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Cooling performance of earth-to-air heat exchangers applied to a poultry barn in semi-desert areas of south Iraq

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Abstract: Earth-to-air heat exchangers (EAHE) can reduce the energy consumption required for heating and cooling of buildings. The composition and the thermal characteristics of the soil influence the heat exchange capacity, and the soil moisture can furthermore affect thermal performance of EAHE. The aim of this study was to compare the thermal performance of EAHE in dry and artificially wetted soil. Tests were carried out in the Basra Province (Iraq), in a semi-desert area. Two experimental EAHE were built in a poultry barn and tested from June 2013 to September 2013. The pipe exchangers were buried at 2 m deep. One heat exchanger operated in dry soil (DE), while the other one operated in artificially wetted soil (WE). In the WE system, a drip tubing placed 10 cm above the air pipe wetted the soil around the exchanger. Air temperatures at the inlet and at the outlet of both the exchangers as well as soil temperature at 2 m deep were continuously monitored. The experimental results confirmed that wetting the soil around EAHE improves the general heat exchange efficiency. The coefficient of cooling performance (COP) of the earth-to-air heat exchangers system was evaluated on the basis of the ratio between the heat removed from the air or added to the air and the energy input. During the day, with an average COP of 6.41, the WE system cooled the air more than the DE system, which reported a value of 5.07. On average, in the hottest hours of the day, the outlet temperature of the WE was 37.35°C while in the DE it was 38.91°C. Moreover, during the nighttime, the WE system warmed the air more than the DE system.

Keywords: Earth-to-air heat exchangers, thermal performance, cooling, artificially wetted soil, poultry barn, heat stress

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1 Introduction

The global warming, that is now a reality, can have repercussions on social and environmental systems. Detrimental effects are remarked especially during heat waves on livestock health, welfare and productivity[1]. In Iraq the climate is characterized by a long, dry and very hot summer season. Since many years studies on the effects of climate on livestock production were carried out with specific reference to Iraqi conditions[2]. Heat stress due to high temperatures is one of the biggest problems that broilers breeders have to face, And performance drops in poultry production due to the high temperatures in Iraq has been reported[3]. Heat stress in broilers and laying hens not only adversely affects physiological response and production[4], but also inhibits immune function[5,6]. Sensible heat flow in poultry under stressful conditions has been studied in order to find suitable rearing solutions[7].

The animal breeding in hot climates can be carried out only by adopting specific interventions of environmental control. Appropriate actions to protect animals from heat stress, including specific cooling systems, have been studied and suggested in literature[8-10]. The evaporative cooling ventilation air to reduce heat-stress of broilers is widely adopted in southern Iraq. In alternative to commercial cellulose panels, some waste materials commonly used to prepare evaporative pads can reduce costs and provide good performances as tested in researches around the world[11]. The installation of evaporative pads should be clearly defined in order to guarantee good cooling performance[12]. However, during the hottest months of summer (June-September), the evaporative cooling system alone is not able to create the minimum acceptable conditions for the poultry production especially in areas where relative humidity is high. In such conditions, other cooling systems have to be coupled with evaporative cooling[13].

The success of indoor thermal comfort for animal husbandry has increased the interest of air conditioning solutions based on renewable energy sources. The earth-to-air heat exchanger (EAHE) is a geothermal system able to reduce the energy consumption required for heating and cooling the buildings[14]. Furthermore, the cheapness and low carbon dioxide emissions represent other important advantages of this technology[15,16].

Many authors found that due to its high thermal inertia, the soil can be used as a heat sink in summer time and as a heat source in wintertime[17-19]. The temperature of the soil remains constant over a depth of 4 m[20,21]. Meanwhile, this depth can vary in relation to the geographical location and latitude, and can change annually as result of climatic changes (temperature, relative humidity and rainfall rate) as documented in many researches[22-24]. Several works have explained the relations between the heat exchange capacity and the composition, the moisture and the

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thermal characteristics of the soil[25-28]. All these factors directly or indirectly affect the performance of cooling or heating of EAHE together with the characteristics of the pipes[29-31]. In particular, in more recent studies, researchers[32,33] have found that the system provides better thermal performance by increasing the pipe length, burying the pipe at a depth up to 3 m, enlarging the surface of the pipe, reducing the pipe diameter and the air flow rate inside the tube.

Underground cooling system can be effective in southern Iraq, which is considered a semi-desert region. In such area, the air temperature is highly differs from the ground temperature as well as a great variation of temperatures between summer and winter, and in summer between day and night. Therefore, in summer, when the external air has a higher temperature than the soil, the air can be cooled in the ground before being used for the ventilation in the poultry barn. On the other hand, in wintertime, the air can be heated since outside air has a lower temperature than the ground. Same condition occurs in the day and night during the summertime, provide cooling during the day and heating during the night.

It is important to remark that if the soil around the pipe is wetted, the number of contact points between the soil and the outer surface of the pipe is increased[34]. As a result, the thermal conductivity coefficient increases as well[35]. The aim of this work is to demonstrate the effect of thermal conductivity on the performance of EAHE systems by comparing the performance during the summer period in dry soil and in artificially wetted soil around the pipe.

2 Materials and methods

An experimental system was installed in southern Iraq that considered as a desert or semi-arid area. A poultry house was chosen for the test, in a farm located in Al Zubair, Basra Province (30°19′0″N, 47°42′0″E).

Trials started at the beginning of June 2013 and finished at the end of September 2013.

The EAHE systems tested in the present study consisted of two parallel pipelines made up of PVC tubes buried at 2 m deep. The scheme of Figure 1 shows the main characteristics of the pipes and gives information on the experimental plan.

The length of each pipe was 37 m while the diameter was 20 cm. The distance between the two pipelines was 5 m. In the area where the tests were carried out, the water table was deeper than 2 m throughout the year. Therefore, the portion of soil where the pipes where placed was not affected by the ground water during the whole experimental period. Because of the high air humidity at the inlet, the pipes were positioned with a slope of 1% in order to collect the condensing water formed inside the system. Figures 2, 3 and 4 show some phases of experimental plant in the poultry farm.

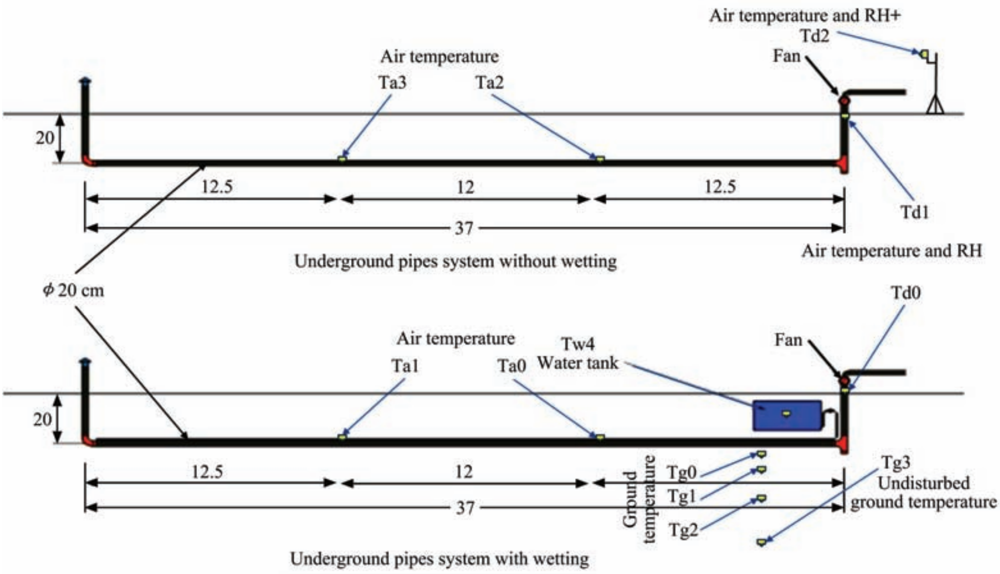


Figure 1 Scheme of the EAHE: DE (above) and WE (below)

Figure 2 Preparation of the slope for the pipes

Figure 3 Installation and testing of the moisturizing network

Figure 4 Installation of the data recording devices

The soil around one pipeline was wetted by a drip tubing placed 10 cm above it. Therefore, one EAHE operated in dry soil (DE) and the other one operated in artificially wetted soil (WE). The wetting system was equipped with a plastic, uninsulated 1 m^3 water tank, which is able to contain the amount of water necessary for wetting the ground for a period of 6 d, working for 20 min every 48 h at 6:00 a.m. The water tank was buried at 2 m deep in order to maintain the water temperature similar to earth temperature. In each EAHE system, a 125 W axial extractor fan pulled the external air through the pipe inside the poultry barn running continuously. Each fan generated an air flow at the rate of 1670 m^3/h.

As shown in the diagram of Figure 5, probes and data logger system were based on Arduino platform. With “First Arduino”, two analog thermometers (Atlas Scientific mod. ENV-TMP) were placed inside each pipeline to measure the air temperature at a distance of 12.5 m (Ta1, Ta3) and 24.5 m (Ta0, Ta2) from the pipe inlet.

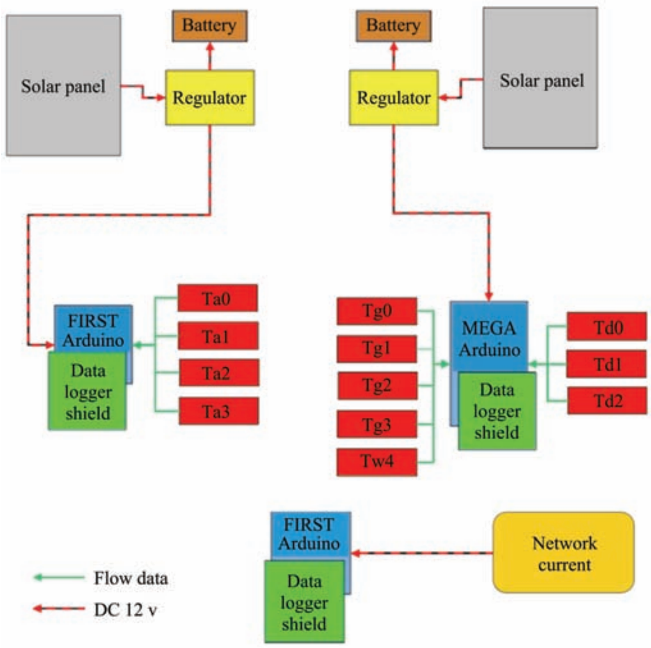


Figure 5 Hardware flow of data of the recording system (First Arduino and Mega Arduino)

All the other probes were mounted on “Mega Arduino” data logger. Two digital thermo-hygrometers (Honeywell HumidIcon^{TM}: HIH-6130/6131 Series) were placed at the pipe outlet of WE and DE (Td0, Td1) and one outside the system, in proximity of the pipes inlet, at 2 m above the ground (Td2). In addition, three analog thermometers (Tg0, Tg1, Tg2) were installed to measure the soil temperature at different distance from the pipe (0.25 m, 0.50 m, 1.00 m), one analog thermometers to measure the temperature of the undisturbed ground (Tg3), and another analog thermometers to measure the temperature of the water in the tank (Tw4). All measurements were collected every 15 min for all the four months of trials on a data-logger Adafruit (mod. Data Logging Shield for Arduino).

An anemometer (Multifunction DO 9847, AP472 S2) was used to check the air velocity in different points. The measures were repeated four times during the four months of trials.

In the area where the experiment was carried out, energy outage was relatively frequent. For this reason, the data logging system was equipped with a power unit consisting two solar panels and two batteries to enable continuous data recording. Meanwhile, since the air fans were powered by the electrical grid, a monitoring system was deployed to assess the power supply itself and to detect the periods of fans inactivity. Data collected during these periods (power outages) were excluded from the analysis.

Since the air was warmer than the soil during the day and colder during the night, two separated periods were considered to better evaluate the thermal performance of EAHE. The first period was the hottest part of the day (from 12:00 a.m. to 4:00 p.m.) while the second period was the coldest part of the day (from 2:00 a.m. to 6:00 a.m.).

Table 1 reports the abbreviations used in the present work.

Table 1 Abbreviations used in this paper

Ta (Tgr_NOR)	Undisturbed soil temperature
To (T_ext)	External air temperature
Ti (Tout_WE or Tout_DE)	Air temperature at WE or DE outlet
Δ*T* WE	Difference between inlet and outlet temperatures, WE
Δ*T* DE	Difference between inlet and outlet temperatures, DE
Δ*T* (Ta-To)	Difference between undisturbed soil and open-air temperature
ε WE %	Cooling efficiency of WE
ε DE %	Cooling efficiency of DE

To evaluate the performance of the two systems, the cooling efficiency and coefficient of performance were calculated. The thermal efficiency of EAHE (ε), which expresses the effectiveness of the system in exchanging heat with the ground, is described by the following equation:

$$\varepsilon = \frac{Ti - To}{Ti - Ta} 100$$

Abbreviations used in tables and figures of the present work are the following:

The coefficient of cooling performance of the earth-to-air heat exchangers system was evaluated by using the following equation[36]:

$$COP = \frac{Q_{out}}{W_{in}}$$

where, *COP* is the coefficient of cooling performance of WE or DE; Q_{out} is the heat removed from the air or added to the air, expressed in Watt (W); W_{in} is the energy input, that is the amount of electrical energy consumed by the fan in Watt (W).

The amount of heat transferred, removed or added, to the air is expressed by the equation of heat exchange[37]:

$$Q_{out}=mC_p\Delta T$$

where, m is the mass flow rate of the air, kg/s; C_p is the specific heat at constant pressure, kJ/kg·°C; ΔT is the difference between air temperature at the entrance and at the exit of the system:

$$\Delta T = (Ti - To).$$

Air velocity inside the tubes was represented by calculating the average values of readings taken at the outlet of pipes at the beginning and during the experiment. The surface of the air exit point was divided into nine portions, collected measures in each part and calculating the average value of the air velocity. The measures were repeated four times during the four months of trials.

Since the experiment lasted four months during summer 2013, the use of data collected in the entire experimental period appeared to be the most logical choice. However, the power of main statistical tests was too high, resulting all differences being significant due to the large amount of data (9087 records for each indicator). Hence, to reduce the size of the data set and minimize information loss, eight days (June 2, 4, 12 and 19, July 7 and 17, August 4 and 8) were selected in order to create a model of the average day, which is a real day representative of the whole experimental period. The average day was calculated considering the sum of squared differences between the mean external temperature among all the days at every time of the day and the external temperature measured at the same time. At last, the average day had the lowest sum of squared differences.

Two different data sets were built. One included the data measured during the whole day while the other included only those collected during the four hottest hours of the day (from 12:00 to 16:00). Data were analyzed using R[38]. A mixed model for longitudinal data with an autoregressive covariance structure was built for each response variable in order to assess the effect of type of EAHE. The outlet air temperature and COP measured both during the whole day and during the hottest four hours of the day were investigated, and the heat transfer efficiency was analyzed just for the hottest four hours of the day. All statistical models included the fixed effects of type of EAHE (DE or WE), time (15 min interval) and type of EAHE per time interaction. Appropriate variance–covariance structure was selected based on Akaike's information criterion. The day was treated as the repeated subject and the random effect of time was included in the models. When the interaction of type of EAHE per time was found to be significant (p<0.05) in the mixed model, post-hoc pairwise comparisons were performed for every time of the day using the Tukey's method. The differences were considered significant when p<0.05. Least square means and standard errors of the mean are reported.

3 Results

During the period from June to September the maximum temperature reached by the external air was 52.30°C while the minimum was 18.10°C. The maximum soil temperature was 32.47°C while the minimum was 28.54°C. The air velocity in the pipes was 2.9 m/s on average.

During the whole day (Table 2), the outlet air temperature was significantly affected by the type of EAHE (p = 0.017), time (p < 0.001) and by the interaction of type of EAHE per time (p = 0.012). The outlet air temperature was lower in WE (35.08°C) than in DE (35.78°C). The values of relative humidity of WE (18.51%) and DE (17.2%) showed significant differences with the relative humidity of external air (14.55%).

The differences in outlet air temperature between WE and DE were found to be significant during the central part of the night (from 01:00 to 04:30) and throughout the day (from 07:15 to 21:30), while no differences were detected during late evening after sunset (from 21:45 to 00:45) and early morning before sunrise (from 04:45 to 07:00). In particular, during the hottest period of the day (Table 3) from 12:00 to 16:00, the COP was found to be significantly affected by the type of EAHE (p<0.001) and the time (p<0.001). In this part of the day, the coefficient of cooling performance was higher in WE (6.41) that in DE (5.07).

Table 2 Effects of type of EAHE (ET) on outlet air temperature and coefficient of performance (COP), recorded during the whole day (24 hours). SEM = Standard Errors of the Mean

	EAHE type (ET)			P values		
	DE	WE	SEM	ET	time	ET X time
Outlet air temperature/°C	35.78	35.08	0.14	0.017	<0.001	0.012
COP	1.48	1.48	0.29	<0.001	<0.001	NS

Table 3 Effects of type of EAHE (ET) on outlet air temperature, coefficient of performance (COP) and heat transfer efficiency, recorded during the hottest hours of the day (12:00 - 16:00). SEM = Standard Errors of the Mean

	EAHE type (ET)			P values		
	DE	WE	SEM	ET	time	ET X time
Outlet air temperature/°C	38.91	37.35	0.09	<0.001	<0.001	NS
COP	5.07	6.41	0.08	<0.001	<0.001	NS
Heat transfer efficiency/%	39.95	50.62	0.46	<0.001	<0.001	NS

Moreover, in the hottest period of the day, the average air temperatures at the different lengths of the pipe 12.5 m and 24.5 m were 41.27°C and 39.44°C for WE while 41.35°C and 40.52°C for DE (Table 4).

Table 4 Temperatures (°C) measured at different lengths of the pipeline of the dry and artificially wetted EAHE during the hottest four hours of the day (12:00 AM to 16:00 PM)

	Average	SD	Max	Min
T ext	46.03	2.14	52.30	40.30
T_WE 12.5	41.27	1.92	45.60	36.71
T_WE 24.5	39.44	1.35	42.69	36.02
T out_WE	37.78	0.96	40.60	35.20
T_DE 12.5	41.35	1.86	45.40	36.55
T_DE 24.5	40.52	1.41	43.94	36.69
T out_DE	39.18	1.15	42.70	36.30

Note: T_WE 12.5: air temperature at a distance of 12.5 m from entrance, WE; T_WE 24.5: air temperature at a distance of 24.5 m from entrance, WE; T_DE 12.5: air temperature at a distance of 12.5 m from entrance, DE; T_DE 24.5: air temperature at a distance of 24.5 m from entrance, DE.

Because of the wide difference between the external temperature and the undisturbed soil temperature at 2 m deep, the possibility of cooling and heating was high for both the systems (WE and DE).

Figure 6 shows the air temperature variation between night and day and the difference with the temperatures at the exit of wet and dry lines for the entire month of August 2013.

Furthermore, figure 7 proves that WE has a greater capacity to cool or heat the air rather than the DE. In the average day, the temperature difference between the two experimental lines shows significant values. The relative humidity of WE (18.51%) and DE (17.2%) also had significant differences, while the relative humidity of external air was 14.55

Figure 8 reports the results in terms of performance coefficient of the EAHE systems during the average day, shown that the cooling COP during the hottest hours of the day of the WE (6.41) was greater than DE (5.07).

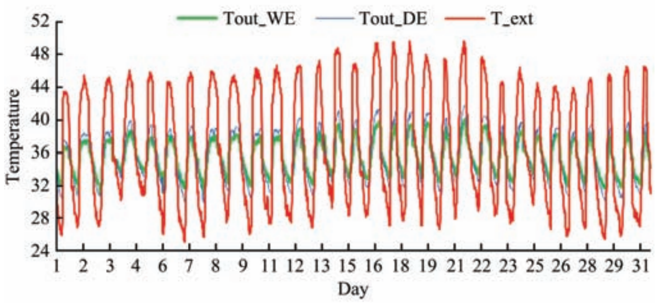
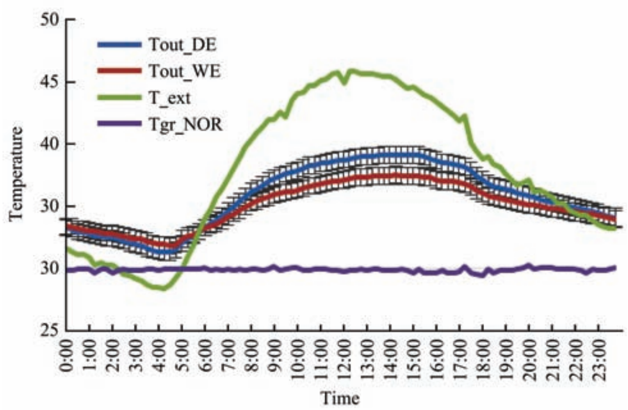


Figure 6 Air temperatures at the outlets of the EAHE in relation with the outside temperature during August 2013



Note: Tgr_NOR = undisturbed soil temperature at 2m, Tout_WE = outlet air temperature for wet pipe, Tou_DE = outlet air temperature for dry pipe, T_ext = external temperature at the experimental site

Figure 7 Air temperatures at the outlets of the EAHE systems in relation with outside and ground temperature during the whole day

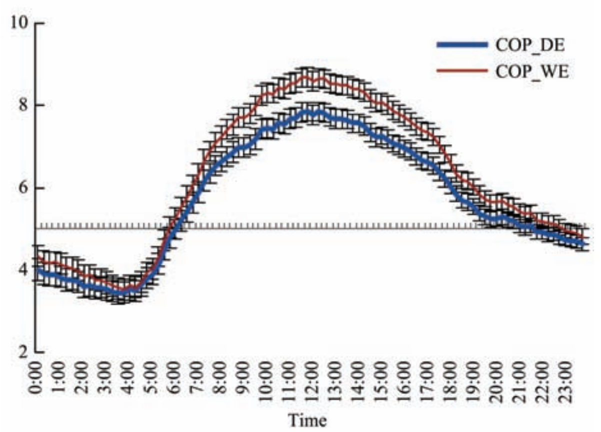


Figure 8 Coefficient of performance of EAHE systems during the average day

The effect of pipes length on the performance of the two different kinds of pipes is reported in Figure 9, which shows the air temperature in the dry and artificially wetted EAHE measured in different positions during the hottest period of the day. It is clear that the first one-third of the pipe length is the most effective part in the air cooling. The differences between the two systems were 0.08°C, 1.08°C and 1.40°C at 12.5 m, 24.5 m and 37 m, respectively.

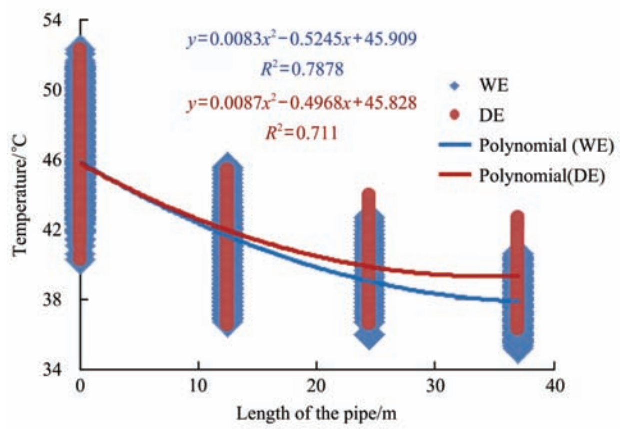


Figure 9 Air temperature in the dry and artificially wetted EAHE measured at different length of the pipeline during the hottest period of the day (12:00 a.m. to 4:00 p.m.; period 1 June -15 August 2013)

4 Discussion

The difference between the external temperature and the air temperature at the exit of wet and dry lines referred to the average day of summer (Figure 7) confirm the results of different researches[18,19,39]. The study states that wetting the soil surrounding the pipe leads to increase the heat dissipation by raising the thermal conductivity value of the soil. Therefore the moisture effect of soil on the heat exchange can be considered as a significant parameter affecting thermal performance, confirming the results obtained in many researches[40,41,28].

The data of the hottest period of day demonstrates that WE are able to reduce the air temperature better than DE. In fact the average ΔT was 1.56°C higher in WE than in DE, showed a higher efficiency.

In the night period, the environmental conditions are reversed and the outside temperature is lower than the ground temperature. Therefore, in both EAHE, the temperature at the outlets raises during the night hours. However, the temperature increase for the wet line is greater than for the dry line.

The cooling COP during the hottest hours of the day for WE is higher than for DE (6.41 and 5.07 respectively). Analogous performances for the DE system were obtained in other researches[37]. In that case, during the cooling tests in very similar environmental conditions with high summer temperatures, the DE achieved a maximum COP of 5.5.

During the day, the hot air entered the pipes increases the temperature of the soil around the line, which negatively affects the performance of the system with time. In opposite, the colder air flowing into the pipes during the night and decreases the temperature of the ground around the line. The difference between the COPs of the two systems during the whole day demonstrates that with the increased coefficient of thermal conductivity of the soil around the pipe, the WE system resists better to the variation of the ground temperature.

The performance of the EAHE depends on several input parameters, among which the length of the pipes is one of the major factors. The effect of the pipe length is demonstrated by the difference between the air inside the tube at given distances. In this research, the results are consistent with other studies[22,31], confirming that the biggest cooling effect is achieved in the first part of the pipe length. Moreover, even at the exit point of the pipe the WE still shows a significant cooling performance while the air temperature in the DE becomes steady at that point.

5 Conclusions

The relatively cold soil can reduce the electrical costs for cooling the air in a semi-desert area as the Basra Province (Iraq). Both DE and WE cooling systems can be considered as useful solutions to reduce heat stress of animals in poultry barns during the hottest periods, but the use of WE in livestock barns can give better results in reduction of temperature. In the trials, during the hottest hours, the average cooling COP of WE was 1.70 points higher than the one of the DE, whereas the average ΔT was 0.76°C higher in WE than in DE.

The soil wetting technique around EAHE can improve the heat exchange efficiency. The length of pipe has a significant impact on the performance of EAHE systems, but with an artificial wetting this effect becomes more remarkable compared to the dry system. By adding a drip water tube, the WE system reduces the temperature of the incoming air more efficiently than the DE system, especially when the temperatures difference between the outside air and the soil is low. However, an economic analysis would be useful to assess the real convenience to invest for the water drip system, also taking into account the scarce availability of water in desert or semi-desert areas.

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