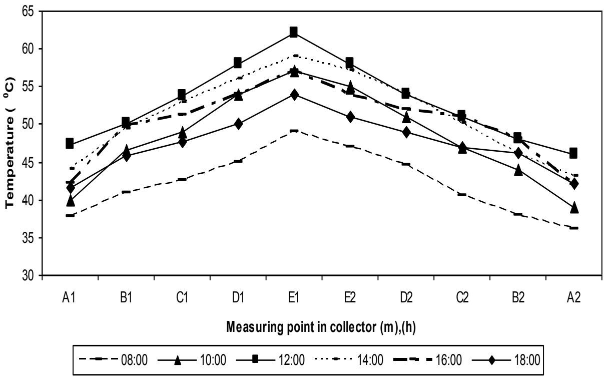

Figure 6. Temperature distribution (°C) at specified points and heights under collector in solar chimney system.

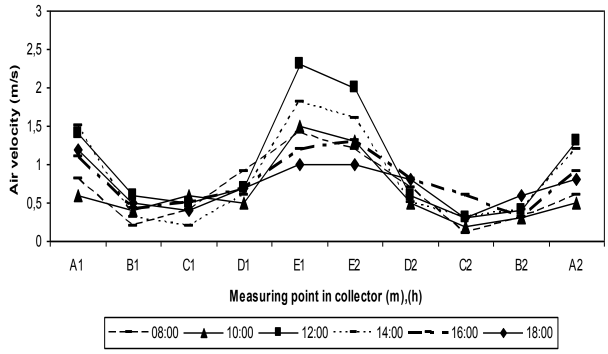

Figure 7. Air velocity distribution (m/s) at specified points and heights under collector in solar chimney system.

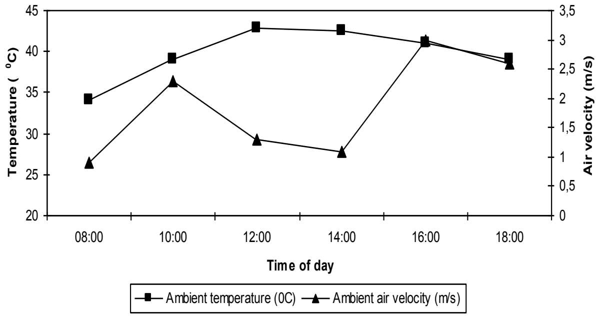

Figure 8. Ambient temperature and air velocity on measurement times in solar chimney system.

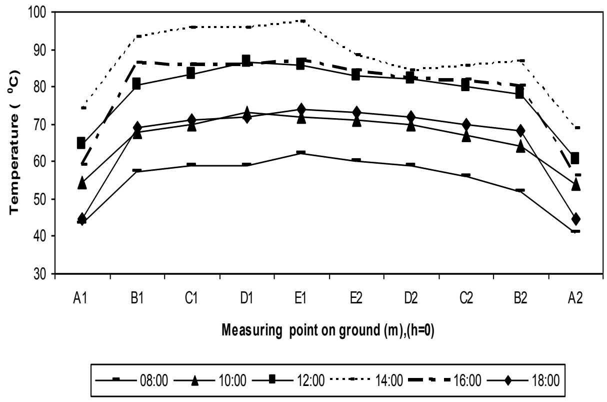

Figure 9. Temperature of ground floor (°C) at specified points under collector in solar chimney system.

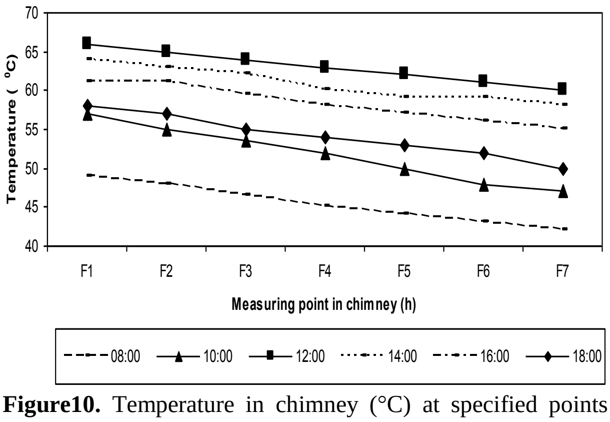

Figure10. Temperature in chimney (°C) at specified points and heights in solar chimney system.

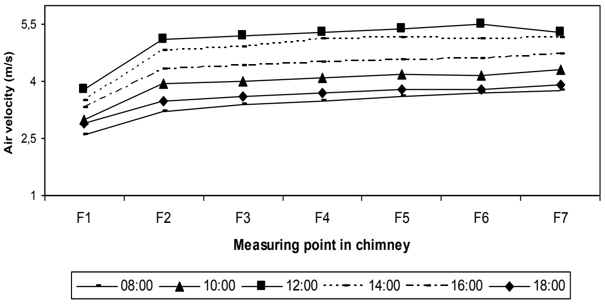

Figure 11. Air velocity (m/s) at specified points and heights in solar chimney system.

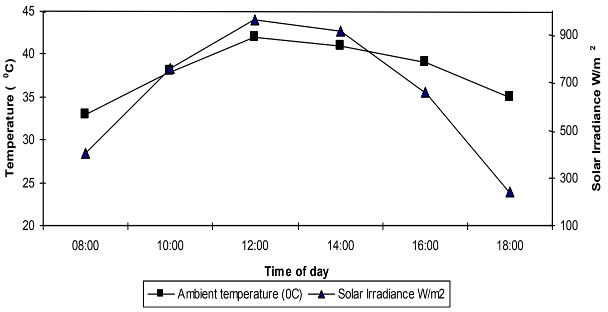

Figure12. Ambient temperature and solar radiation on measurement times in solar chimney system.

The measurements, at the same day at specified hours at the specified points and heights (Figure 3), showed that as the temperature rises under collector at the F_1 point and temperature at F_2 point reaches the maximum value, the temperature at F_3 - F_7 point decrease as rise up in chimney (Figure 10). This case has been linked to two conclusions. The first: as hot air rises, the temperature falls; the second: outer portion of the chimney is insulated. Air velocity in chimney was slow due to larger diameter (1.2 m) of the funnel at the point of F1 and it rises rapidly at the point F_2 due to the sudden contraction in chimney sections. But, the air flow rises very little at F_3-F_7 points due the interior surface of the chimney is smooth, the friction is minimal and due to the height of the chimney, the natural absorption has been observed (Figure 11), Measurements made shows that solar radiation is an important parameter in determining the environmental temperature (Figure 12).

CONCLUSIONS

The following results were found from solar chimney system established in Adıyaman University campus considering solar radiation of Adıyaman, ambient temperature, ambient air velocity conditions, at certain points and heights of the collector and the chimney.

1. Ambient temperature is an important factor affecting the performance of the solar chimney system,
2. In terms of solar radiation transmissivity, 0.004 m thick glass can be a good coating for a collector,
3. Special prepared ground in solar chimney system reached the maximum temperature (Figure 2),
4. The heat under collector increases towards chimney and decreases upwards in chimney,
5. In solar chimney system, air flow at the entrance of the collector is slightly higher than under the collector, fall a minimum value, and quickly rose in the chimney's entrance,
6. Environment air velocity didn't have affect in a solar chimney,
7. Most importantly, the performance of solar chimney is low in the morning and evening hours, noon hours is very high in performance,
8. The temperature measurement during the day showed that temperature distribution in the south wall was found to be slightly higher than in the north wall.
9. In this study, temperature difference between the collector outlet and the ambient usually can reach 21-26 °C but in Xinping, study 24.1 ^{o}C (Xinping *et al.*, 2007) , which generates the driving force of air-flow in the setup. This is the greenhouse effect produced in the solar collector. It is found from the analyses of temperature distribution in the solar chimney that air temperature inversion appears in the latter chimney after sunrise.

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