J. Appl. Comput. Mech., 8(2) (2022) 429-437
DOI: 10.22055/JACM.2020.31237.1843

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

Heating Capacity of an Earth to Air Heat Exchanger in Arid Regions - Experimental Investigation

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Received September 29 2019; Revised January 12 2020; Accepted for publication January 12 2020.
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Abstract. Heating capacity of an earth to air heat exchanger EAHE equipped with an exterior fan in the arid region like the Southwest of Algeria is investigated experimentally. In-situ measurement of annual undisturbed subsoil vertical temperature profile is shown that it was 28°C at a depth of 1.5 meters. The EAHE made of 66 meters of PVC tube is demonstrated a heating capacity of 13°C and a cooling capacity of 7°C and a big dependence on local climate conditions. Great potentials and thermal comfort with less energy consumption are represented by earth to air or air-ground heat exchanger in the arid regions like the South of Algeria.

Keywords: Arid regions; Earth to air heat exchanger; Thermal comfort; Natural ventilation; Heating; Cooling.

1. Introduction

Renewable energies appear as a solution to thermal comfort while reducing energy consumption. The idea of using the soil as a heat source of or heat sink return to 3000 years B.C by Iranian engineers who combined the wind towers with the underground water pipes where air enter by the tower inlet goes through these pipes and lose a few degrees before being injected into the living spaces occupied by the inhabitants. The same idea was applied by the Algerian desert population in the Adrar region. The technique called Fougaraha was invented to provide water supply and pre-cooling or ventilation for homes [1]. At the same time, the inhabitants of the region of Benni-Abass (South-west of Algeria) build their own summer room in the basement to enjoy a few degrees less in summer compared to the outside air (sometimes reaches 50°C) and also used as a food storage warehouse in winter.

To benefit from soil cooling and heating potential, air-ground or earth to air heat exchanger is invented. The technique principle is simple; create a heat transfer between the subsoil and the medium that passes through the buried pipes. The result is preheating in winter and pre-cooling in the summer, which reduces the need for air conditioning systems [2,3]. Bansal et al. [4-6] showed some important studies in order to characterize the performance of EAHEs. In their works, various conditions were addressed. Papakostas et al. [7] compared the numerical and experimental data of a one-dimensional D ETAHE. The identification of the vertical temperature profile of the region is the first step. Studies have shown that annual sub-soil temperature at certain depth remains unchanged. The first harmonic model for estimating subsurface temperature was presented by Thomson in 1826 [8] and was developed by Kelvin as follows:

$$T_s(z,t) = T_{s,average} - \sum_{n=1}^{\infty} e^{-z\sqrt{n\pi/\alpha_s t_p}} * T_{amplitude,n} * \cos\left[\frac{2\pi n}{t_p}(t - PL_n) - z\sqrt{\frac{n\pi}{a_s t_p}}\right] \tag{1}$$

where,
T_s (z,t): unchanged soil temperature at z (m) depth and time t of the year in °C.
T_s, average: average annual soil temperature at depths z and times t in °C.
$T_{amplitude,n}$: amplitude of the temperature wave at the surface of the ground (z = 0), estimated equal to 1/2 the difference between the maximum and the minimum of the average monthly temperature.
z: soil depth in meters (m).
t: time of the year (in days) that starts on the first of January.
t_p: cycle 365 period of soil temperature, in days.

Published online: March 25 2020

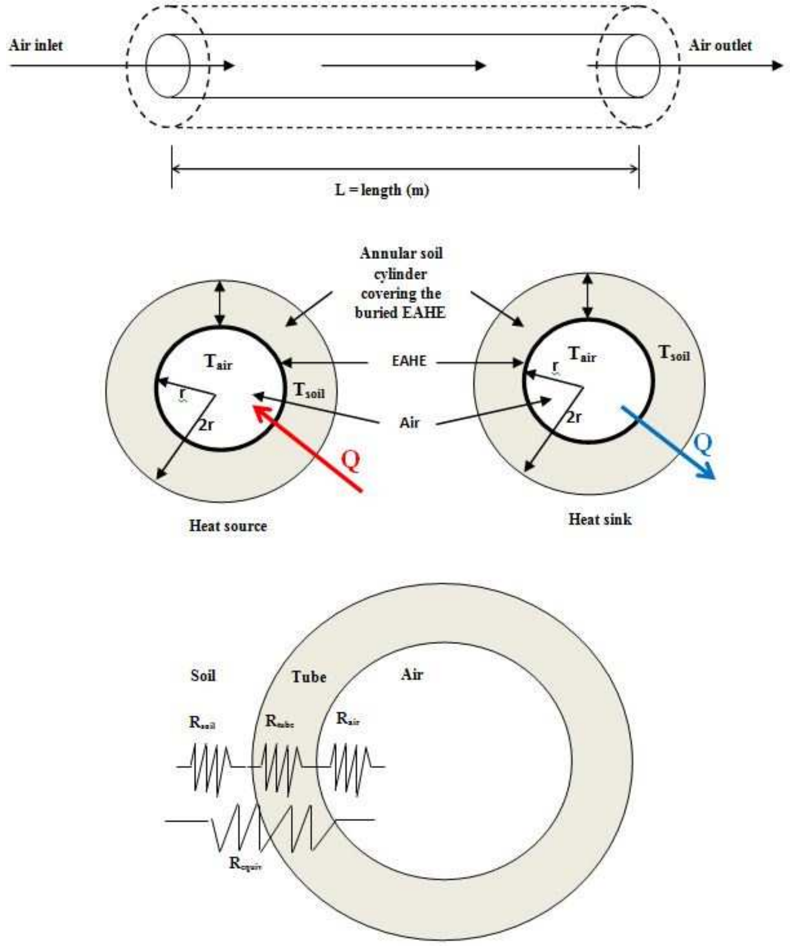


Fig. 1. Transversal and longitudinal schematic representation of an EAHE.

a_s: thermal diffusivity of the soil, in m²/day.
Another sinusoidal model was proposed by ASHRAE to calculate underground temperature as follow:

$$T_s(z,t) = T_{s,average} - \sum_{n=1}^{\infty} e^{-z\sqrt{n\pi/a_s t_p}} * T_{amplitude,1} * \sin\left[\frac{2\pi n}{t_p}\left(t - PL_1^{'}\right) - z\sqrt{\frac{\pi}{a_s t_p}}\right] \quad (2)$$

$$PL_1 = P_1^{'} - \frac{t_p}{4} \quad (3)$$

The length of thermal (temperature) penetration into the soil is a function of the thermal diffusivity of the soil [9] given by:

$$\delta_{jour} = \sqrt{\frac{24 * 3600 * a_s}{\pi}} \quad (4)$$

where, a_s is the thermal diffusivity of the soil. The numerical models provided in the literature can be used to identify the sub-soil vertical temperature profile anywhere in the world but some characteristics can change from a site to another due to soil composition, presence of moisture and other factors. It will be much better to identify the vertical temperature profile for the concerned site of the study for better results [10]. The presence of a heat exchanger in the form of a buried tube, as shown in Fig. 1, creates a cylindrical layer of soil that surrounds this tube.
The thermal resistance of the cylindrical layer of the ground of a radius r1 which surrounds the buried tube is given by [11]:

$$R_s = \frac{\ln\left(\frac{r_1}{r}\right)}{2\pi L k} \quad (5)$$

$$r_1 = 2r \quad (6)$$

$$R_c = \frac{1}{2\pi L h} \quad (7)$$

$$h = \frac{Nu * k_{air}}{d} \quad (8)$$

Thermal conductivity of the air is given by:

$$k_{air} = 0.02442 + \left(10^{-4}\left(0.6992T_a\right)\right) \tag{9}$$

and Reynolds number is calculated as follow:

$$\mathrm{Re} = \frac{v * d}{\upsilon} \tag{10}$$

Air kinematic viscosity ν can be calculated by Han by relation [12] as follow:

$$\upsilon = 10^{-4}\left(0.1335 + 0.000925T_a\right) \tag{11}$$

For a laminar airflow regime inside a tube Nusselt number is equal to [13]:

$$Nu = 4.36 \quad if \quad \mathrm{Re} < 2300 \tag{12}$$

For a circular tube and laminar regime airflow (0.5 ≤ Re ≤ 2000) or turbulent (2300 ≤ Re ≤ 2000), Nusselt number proposed by [14,15]:

$$Nu = \frac{\left(\frac{f'}{8}\right)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7\left(\frac{f'}{8}\right)^{0.5}\left(\mathrm{Pr}^{0.67} - 1\right)} \tag{13}$$

Friction coefficient f' for smooth tubes is determined by [13]:

$$f' = \left(0.79\ln\mathrm{Re} - 1.64\right)^{-2} \tag{14}$$

The efficiency of the air-ground heat exchanger is represented by a dimensionless number called daily temperature efficiency or thermal efficiency calculated as follows [16-19]:

$$\varepsilon = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{soil}} \tag{15}$$

where T_{soil}: soil temperature in °C. Total energy at EAHE outlet of the system is calculated as follow:

$$Q_{out}(\mathrm{W}) = \dot{m}_{vent} Cp_{air}\left(T_{inlet} - T_{outlet}\right)N_{pipe}^{2} \tag{16}$$

$\dot{m}_{vent}$: ventilation massique flow rate (kg/s).
Cp_{air}: specific heat of air equal to 1.007 (J/kg. K).
N_{pipe}: tubes number (in our case Npipe = 1).
For the earth to air heat exchanger equipped with exterior fan, fan energy consumption is calculated by the relation:

$$P_{fan} = \frac{\Delta P_t q}{\eta f_{an}} \tag{17}$$

ΔP_t: total pressure difference created by the presence of the fan (Pa).
q: volumetric flow rate generated by the fan (m^3/h).
η_{fan}: fan total efficiency.
The air temperature at the outlet of the heat exchanger is given by

$$\Delta T_f = \frac{\Delta P_t}{\eta f_{an}\rho C_p} \tag{18}$$

The air outlet temperature when using a sensitive powerful fan generates a significant amount of heat is given by

$$T_{final-outlet} = T_{EAHE-outlet-without-fan} + \Delta T_f \tag{19}$$

Fan equipped system Performance coefficient is given by

$$\mathrm{COP} = \frac{Q_{out}}{Q_{ventilator}} \tag{20}$$

Q_{fan}: energy consumption of the fan in Watt. Some analyses on heat exchangers can be found in [20,21] for different used conditions and various considered configurations.

2. Experimental Setup and Methodology

For the present study, open-loop horizontal earth to air heat exchanger was made of 60 m PVC pipes (thicknesses: 0.002 m, diameter: 0.11m) with a thermal conductivity coefficient equal to 0.2 W/m. K. The pipe was buried in sandy-loam soil at 1.5 m underground. The inlet and the outlet were made also of 3 m PVC pipe for each side with 1.5 m underground and 1.5 m on the ground equipped with thermal insulation for the inlet and outlet side (exposed to outside weather conditions). The air inlet and the outlet were made of PVC elbows with solar protection on the top. ETAHE inlet was directed in the direction of prevailing winds (North) and was equipped with an exterior fan of 33 Watt and an airflow speed of 3 m/s. DL-53 sensors were installed at the EAHE inlet and outlet to measure the temperature and humidity of the air entering and leaving the buried pipe. Also, air velocity was measured by UT-361 Anemometer. The EAHE outlet was directed to the South. Fig. 2 shows the experimental set-up of the studied case.

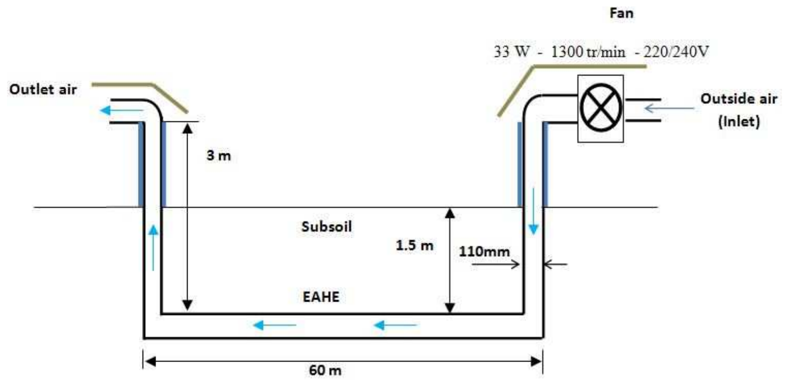


Fig. 2. Experimental setup and earth to air heat exchanger schematic representation

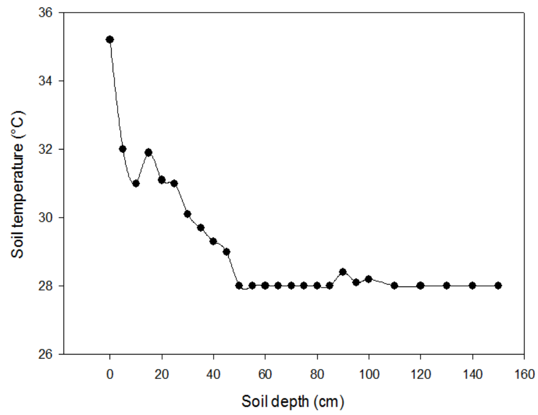
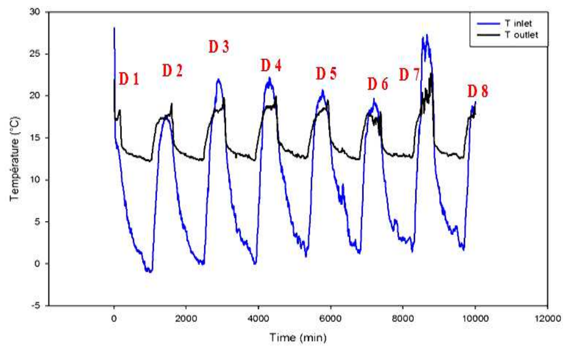
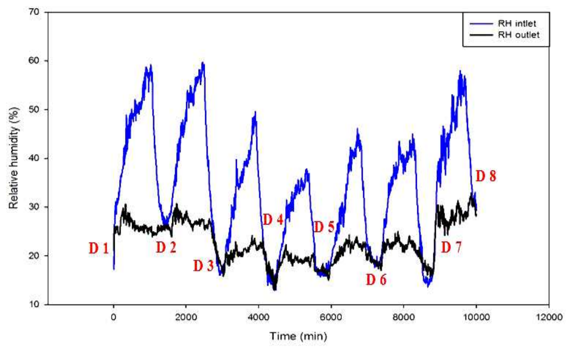


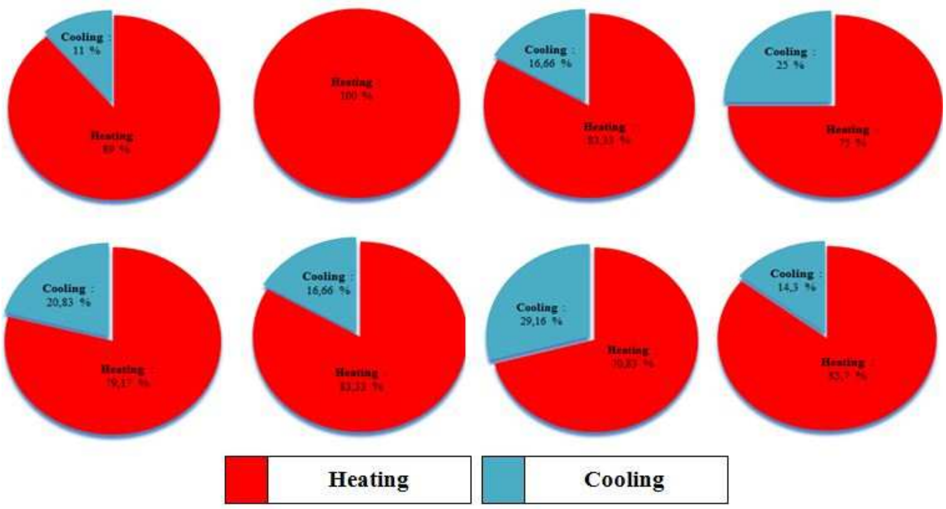
Fig. 3. Annual undisturbed vertical temperature profile of the site of study.



(a) Temperature



(b) Relative humidity



(c) Heating/cooling

Fig. 4. Thermal and hygrometric regime of the studied system.

Table 1. Heating and cooling regime at the outlet of the EAHE equipped fan.

	Earth to air heat exchanger with fan and solar protection							
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
Heating (%)	89	100	83.33	75	79.17	83.33	70.83	85.7
Cooling (%)	11	0	16.66	25	20.83	16.66	29.16	14.3

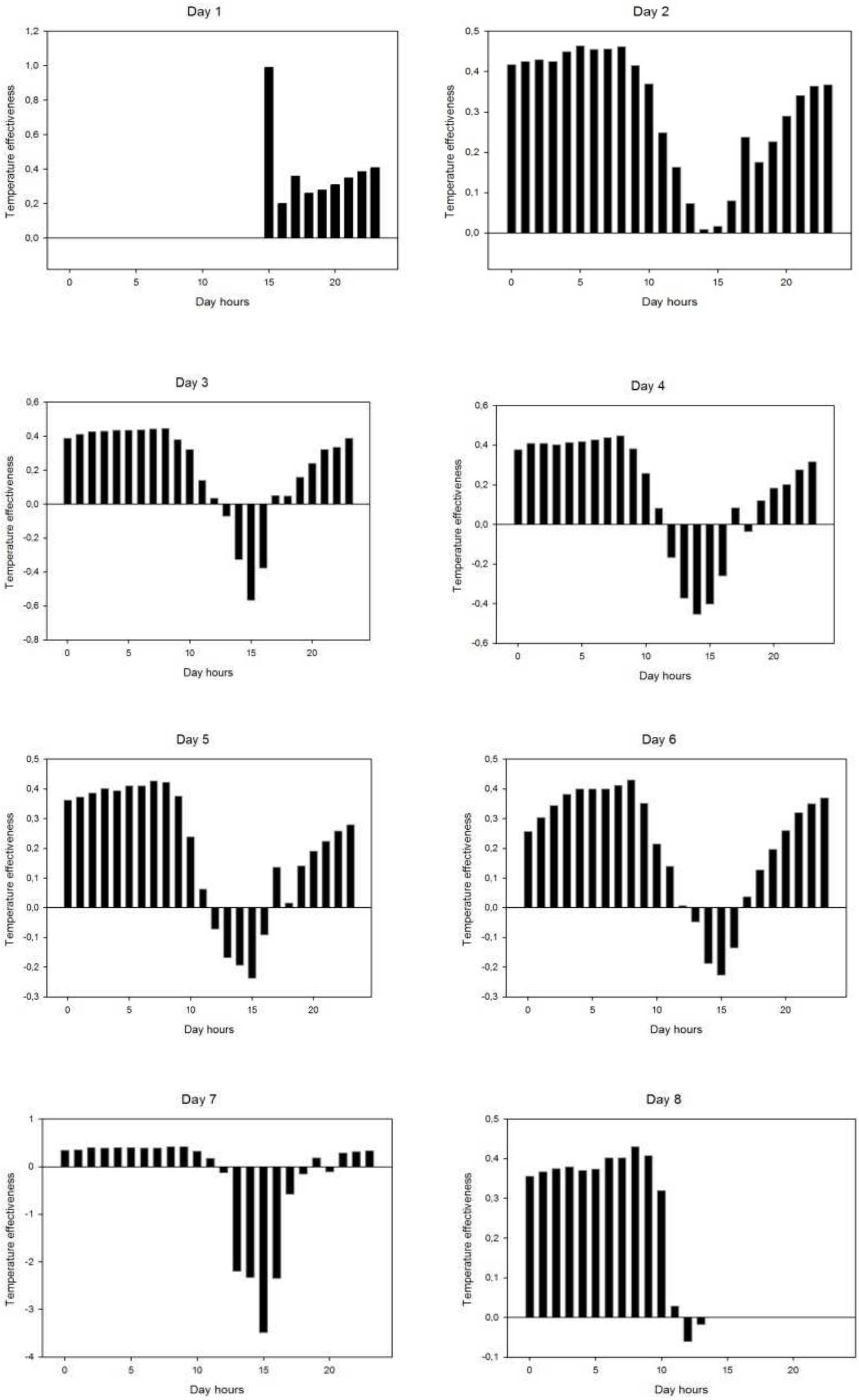


Fig. 5. Temperature efficiency of the studied system

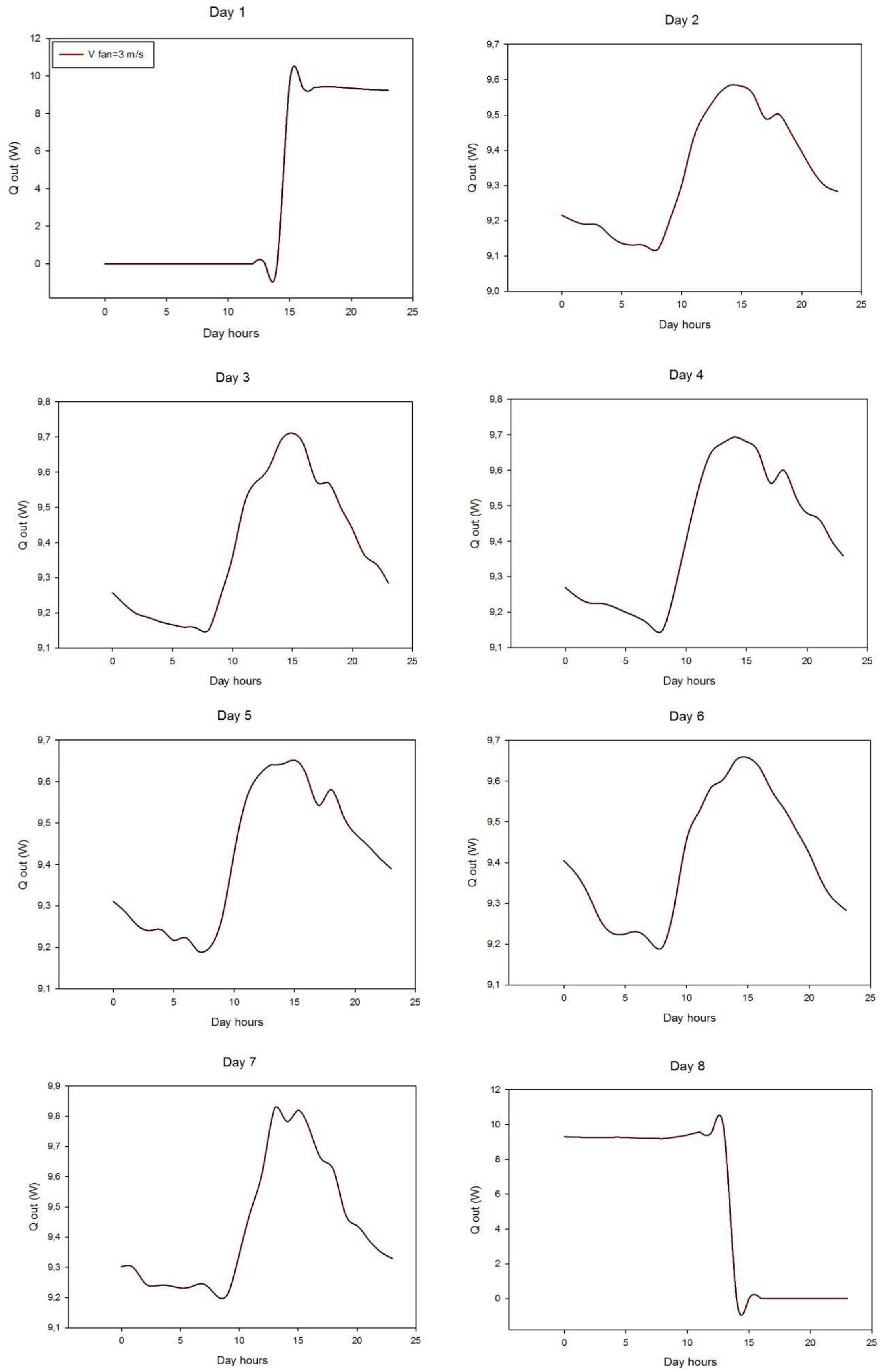


Fig. 6. Total outlet energy (W) at the EAHE outlet equipped with exterior fan

The experience was carried out in December 2018. The winter season in the Southwest of Algeria is characterized by severe conditions where the temperature reaches negative values. Based on an in-situ measurement in the site of the study, authors have found that the vertical temperature profile of the site follows an exponential regime. The temperature at the buried depth considered as an annual undisturbed vertical temperature profile is 28 °C, see Fig. 3.

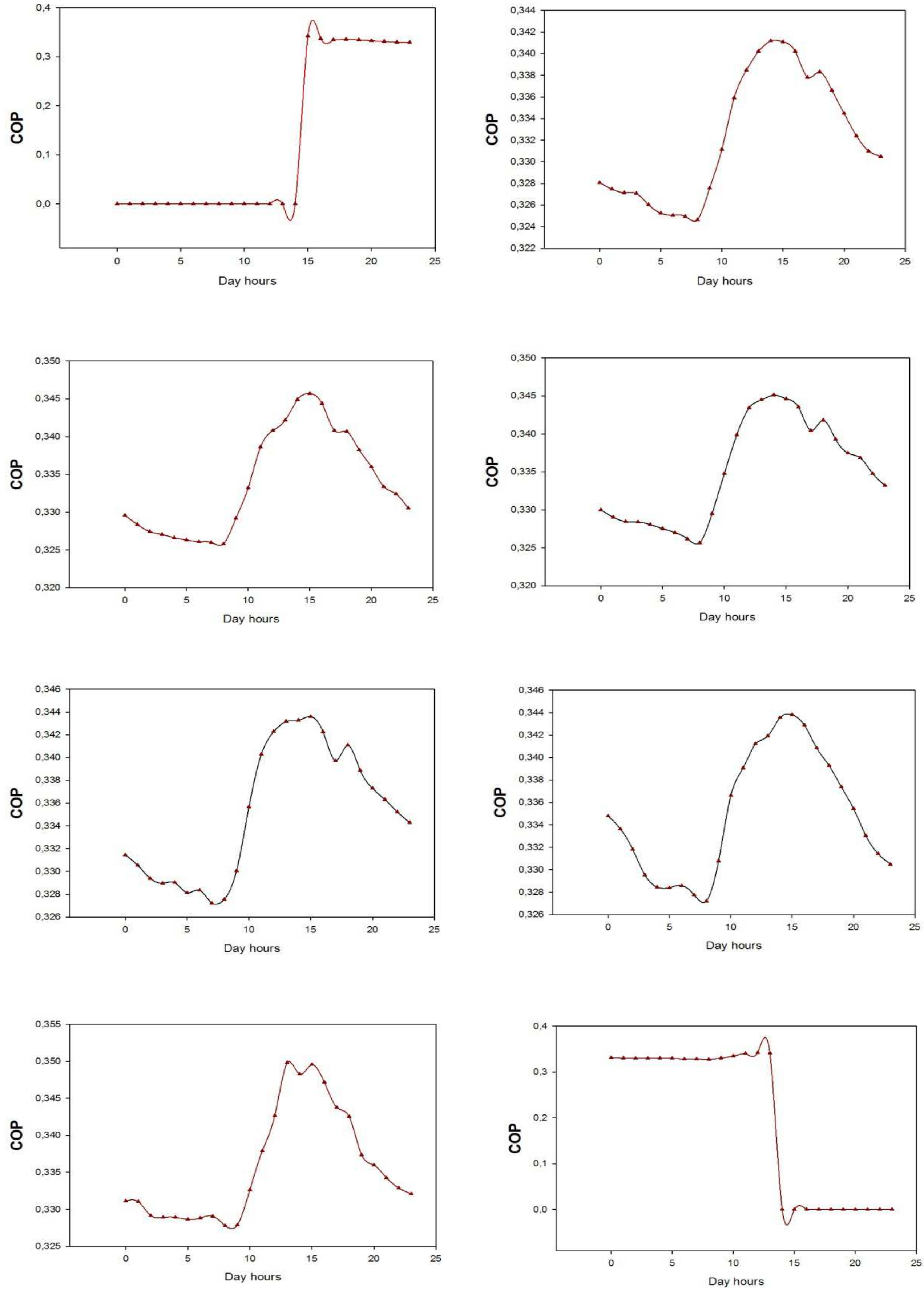


Fig. 7. Performance coefficient of the studied system

3. Results and Discussion

The experimental study was conducted between December 2018 and February 2019. For outside, the temperature was situated between -1°C for the lowest and 27°C for the highest. At the same time, 12.2 °C was the lowest temperature value for the EAHE outlet and the highest was 22.5°C. Even with outside temperature was (-1)°C, EAHE rise this negative temperature to 12.2°C by approximately 13.2 °C which reduce at least half of heating needs for this cold climate.

Earth to air heat exchanger works as a thermal regulator of air passing through the buried tube. The difference between the highest and lowest value of temperature was 20.15°C for inlet while it was 7.5°C for the EAHE outlet. These results show the capacity of the technique equipped of an exterior fan of reducing the range of temperature variation and to give more stability of the system even with severe climate conditions in comparison to system without fan studied before depended greatly on local weather conditions. For relative humidity, it was situated between 13 and 59 % for EAHE inlet and 15 to 31 % for the outlet. The system was able to increase the temperature by 13°C, as shown in Fig. 4, through heat exchange between the experimental device and the subsoil (characterized by a constant temperature).

For the whole day, with a constant ventilation flow rate provided by the fan, the outlet temperature was stable with a reduced variation interval. This result confirms the potential of EAHE performed such heat exchange even with negative temperatures.

Two thermal regimes are present even with the use of the fan:

From 17h00 to 11h00: Heating (ΔT_{max} = 13°C) and from noon to 4 pm: Cooling and get its maximum at 14:00 to 15:00 with 6.8°C. This thermal regime induces a hygrometric regime as follows:

From 17:00 to 11:00: Dehumidification or $HR_{inlet} > HR_{outlet}$ and from noon to 4 pm: Humidification or $HR_{inlet} < HR_{outlet}$ associated with a cooling regime. For temperature efficiency or thermal efficiency presented in Fig. 5, the values were positive and negative. Positives with 0.4 between 00h00 to 10h00 and 17h00 to 23h00. Negatives with (-0.2 to -0.4) between 4 and 5 pm.

The positive values of EAHE thermal efficiency were related to the heating regime and the negative values were related to the cooling regime which also confirms the great dependence of this type of earth to air heat exchangers with exterior parts exposed to local climatic conditions despite these effects are reduced through thermal insulation.

With a constant air velocity at the exchanger inlet equal to 3 m/s, the total heat output was situated between 9.1 and 9.8 (W), see Fig. 6. The maximum values were between 10:00 and 16:00 which shows the great dependence on external climatic conditions. Also, the coefficient of performance COP was between 0.325 and 0.345 and the maximum values were also between 10:00 and 16:00, see Fig. 7. Thermal regime shows that the major part was a heating case with 85 % in comparison with the cooling regime, see Table 1. In the winter season, hating needs are the most needed which improves indoor thermal comfort in arid regions like the South of Algeria.

4. Conclusion

The system consisting of the earth to an air heat exchanger with the outdoor fan gives the following results:

- The physical model was able to increase the temperature by 13 °C through heat exchange between the experimental device and the subsoil.
- The outlet temperature, for the whole day, with a constant ventilation flow rate provided by the fan, was stable with a reduced variation interval; this result confirms the potential of EAHE performed such heat exchange even with negative temperatures.
- In this situation, two thermal regimes were present even with the use of the fan:
- From 17h00 to 11h00: Heating (ΔT_{max} = 13°C) and from noon to 4 pm: Cooling and get its maximum at 14:00 to 15:00 with 6.8°C.
- This thermal regime was induced by a hygrometric regime as follows:
- From 17:00 to 11:00: Dehumidification or $HR_{inlet} > HR_{outlet}$ and from noon to 4 pm: Humidification or $HR_{inlet} < HR_{outlet}$ associated with a cooling regime.
- Positive values of temperature efficiency (or thermal efficiency) with 0.4 between 00h00 to 10h00 and 17h00 to 23h00.
- Negatives values of temperature efficiency (or thermal efficiency) with (-0.2 to -0.4) between 4 and 5 pm.
- The positive values of EAHE thermal efficiency were related to the heating regime.
- The negative values of EAHE thermal efficiency were related to the cooling regime which also confirmed the great dependence of this type of earth to air heat exchangers with exterior parts exposed to local climatic conditions despite these effects were reduced through thermal insulation. The total heat output, with a constant air velocity at the exchanger inlet equal to 3 m/s, was situated between 9.1 and 9.8 (W). The maximum values of total heat output were between 10:00 and 16:00the which shows the great dependence on external climatic conditions. The coefficient of performance COP was between 0.325 and 0.345 and the maximum values were also between 10:00 and 16:00. The thermal regime reported that the major part was a heating case with 85 % in comparison with the cooling regime. In the winter season, heating needs are the most needed which improves indoor thermal comfort in arid regions like the South of Algeria.

Author Contributions

N. Sakhri experimentally simulated the considered configuration; Y. Menni analyzed the experimental results; A.J. Chamkha developed the mathematical modeling. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

Acknowledgments

Not applicable.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Funding

The authors received no financial support for the research, authorship, and publication of this article.

Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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How to cite this article: Sakhri N., Menni Y., Chamkha A.J. Heating Capacity of an Earth to Air Heat Exchanger in Arid Regions - Experimental Investigation, *J. Appl. Comput. Mech.*, 8(2), 2022, 429–437. https://doi.org/10.22055/JACM.2020.31237.1843