

THREE COOLING SEASONS MONITORING OF ENERGETIC PERFORMANCE ANALYSIS OF AN EAHE (EARTH TO AIR HEAT EXCHANGER) ASSISTED SOLAR GREENHOUSE BUILDING

Onder Ozgener¹ and Leyla Ozgener²

ABSTRACT

In the summer of 2009, the project entitled Utilization of Earth to Air Heat Exchangers for Solar Greenhouses pre Heating and Performance Analysis (UEAHESGHPA) in the Ege University Project No: 09GEE003 was launched. The solar greenhouse building is expected to have an annual cooling load of 12MWh. For decreasing the energy consumption rate of the system the authors suggest a hybrid system, incorporating a solar photovoltaic cell system (PV) assisted Earth-to-Air Heat Exchanger, which was developed in 2010. The principal idea is to use the PVs to meet the electricity expenses of the fan during summer cooling seasons when the required summer peak load cooling can be generated very efficiently and cheaply. The first three cooling seasons were monitored; the results of which were then presented. (See Appendix 1 for nomenclature.)

KEYWORDS

energy, efficiency, monitoring

1. INTRODUCTION

Direct use of the underground as heat source, heat sink, and heat storage has a long history extending from thousands of years ago to the present. These traditions have been modified to assist in the current need to achieve energy efficient building technologies. Natural energy sources seem ready again to play a major role in the effort to achieve large reductions in energy usage in existing and new buildings (Morofsky, 2003). This requirement will be clear as the response to the post-2012, post-Kyoto world is formulated (Morofsky, 2005). The Kyoto protocol stimulated countries worldwide to reduce CO₂ production, which resulted in two important measures. Firstly, there are now efforts focused on producing electricity with higher efficiency. Old power plants are more rapidly phased out and replaced with new, more efficient plants. Secondly, attention was drawn to energy use in general, bringing a more efficient use of

¹Solar Energy Institute, Ege University, Bornova, Izmir, Turkey. Currently as a visiting Associate Professor in Cornell Energy Institute, Cornell University, 2102A Snee Hall, 14853 Ithaca, New York, USA.

²Department of Mechanical Engineering Faculty of Engineering, Celal Bayar University Muradiye, Manisa, Turkey. Currently as a visiting Associate Professor in Cornell Energy Institute, Cornell University, 2102A Snee Hall, 14853 Ithaca, New York, USA.

Correspondence to: Tel: +1 607 254-7211, +90 232 311 1242. E-mails: oo36@cornell.edu, Onder.Ozgener@ege.edu.tr (Dr. O. Ozgener), lo64@cornell.edu, Leyla.Ozgener@cbu.edu.tr (Dr. L.Ozgener)

energy in production processes, buildings, etc. This not only reduced the consumption of electricity, but also lowered the spending of primary energy sources (De Paepe and Janssens, 2003).

According to US EPA (Environmental Protection Agency), GeoExchange systems are the most energy-efficient, environmentally clean, and cost effective space conditioning systems available. EAHE systems are among these GeoExchange systems, also called underground air tunnels or ground tube heat exchangers, and prove to be an interesting technique to reduce energy consumption in a building.

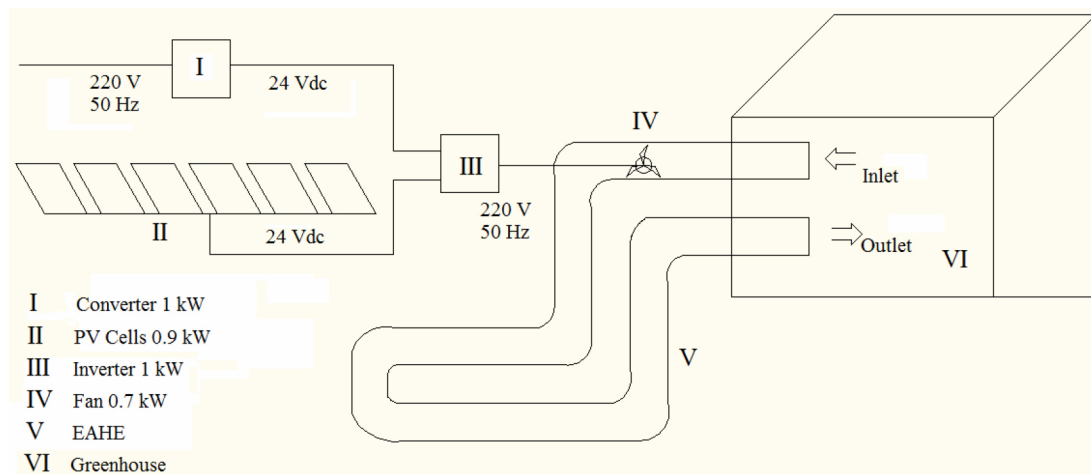
In this paper, the operation and Coefficient of Performance (COP) of an EAHE system are monitored. The results of the first three cooling seasons of operation of the system are presented, and the authors present an overview of these monitoring results for the 2009–2011 cooling seasons. Using these measurements, an attempt will be made to evaluate the original design; the motivation behind the present work.

The main objectives of the present case study are (i) to give a recent energetic performance assessment of the entire system into heat flux of density, q (W/m^2) (Popiel et al., 2001; Popiel and Wojtkowiak, 2004) transferred to soil, monthly cooling loads, and (ii) to investigate and monitor the COP value (energetic efficiency) of EAHE as a case study.

2. DESCRIPTION OF CASE STUDY

A schematic diagram of the experimental system is given in Figure 1. This system mainly consists of six separate circuits: (i) the converter, (ii) the 0.9 kW PV cells, (iii) the inverter, (iv) the fan (air blower) circuit for greenhouse cooling, (v) the ground heat exchanger (underground air tunnel or EAHE), (vi) the greenhouse. The PV assisted EAHE system was installed at the Solar Energy Institute of Ege University (latitude $38^\circ 24' \text{ N}$, longitude $27^\circ 50' \text{ E}$), Izmir, Turkey. A Solar greenhouse was positioned towards the South along the North-South axis it was to be conditioned during the summer and winter seasons according to the needs of the agricultural products to be grown in it. Figure 1 shows a schematic of the system which utilizes an underground galvanized pipe in combination with a blower to keep the greenhouse temperature at the set condition. A positive displacement type of air (twin lobe compressor) blower of 736 Watt capacity and volumetric flow rate of $5300 \text{ m}^3/\text{h}$ was fitted

FIGURE 1. Basic simplified PV assisted EAHE system schema adopted from (Yildiz et al, 2011).



with the suction head positioned in the southwest corner of the greenhouse (Ozgener and Ozgener, 2010a-d, Ozgener and Ozgener, 2011; Ozgener et al., 2011, Yildiz et al., 2011, Yildiz et al., 2012, Ozgener et al., 2013).

3. ANALYSIS OF EAHE SYSTEM

The design of an Earth-to-Air Heat Exchanger (EAHE) requires knowledge of its total thermal resistance (R_{Tot}) and temperature distribution in ground, as well as defining heat extraction or heat rejection loads for successfully heating and cooling building applications. In this research, a 47m long horizontal, 56cm nominal diameter U-bend buried galvanized experimental EAHE was designed and installed in the Solar Energy Institute, Ege University, Izmir, Turkey for study (Ozgener et al., 2011).

3.1. Efficiency

The Coefficient of Performance of the overall cooling system (COP) is the ratio of the greenhouse cooling load to the work input to the blower (fan) which assumes that the sensible cooling load is equal to the cooling capacity of the tunnel (EAHE) (Ozgener and Ozgener, 2010a-d, Ozgener and Ozgener, 2011; Ozgener et al., 2011).

$$COP = \frac{\dot{Q}_r}{\dot{W}_b} = \frac{\dot{m}_a c_p (T_{i,a} - T_{o,a})}{\dot{W}_b} = \frac{q_L L}{\dot{W}_b} = \frac{\left(\frac{T_f - T_s}{R_{Tot}} \right) L}{\dot{W}_b} \quad (1)$$

where in most cases “ q_L ” means “ q_L is \dot{Q}_r load per unit length of the Earth-Air-Earth exchanger,” as given below

$$q_L = \frac{\dot{Q}_r}{L} \quad (2)$$

In this analytical method, R_{Tot} is composed of the convection resistance inside the pipe (R_{convec}), conduction resistance of the pipe wall (R_{pipe}), and conduction resistance of the soil (R_{soil}). Thus R_{Tot} can be presented by Eq (3)

$$R_{Tot} = R_{convec} + R_{pipe} + R_{soil} \quad (3)$$

Eq. (3) is a very simplified model defining of total thermal resistance,

$$T_f - T_s = q_L \times R_{Tot} \quad (4)$$

where q_L is the heat rejection (discharge) rate per unit tunnel (pipe) length.

3.2. Defining Heat Flux of Density

For determination of the thermal interaction of engineering systems such as buildings, pipelines, ground heat storage, and heat pump ground heat exchangers with the ground, precise knowledge of the natural ground temperature distributions are required. The ground temperature distribution is affected by the following factors: (i) structural and physical properties of the ground, (ii) ground surface coverage, and (iii) climate interaction determined by air temperature, wind, solar radiation, air humidity and rainfall (Popiel et. al. 2001). The recorded experimental thermal data of various parameters were taken from the system. The data does

not belong to one day or measurement; all data reflect average actual values of the system under different operating conditions.

Heat flux of density q , W/m^2 transferred to soil can be obtained through the following equation

$$q = -k \frac{\partial T}{\partial x} = \frac{-1}{R_{\text{soil}}} \frac{\partial T}{\partial x} \quad (5)$$

In this case, x is depth below the ground surface and its maximum value is 3m, k is heat conductivity of soil (W/mK), and ∂T is ground (soil) temperature differential in degrees Celsius.

3.3. Measurements and Uncertainties

In the present study, the temperatures, air flow rates, voltages, and currents were measured with the appropriate instruments described previously. The data collection was made at an interval of every second and the hourly average values are also recorded. As known, errors and uncertainties in data recording and experiments may arise from instrument selection, instrument condition, instrument calibration, environment, observation, and reading and test planning (Witte et al., 2005; Ozgener and Ozgener, 2008, 2009; Ozgener, 2010). An uncertainty analysis was needed to prove the accuracy and reliability of the experimental data taken. The resulting total uncertainties of the measurements are given in Table 1. In the experiments, IR effects on air temperature measurements and the errors in the thermal properties because of non uniform conditions in the soil were neglected. The data was recorded by using an Elimko E-680 data logger. E-680 series universal data loggers are new generation microcontroller based instruments compatible with IEC (International Electrotechnical Commission) 668 standards. The E-680 series indicates measurements from 32 different points on the instrument display and determines the alarm conditions by comparison of two set points for each channel. The instruments can be connected to an RS-485 communication line and the data can be collected and stored in a centrally located PC. It has a resolution of 0.1°C , 1 W/m^2 for temperature and an accuracy of 0.5% (Ozgener and Ozgener, 2010a,b); TESTO 6621 temperature and relative humidity (RH) transmitters have $\pm 0.5^\circ\text{C}$, and $\pm 2.5\%$ RH, respectively. Air flow velocities were measured by a Lutron AM-4206M anemometer, and its accuracy and resolutions are $\pm 2\%$ 0.2 m/s , 0.01 m/s , respectively.

5. RESULTS AND DISCUSSION

In the study the recorded experimental thermal data of various parameters (e.g., temperatures, relative humidities, and volumetric flow rates) were taken directly from the system.

The thermodynamic properties of the air are based on the actual data taken from the system measured and recorded average value of 2009, 2010, and 2011 cooling seasons, respectively. The thermodynamic properties of the air were obtained from general thermodynamic tables and software. The fan in operation in the experiment may vary depending on the cooling days and operating strategy.

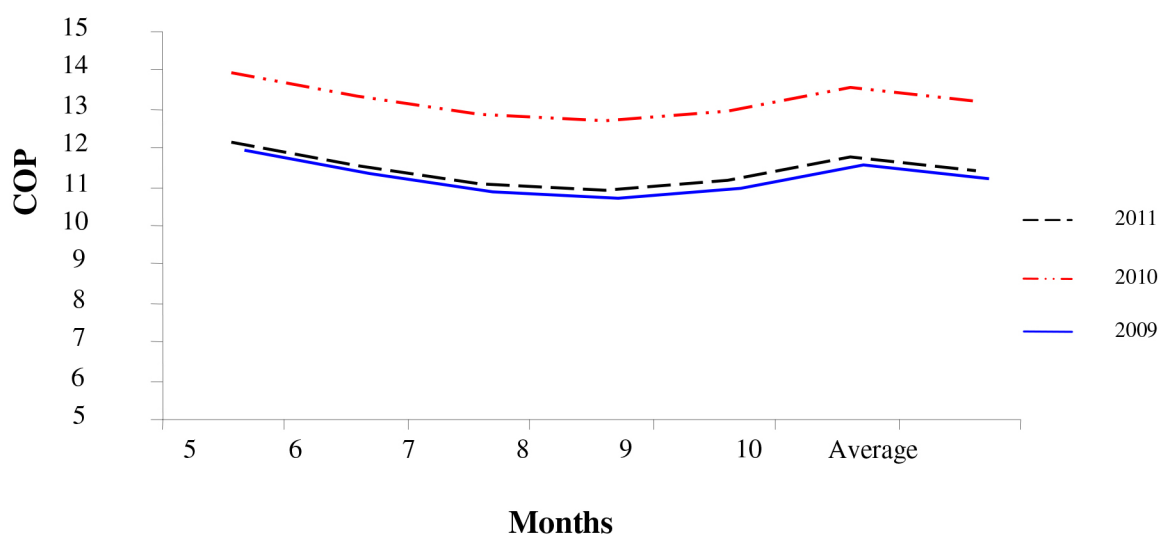
According to experimental results, normalized air density was assumed to be 1.196 kg/m^3 ; the monthly distribution of average temperature of air flowing in buried EAHE measured June 2009 and October 2011 is illustrated in Table 2 along with the heat rejection rates of the system which were calculated for each state. Using equation (1), the minimum seasonal COP value of the system is determined to be 11.6.

TABLE 1. Total average uncertainties of the measured and calculated parameters of the system.

Item no	Measured quantities		
	Description	Unit	Total uncertainty (%)
1	Temperature by using PT 100 resistant thermocouples and transmitters	°C	±0.5–1
2	Temperature by using infrared thermometer	°C	±1.00
3	Air flow velocity by anemometer	m/s	±1.0
4	Relative humidity (RH) transmitters	RH	±2.5
Item no	Derived quantities		
	Description	Unit	Total uncertainty (%)
1	Mass flow rate	kg/s	±2
2	Energy rate	kW	±1
3	Heat flux of density	W/m ²	±5
4	Energy efficiency (COP)	–	±4
Uncertainty in reading values of table			±0.20

5.1. Monitoring Results

Average monthly COP monitoring results of the system are given in Figure 2. A number of variables have been monitored with a relatively high frequency from June 2009 until October 2011. The study focused on the heat rejection rates, air temperatures and its mass flow rates, heat flux of density, etc. The monitored COP values are obtained for a range from 1 to 10 for different ambient temperature values for a better coverage and presentation of how the varying reference state temperature affects the performance of the system in terms of energy demands.

FIGURE 2. Average monthly monitored values of COP of the system for between 2009 and 2011 cooling seasons.

As can be seen from Figure 2, average monthly COP values can be found between 9 and 14. COP values are evaluated in terms of the system by using Eq. (1). The highest COP value in the 2010 cooling season occurred in June, yet the lowest COP value occurred during the 2009 heating season in September. In addition, the heat rejection rate (produced cooling load) average heat flux value is given in Table 2. It is obvious from the table that the highest produced cooling load occurs in 2010. As shown in Fig. 2, the data obtained during the measurements reveal that the mean cooling capacity of the EAHE is about 6 kW, and the amount of energy that can be produced is nearly 12 MWh for 6 months or a cooling season.

The heat flux density is a function of the distribution of soil temperature and the effect of soil content. In this case, heat flux of density was defined by using Eq (5) and the R_{soil} value (Ozgener et. al, 2011). A recorded experimental thermal data of 3m depth of ground and ground surface were taken from the system. In 2009, the average heat flux of density q , W/m^2 transferred to the soil was found to be 4.75W/m^2 during the monitoring of three consecutive cooling seasons. The mean value of heat flux density was measured as 4.35W/m^2 for the 2010

TABLE 2. Monitoring of thermodynamics specifications of the system between 2009 and 2011.

	Average Value	Cooling Season		
		June 2009–October 2009	May 2010–October 2010	May 2011–October 2011
Cooled Days	133.3	130	150	120
Shut off period for regenerate to soil (hours)	1948	1812	2160	1872
Intervals with valid data	29480	15000	43200	30240
Average inlet temperature (°C)	33.3	32	35	33
Average outlet temperature (°C)	27.6	27	28	28
Average temperature of air flowing in EAHE (°C)	30.5	29.5	31.5	30.5
Average circulated air mass flow rate (kg/s)	1.58	1.70	1.39	1.64
Yearly total produced sensible cooling load (MWh)	11.1	11.1	14.0	8.2
Average heat flux of density q , (W/m^2)	4.43	4.75	4.35	4.2
Total consumed electricity (kWh)	873.6	915	1000	706
Yearly total rejected thermal load to soil (MWh)	11.1	11.1	14.0	8.2
Yearly total average mass flow rate of condensed water vapor (kg/season)	7440	7200	8640	6480
Percentage of the energy saving by using PV	26	—	19	21
Real availability (%)	99	99	99	99
Technical availability (%)	95	95	95	95

cooling season. When the variation of soil temperature measured for 6 months between May and October was examined taking account of the seasons, it was found that the heat flux was high in spring months, reduced in the summer, and reached its minimum level (0.88 W/m^2) in July 2011. The maximum heat flux density was 4.6 W/m^2 in May 2011. The yearly average heat flux densities are illustrated in Table 2.

In the present study of the system, there were repetitive machine faults which occurred on the electric, electronic grid fed and mechanic control of the system. A considerable number of the types of faults and problems, such as electronic automation, over and lower load electricity problems, mechanic system faults, and other problems were experienced. For this reason, we observed different COP values.

It can be said that by removing all electric, electronic, and mechanic defects the failure rates of the PV assisted EAHE system can result in improvement of lifetime and real availability of the system. The technical availability is the ratio of operation hours to total machine hours available in a heating season. The technical availability of the system is almost constant, which is around 95–100%, in a year. This is because of the electric-electronic automation faults.

The real availabilities of the system has been analyzed based on total machine hours in the month, excluding machine hours lost due to regenerate to soil. The real availability is the ratio of generation hours to total machine hours. The real average availability of the system is less than 100%, in a year. This is due to the electric-electronic automation faults during the cooling period.

5. CONCLUSIONS

In this study, the authors have presented a general overview of the monitoring data. The EAHE at Ege University has, during its three cooling seasons of operation, rejected 33.3MWh of heat into the ground (soil). The heat flux density was defined by using the recorded experimental thermal data of 3m depth of ground and ground surface, and its average value was found to be 4.43 W/m^2 . Experimental results also show that the mean cooling COP value was determined to be 12.4 for 3 years of successive cooling seasons.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided for the project under Project No. of 09GEE003 and 10GEE007 by Ege University University Research Fund, and also are thankful to TUBITAK (The Scientific and Technological Research Council of Turkey). Dr. L. Ozgener and Dr. O. Ozgener are awarded a grant by TUBITAK as fellow at Cornell University, Ithaca, New York, USA. Finally, the authors would like to thank Prof. Jefferson W. Tester and anonymous reviewers due to their review and getting constructive comments, which caused increasing the quality of the subject paper.

REFERENCES

- De Paepe M, Janssens A. 2003. Thermo-hydraulic design of Earth-to-Air heat exchangers. *Energy and Buildings* (35):389–397.
- Morofsky E. 2003. Low-energy building design, economics and the role of energy storage, Warsaw, FutureStock.
- Morofsky E. 2005. History of thermal energy storage. *Paksoy, H.O. (ed.) Thermal Energy Storage for Sustainable Energy Consumption*, 3–22.

- Ozgener L, Ozgener O. 2008. Monitoring of energetic and exergetic performance analysis of Salihli geothermal district heating system. *ASME-Journal of Energy Resources Technology* (130/2): 22302-1-6.
- Ozgener L, Ozgener O. 2009. Monitoring of energy exergy efficiencies and exergoeconomic parameters of Geothermal District Heating Systems (GDHSs). *Applied Energy* 86(9): 1704–1711
- Ozgener L, Ozgener O. 2010a. Energetic performance test of an underground air tunnel system for greenhouse heating. *Energy* 35(10):4079–4085
- Ozgener L, Ozgener O. 2010b. Experimental study of the exergetic performance of an underground air tunnel system for greenhouse cooling. *Renewable Energy* 35(12): 2804–2811
- Ozgener L. 2010. Investigation of wind energy potential of Muradiye in Manisa, Turkey. *Renewable and Sustainable Energy Reviews* 14 (9): 3232–3236.
- Ozgener O, Ozgener L, Goswami DY. 2011. Experimental prediction of total thermal resistance of a closed loop EAHE for greenhouse cooling system. *International Communications in Heat and Mass Transfer* 38 (6):711–716
- Ozgener O, Ozgener L. 2010c. Exergetic assessment of EAHEs for building heating in Turkey: A greenhouse case study. *Energy Policy* 38(9):5141–5150
- Ozgener O, Ozgener L. 2010d. Exergoeconomic analysis of an underground air tunnel system for greenhouse cooling system. *International Journal of Refrigeration* 33(5):pp. 995–1005
- Ozgener O, Ozgener L, Tester W. 2013. *A practical approach to predict soil temperature variations for geothermal (ground) heat exchangers applications*. *International Journal of Heat and Mass Transfer* 62: 473–480.
- Popiel C.O., Wojtkowiak J, Biernacka B. 2001. Measurements of temperature distribution in ground. *Experimental Thermal and Fluid Science* (25):301–309.
- Popiel C.O., Wojtkowiak J. 2004. Experiments on free convective heat transfer from side walls of a vertical square cylinder in air. *Experimental Thermal and Fluid Science* (29):1–8.
- Witte, H.J.L., Van Gelder, A.J. 2005. Three years monitoring of a borehole thermal energy store of a UK office building. *Paksoy, H.O. (ed.) Thermal Energy Storage for Sustainable Energy Consumption*, 205–219.
- Yildiz A, Ozgener O, Ozgener L. 2011. Exergetic performance assessment of solar photovoltaic cell (PV) assisted Earth-to-Air Heat Exchanger (EAHE) system for solar greenhouse cooling. *Energy & Buildings* 43 (11):3154–3160
- Yildiz A, Ozgener O, Ozgener L. 2012. Energetic performance analysis of a photovoltaic assisted closed loop EAHE for solar greenhouse cooling: An experimental study for low energy architecture in Aegean Region. *Renewable Energy* 44:281–287.

APPENDIX 1: NOMENCLATURE

COP	cooling coefficient of performance of the system (dimensionless)
C_p	specific heat of the air (kJ/kg K)
k	coefficient of thermal conductivity of pipe (W/m°C)
L	total length of earth air earth heat exchanger length (m)
\dot{m}_a	mass flow rate of air (kg/s)
q	heat flux of density (W/m ²)
q_L	discharged heat rate in Watt per meter earth air earth heat exchanger length (W/m)
\dot{Q}_r	rate of heat discharge (kW)
R_{conv}	convection resistance inside the pipe per unit length (K-m/W)
R_{pipe}	conduction resistance of pipe per unit length (K-m/W)
R_{soil}	conduction resistance of soil per unit length (K-m/W)
R_{Tot}	total thermal resistance of earth air heat exchanger per unit length (K-m/W)
T	temperature (K, °C)
T_f	average temperature of air flowing in buried U-tube (K, °C)
$T_{i,a}$	EAHE inlet temperature of air (K, °C)

$T_{0,a}$	EAHE outlet temperature of air (K, °C)
T_s	soil temperature (K, °C)
\dot{W}_b	work rate or power of blower (fan) (kW)
x	depth below the ground surface (m)

Abbreviations

<i>EAHE</i>	Earth to Air Heat Exchanger
<i>EPA</i>	Environmental Protection Agency
<i>IEC</i>	International Electrotechnical Commission
<i>PV</i>	Solar Photovoltaic Cell Systems
<i>RH</i>	Relative Humidity
UEAHESGHPA	Utilization of Earth Air Heat Exchangers for Solar Greenhouses pre Heating and Performance Analysis