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Aplication of Distinct Configurations of Vertical Earth-Air Heat Exchangers for the Warm-Weather Population of Temixco, Morelos (México).

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ABSTRACT

Passive air conditioning techniques are helpful to reduce the electrical consumption of houses, offices, and buildings. Earth-Air Heat Exchangers (EAHE) are part of these techniques. These air conditioning systems consist of buried tubes through which air flows from ambient to inside of a space to be climatized. Depending on their configuration they can be horizontal or vertical. In hot climates such as the one found in Temixco, Morelos, Mexico, it is desirable that, during working hours, the air temperature reaches the temperature of thermal comfort, or close to the stabilized temperature of the ground to be able to condition interior spaces.

This work shows the experimental results of three EAHE systems of vertical pipes made with PVC pipe installed in Temixco, Morelos. Each system consists in a set of three vertical heat exchangers placed in drilled wells, which have a separation of 140 cm between each of them. The first system is 2 inches tubing with a maximum depth of 290 cm, the second is 3 inches tubing with a maximum depth of 285 cm, and the third is 3 inches tubing with a maximum depth of 280 cm. Air at environmental temperature was circulated inside the EAHE tubes with the help of a centrifugal fan. The air temperature inside the exchangers was recorded with the use of thermocouples that were placed over the airflow path. Not only was temperature recorded along the airflow path, but also perpendicular to the tube, into the soil surrounding the buried tubes. In this way, it was possible to observe the thermal disturbance that occurs on the periphery of the tubes due to the circulation of air inside the heat exchangers.

EAHE were operated under various controlled conditions such as airspeed, run time, and overall length of the EAHE. The centrifugal fan used to drive the air into the buried tubes is variable speed, so the air at the outlet of the exchangers had a speed of 2.2 m / s, 4.8 m / s, or 5.4 m / s depending on the diameter of the tubes and the total length of the exchanger. The air velocity at the exit of the exchangers was measured with a rotating anemometer. The duration of the experiments ranged from 2 hours to 12 days. Data collection was carried out during March, April, and May 2020.

With the temperature data obtained, it was possible to observe the temperature difference (ΔT) between the inlet and outlet of the heat exchangers, the coefficient of operation (COP) of the heat exchangers was calculated during the operating hours, and it was observed the thermal impact of the soil during the circulation of air inside the tubes. Results show that it is possible to obtain a ΔT among the inlet and outlet of the EAHE higher than 9 ° C when the diameter of the tubes is 2 inches, while for heat exchangers with tubes of 3 inches diameter the ΔT is 7.3 ° C. The average temperature at the EAHE outlet during the operating periods in all cases was 26 ° C. The average COP for EAHE systems with 3 inches diameter tubes was 6.6, while the experiment where 2 inches tubes were used was 1.6.

1. INTRODUCTION

Geothermal energy, as a renewable and environmentally friendly source of energy, has received an increase in its attention and research during the last decades (Bharadwaj, S. S., & Bansal, N. K. 1981, Esen, H., Esen, M., & Ozsolak, O. 2017, Yu, X., Wang, R. Z., & Zhai, X. Q. 2011). According to its use by humanity, it can be classified into direct and indirect uses. Direct uses are those where the thermal energy of the soil is directly used. This is of great help, since in recent years the energy consumption of buildings has increased, consuming up to 40% of the world's energy consumption (Amanowicz, Ł. 2018, Yang, D., Guo, Y., & Zhang, J. 2016).

The use of geothermal energy to counteract the high energy consumption of buildings is already studied in various parts of the world (Esen, M., & Yuksel, T. 2013, Yu, L., Li, Y. P., & Huang, G. H. 2019, Zhang, X., Zeng, R., Mu, K., Liu, X., Sun, X., & Li, H. 2019). One of the advantages of taking advantage of this energy source to cool or heat a building is that at a depth of no more than 4 meters there is a stabilized temperature (ST), which is the temperature of the ground that remains constant throughout the year (Elminshawy, N. A., Siddiqui, F. R., Farooq, Q. U., & Addas, M. F. 2017, Bharadwaj, S. S., & Bansal, N. K. 1981, Wei, H., Yang, D., Guo, Y., & Chen, M. 2018, Tsilingiridis, G., & Papakostas, K. 2014).

To take advantage of this constant temperature, experimental and numerical investigations of EAHE have been carried out. They have demonstrated the great potential of EAHE as an efficient technology to save energy in the cooling and heating of buildings (Yang, D., Guo, Y., & Zhang, J. 2016, Bisoniya, T. S., Kumar, A., & Baredar, P. 2013, Serageldin, A. A., Abdelrahman, A. K., & Ookawara, S. 2016, Barakat, S., Ramzy, A., Hamed, A. M., & El Emam, S. H. 2016). Among the advantages exposed of these systems is their low operating cost and low environmental impact (Rouag, A., Benchabane, A., & Mehdid, C. E. 2018, Mehdid, C. E., Benchabane, A., Rouag, A., Moummi, N., Melhegueg, M. A., Moummi, A., ... & Brima, A. 2018).

Among the works that have been presented recently Sakhri et. al. (2020) show the behavior of a 60-meter-long horizontal heat exchanger installed in the arid region of Bechar in Algeria at a depth of 1.5 meters. The EAHE managed to obtain a temperature at the outlet of 27 ° C, while at the inlet it was at 39 ° C, achieving a ΔT of up to 12 ° C. Brum et. al. (2019) conducted a numerical

simulation study on the behavior of an EAHE system with up to 5 horizontal pipelines. An important part of their results is that it is preferable and advantageous to install a greater number of exchangers with a smaller radius between tubes, than a single one with a larger diameter, due to the spatial limitations of the place.

Liu et. al. (2019) presented an experimental work of a single U-shaped vertical exchanger for a 16.5-meter deep well. In their work show that with a smaller surface area it is possible to obtain satisfactory results for the temperature at the outlet of the exchanger. Gomat et. al. (2020) showed that the vertical part of a buried heat exchanger has a significant result in the temperature at the exit of the exchanger, even in shallow vertical wells. Díaz-Hernández et. al. (2020) mention that the cost of drilling for the installation of exchangers involves up to 40% of the total, therefore, the deeper the wells, this value will increase. Although for depths greater than 2 meters the change in temperature is not so significant.

However, there are two issues that still need to be addressed. The first is that most of the works presented deal with horizontal tubes, therefore, to have a comfortable temperature at the outlet requires a large heat transfer area, and although there are parallel arrangements of horizontal tubes, they require a large area of land to install them, which represents a limitation in densely populated urban areas (Sarbu, I., & Sebarchievici, C. 2014, Omer, A. M. 2008). The second issue to be addressed is that, to counteract the previous problem, vertical holes have been made to install vertical heat exchangers more than 5 meters deep, which represents a high initial cost if it wants to compare this technology with the cost of install conventional compression conditioning systems.

To address the problems, this work presents the experimental results obtained from three systems of vertical heat exchangers installed in the population with a warm climate of Temixco, Morelos. The area occupied for the installation was 9 m^2. The experimentation was carried out during the months of March, April and May 2020. In addition, a comparison of drilling costs between several wells with a depth of no more than 3 meters is presented, against a drilling of more than 9 meters.

2. METODOLOGY

This study was carried out during the months of March, April and May 2020 at the Institute of Renewable Energies in Temixco, Morelos. During the mentioned months the climate is hot and dry, reaching a temperature during the day up to 35 ° C. The site where the exchangers were installed is at latitude 18 ° 50'25.62 "N, longitude 99 ° 14'10.49" W at a height of 1253 meters above sea level.

2.1 EAHE METODOLOGY

The working fluid is atmospheric air and an S&P TD-250/100 exhaust fan of 30 W was used to drive it. The fan was placed at the inlet of the exchangers and was connected with PVC elbows to the exchangers. At the outlet of the exchangers, the air velocity was measured with rotary anemometers.

The soil of the site where the heat exchangers were installed is of the filling and compaction type, since at the time of the excavations various fragments of foundations and wall backs were found. The average temperature at a depth of 3 meters is 21 ° C ± 0.5 ° C throughout the year. The holes to install the exchangers were made with the help of the PREDATOR pole and extensions made of black steel tubular of Schedule 40; 3 groups of 3 wells were made, in total 9 wells. After inserting the exchangers in each of the wells, the same extracted material was used to fill the wells, avoiding the use of foundation remains or wall backstopping to avoid fracturing the pipe during compaction as the picture 1 shows.



Figure 1: The figure above shows a) the pipe into the well, b) the well backfill with the pipe.

Each group consists of 3 VEAHE made with 2 mm thick PVC pipe connected in series. The horizontal section connecting each well is 140 cm and was thermally insulated with fiberglass duct insulation to prevent the air from increasing its temperature in those areas as shown in picture 2.



Figure 2: The figure above shows the thermal insulation in the horizontal section which connect each exchanger.

The vertical section of each of the exchangers is in a range of 2.6 to 2.9 meters in length. The difference between the lengths of the vertical section of each one is due to the soil conditions at the time of drilling. A scheme with the 3 groups of EAHE and its dimensions are shown in picture 3.

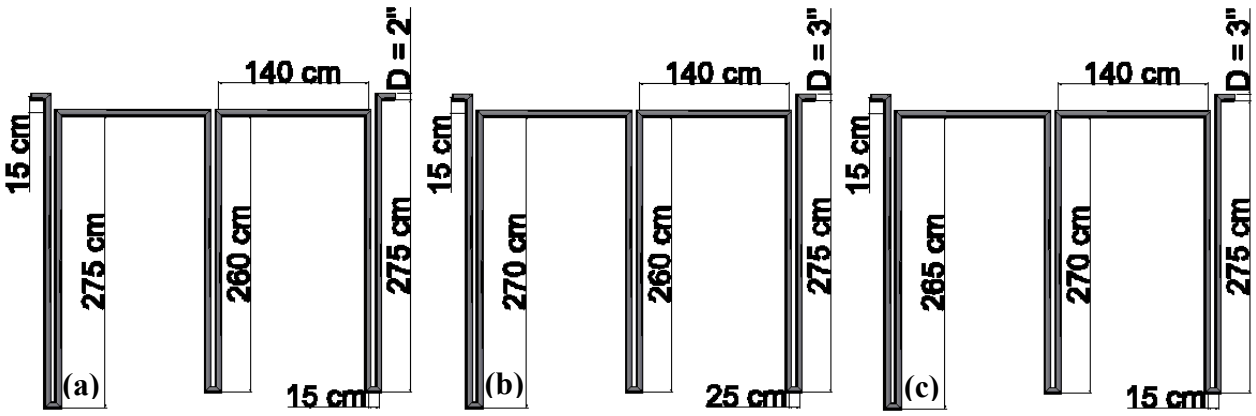


Figure 3: The figure above shows the schemes and dimensions of: a) group 1, b) group 2, and c) group 3.

The characteristics of each EAHE are:

- Group 1 was made with 2-inch pipe and the separation between the centers of the pipe was 15 cm.
- Group 2 was made with 3-inch tubing with a 25 cm spacing between the centers of the tubes.
- Group 3 was also made with 3-inch pipe, but in this case the separation between the centers of the pipes was 15 cm.

2.2 THERMOCOUPLE DISTRIBUTION

The temperature variation of the air along the heat exchanger and the earth surrounding the buried tubes was measured using T-type thermocouples with an error of ± 0.5 ° C. The thermocouples were connected to an AGILENT 34970A data logger. The location of the thermocouples is shown in figure 4. In total, each vertical exchanger consists of 9 thermocouples, 4 inside the tubes to measure the temperature along the path and 5 outside to measure the thermal disturbance that occurs on the ground due to the circulation of air at different temperature.

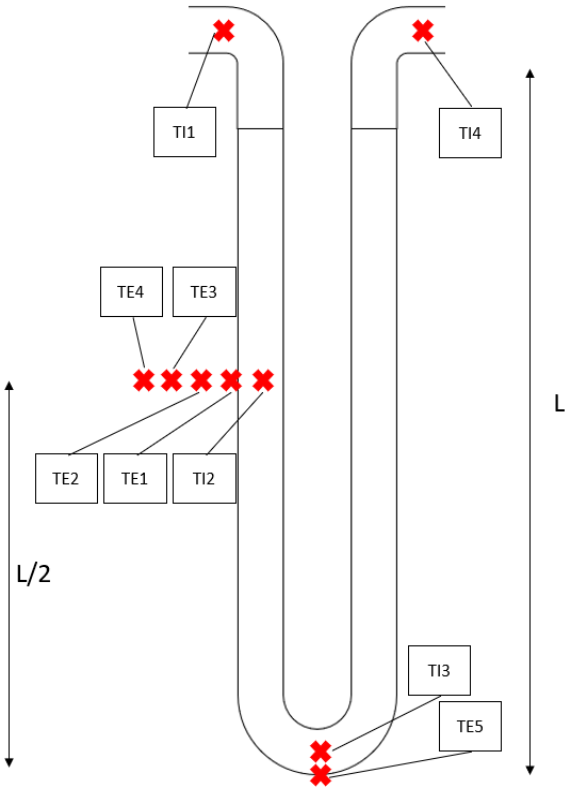


Figure 4: The figure above shows the location of inside thermocouples (TI), and external thermocouples (TE).

Thermocouples that were placed inside the tube were marked TI-1 through TI-4, while thermocouples that measure soil temperature were marked TE-1 through TE-4. TI-1 was placed at the well entrance, TI-2 at the middle of the vertical length of the tube, TI-3 at the lower limit (U) and TI-4 at the well exit. While the outdoor thermocouples, TE-1 to TE-4 were placed at the same distance as TI-2; TE-1 on the outer wall of the tube and from TE-2 to TE-4 in the same direction with a separation of 5 cm between each one. Finally, TE-5 was positioned on the outer wall of the tube at the same depth as TI-3. Some photos of the tubes with the thermocouples are shown below.

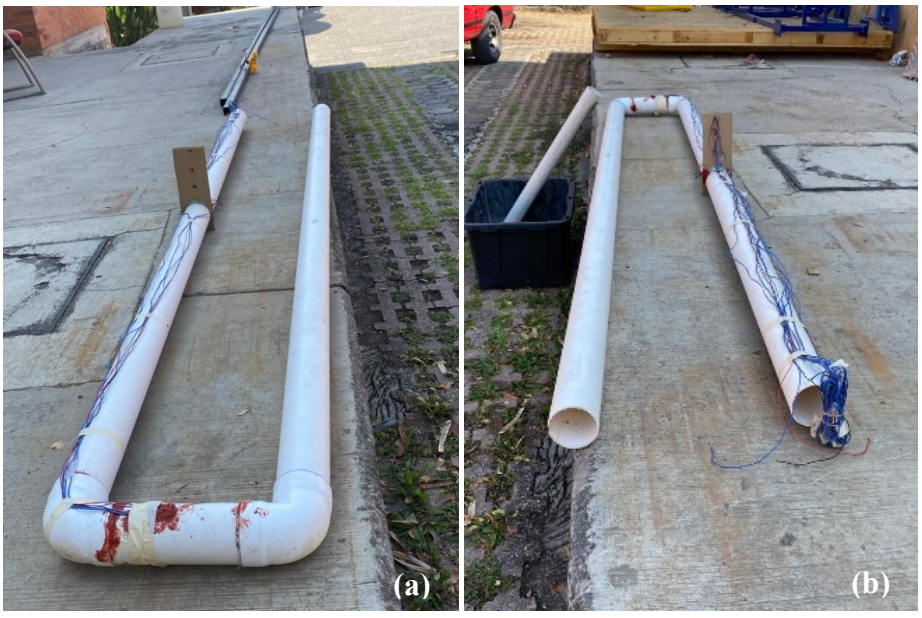


Figure 5: The figure above shows: a) a view from the bottom of the pipe, b) a view from the top of the pipe.

2.3 COP

To know the behavior of the heat exchangers during working hours, the Coefficient of Operation (COP) was used. This coefficient relates the heat power of the exchanger and the electrical power of the air fan. Subsequently, the thermal power of the heat exchanger is calculated from the volumetric flow, the specific heat of the air and the temperature difference between the inlet and the outlet of the buried heat exchanger. The above is observed in the following equation.

$$COP = \frac{P_t}{P_e} = \frac{\dot{m} \cdot Cp \cdot \Delta T}{P_e} \quad (1)$$

Where COP, Pt, Pe, ṁ, Cp, ΔT are Coefficient of Operation, thermal power, electrical power, mass flow, specific heat of the air and the temperature difference.

3. RESULTS

This section will present the results obtained from 6 tests carried out on the heat exchangers. The first 4 tests were performed on the 3-inch exchanger with a 25 cm spacing. The fifth test was carried out with the 2-inch exchanger and the last test was carried out with the 3-inch exchanger with a separation of 15 cm. The experiments were done separately due to two important things. The first one is that, at the time of experimentation, there was only one air impeller; the second is that the drilling of the wells and the installation of the heat exchangers was carried out intermittently.

3.1 TEST 1

The first experiment was conducted on March 23, 2020 on the 3-inch EAHE with a 25-cm separation between the tubes of each well. The total length of the exchanger was 11.8 meters divided into 2 wells. The duration of the experiment was 2 hours and the air speed throughout the experiment was constant equal to 5.4 m / s. During the first experiment, the ambient temperature was maintained at an average of 34.1 ° C. The following graph shows the inlet temperature, the temperature at the outlet of the first well and the temperature at the outlet of the exchanger.

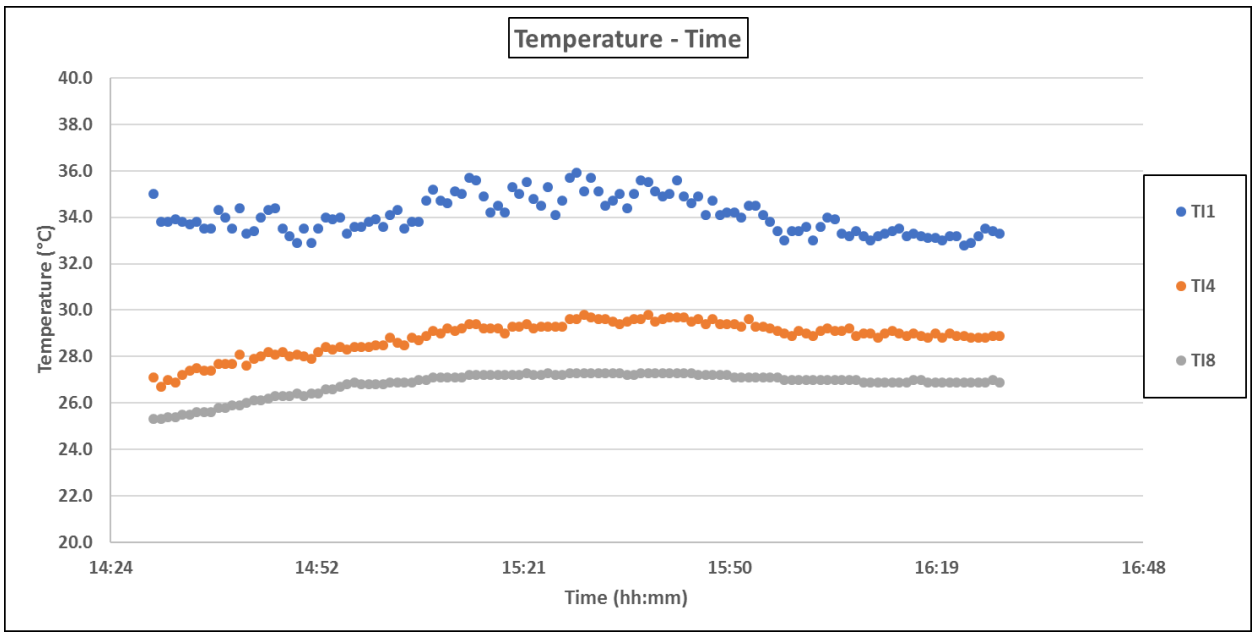


Figure 6: The figure above shows temperature at inlet (blue), first well outlet (orange), and exchanger outlet (grey).

During the first experiment, a temperature at the outlet of the exchanger of 26.8 ° C was obtained. This results in an average ΔT of 7.3 ° C between the inlet and outlet of the exchanger. The COP calculated for the first test was 7.3. The graph in figure 7 shows the thermal disturbance that occurs around the first well. The thermocouple found on the outer wall of the tube (TE1) is the one that has the most change in temperature, as expected. Since the thermocouple that is 15 cm from the wall of the tube (TE4) only changes its temperature by 1.5 ° C.

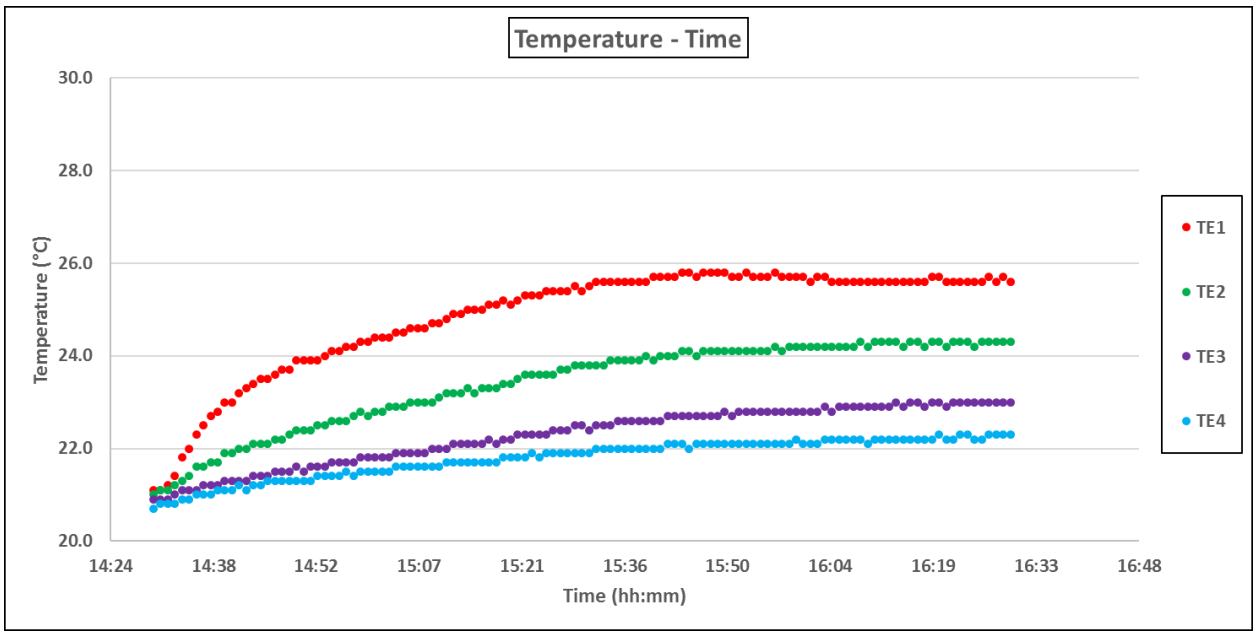


Figure 7: The figure above shows the temperature on the outer wall of the tube (red), to 5 cm (green), 10 cm (purple), and 15 cm (blue) to the pipe.

3.2 TEST 2

The second experiment was carried out on March 24, 2020 on the same EAHE as in the previous test. On this occasion, the duration of the experiment was 3 hours and the air speed throughout the experiment was constant equal to 4.8 m/s. On the second day of experimentation, the average temperature at the inlet of the exchanger (TI1) was 34.6 ° C, while the average temperature measured at the outlet of the exchanger (TI8) was 27.1 ° C. The above results in a COP of 6.7 with a ΔT of 7.5 ° C.

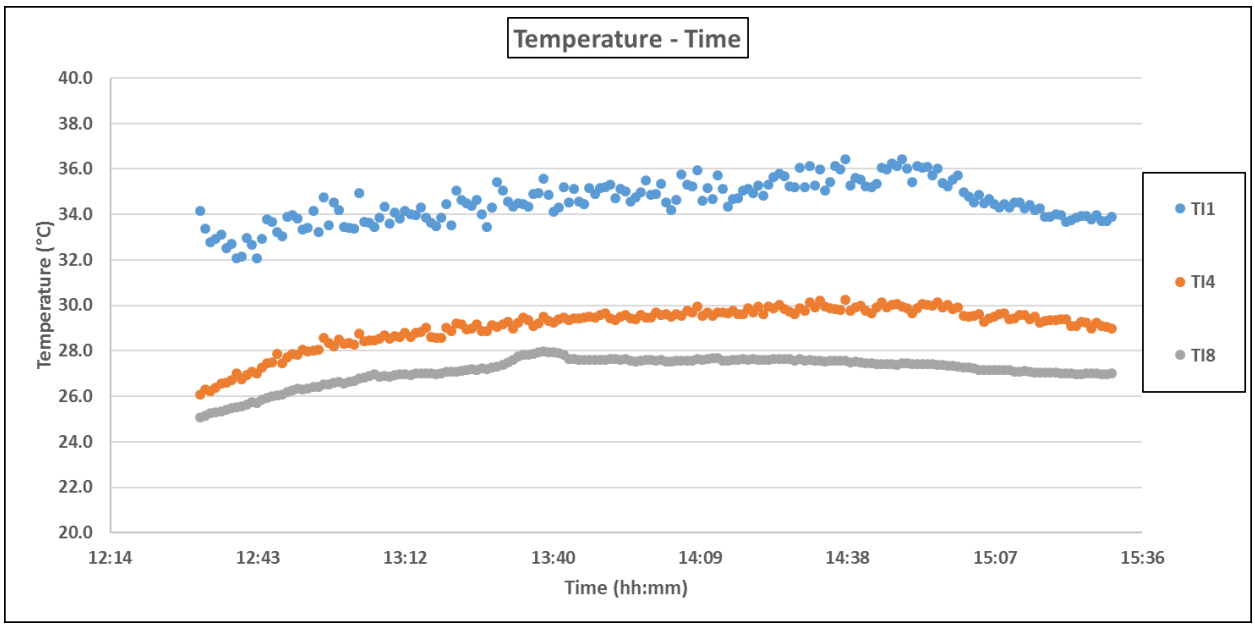


Figure 8: The figure above shows the room temperature between 32°C and 36 °C, and the outlet temperature at 27 °C.

For the thermal disturbance that occurred during the second day of experimentation, the thermocouple furthest from the exchanger wall registered a temperature change of 1.6 ° C during the 3 hours that the experiment lasted. Unlike the previous test, the thermocouple that was placed on the outer wall of the tube measured temperatures above 26.5 ° C for a few moments.

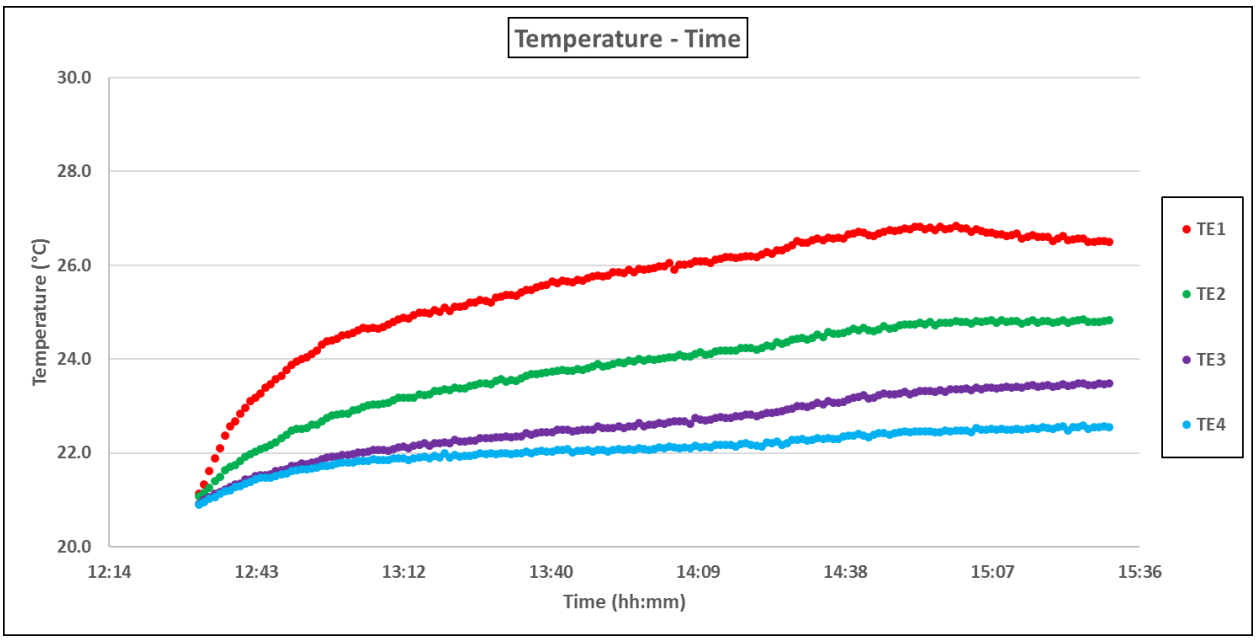


Figure 9: The figure above shows that the thermal disturbance at 15 cm to the pipe was 1.6 °C.

3.3 TEST 3

The third experiment was carried out between March 30 and 31, 2020. For this occasion, work continued with the 3-inch exchanger with a separation of 25 cm, but the total length of the exchanger increased from 11.8 to 18.2 meters by increasing a well more connected in series. The air velocity inside the exchanger was repeated with a value of 4.8 m/s. Although the experiment lasted 20 hours, in this part of the results only the section of time in which the air exchanger operated to lower the ambient air temperature will be presented.

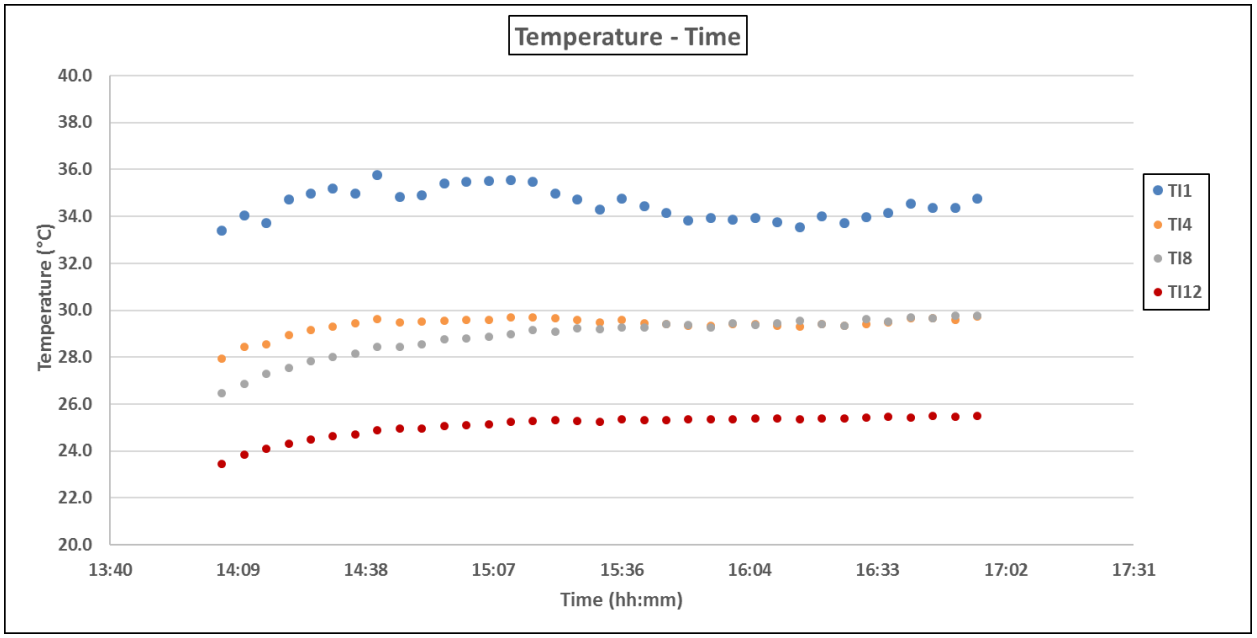


Figure 10: The figure above shows a quasi-constant behavior at outlet of exchanger with a value of 25.7 °C.

On this occasion, an average temperature at the inlet of the exchanger of 34.5 ° C was recorded, while at the outlet of the third well (TI12) the average temperature was 25.1 ° C. In this way, a ΔT of 9.4 ° C and a COP of 8.5 were obtained. The increase in ΔT and COP values are due to the increase in the total length of the exchanger.

On the issue of thermal disturbance, the thermocouple placed 15 cm from the outer wall of the tube registered a change in its temperature of 0.8 ° C, the lowest for the case in which the 3-inch interchange was used with a 25-cm separation. . This is because, unlike previous experiments, in this case the initial temperature of the surrounding earth was 22 ° C and not 21 ° C as in the previous cases.

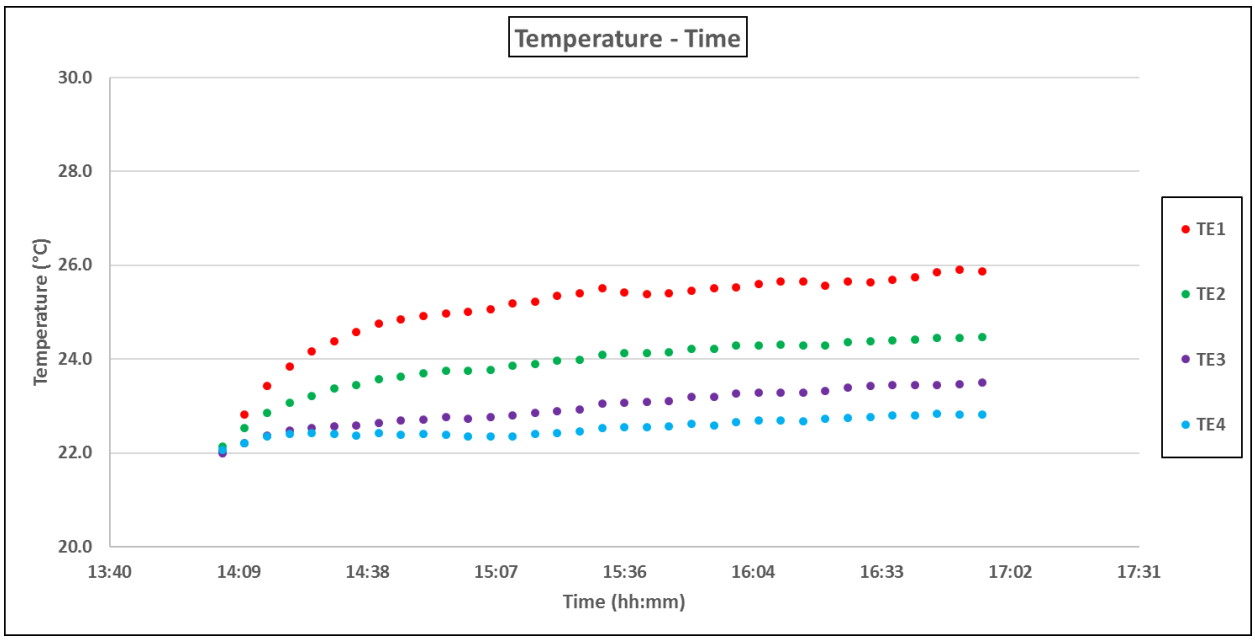


Figure 11: The figure above shows the minimal thermal disturbance in 3-inches pipes tests, with a value of 0.8 °C.

3.4 TEST 4

The fourth experiment took place between April 2 and 13, 2020. The characteristics of the EAHE were the same as in the previous experiment (length and air speed). The duration of this test was 12 days. As in the previous case, the graphs only show the periods in which the heat exchanger worked cooling the outside air.

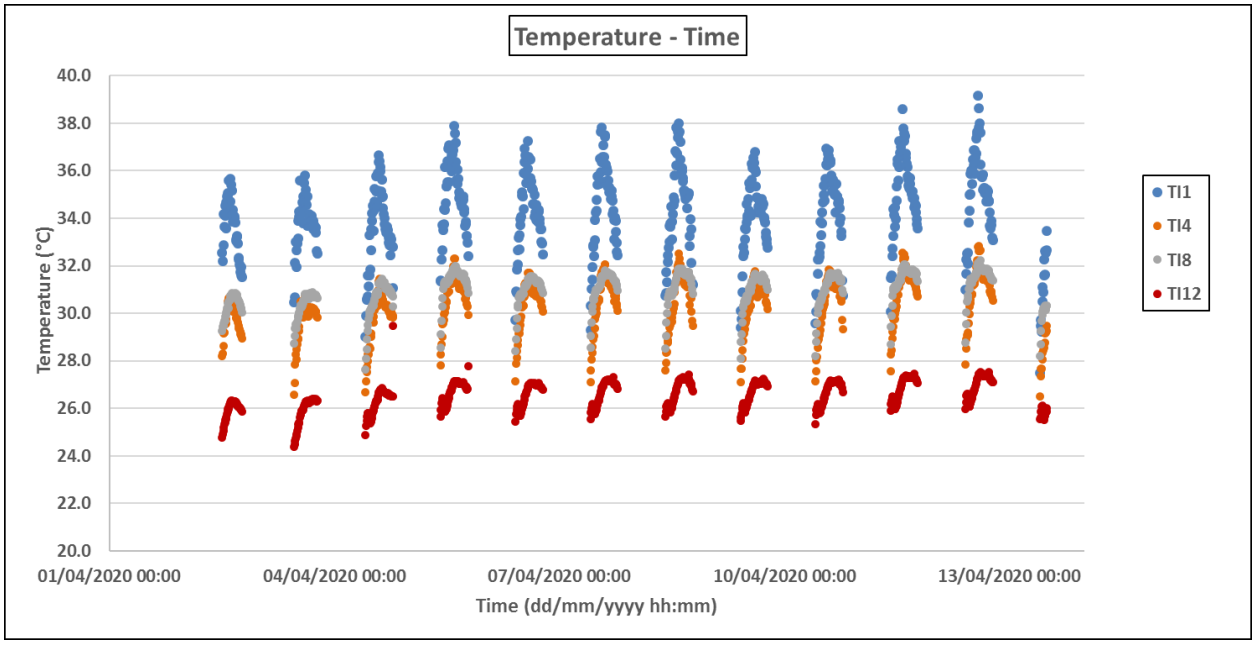


Figure 12: The figure above shows 12 days of performance, with the outlet temperature (red) among 25°C and 27.8 °C.

During the experimentation period of this test, the outside temperature reached 38 ° C on several occasions, while at the exit the temperature was in a range between 25 ° C and 27.8 ° C with an average of 26.6 ° C. The calculated COP was 7.1 with an average ΔT of 7.8 ° C.

The thermal damage of the TE1 thermocouple reached up to 32 ° C, a result that was to be expected due to the temperature that was registered in the TI1 thermocouple. The temperature of the surrounding soil 15 cm from the down comer of the first well registered a change of 1.7 ° C between the first day of experimentation and day 12 as shown in figure 13.

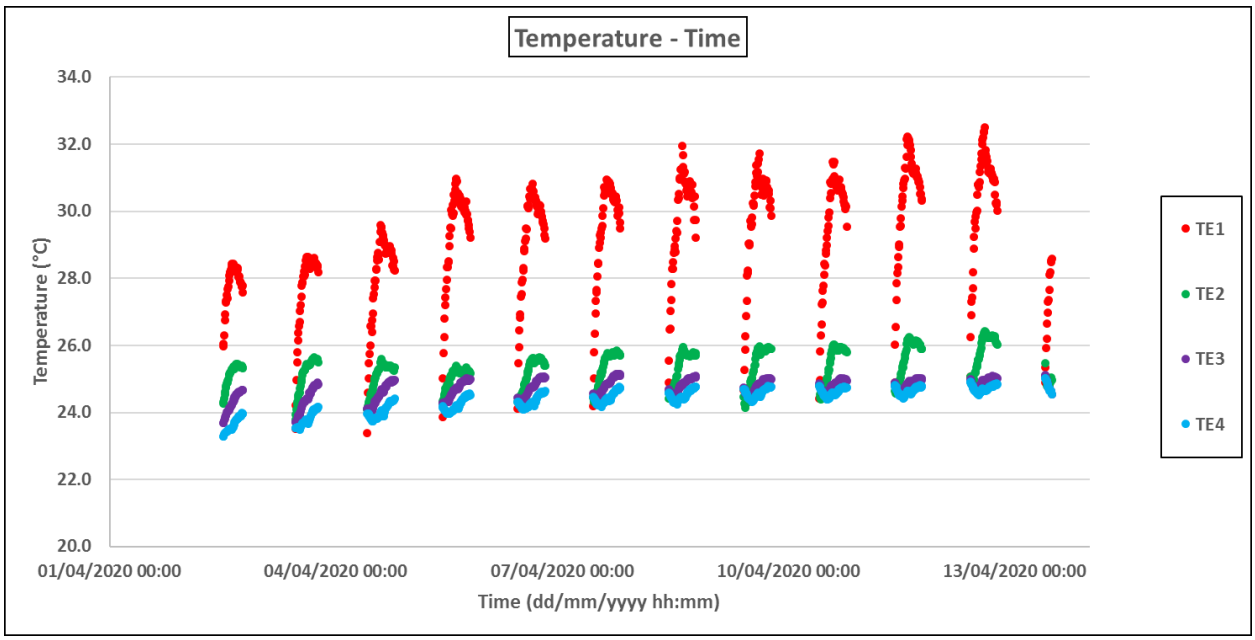


Figure 13: The figure above shows 12 days of performance, the thermal disturbance at 15 cm was about 1.7 °C (blue).

3.5 TEST 5

The fifth test was carried out between April 15 and 27, 2020 with the 2-inch heat exchanger and 25 cm spacing. The 3 wells were used, so the total length of the exchanger was 18.2 meters. The speed measured at the exit of the EAHE was 2.2 m / s, being the lowest of all the tests.

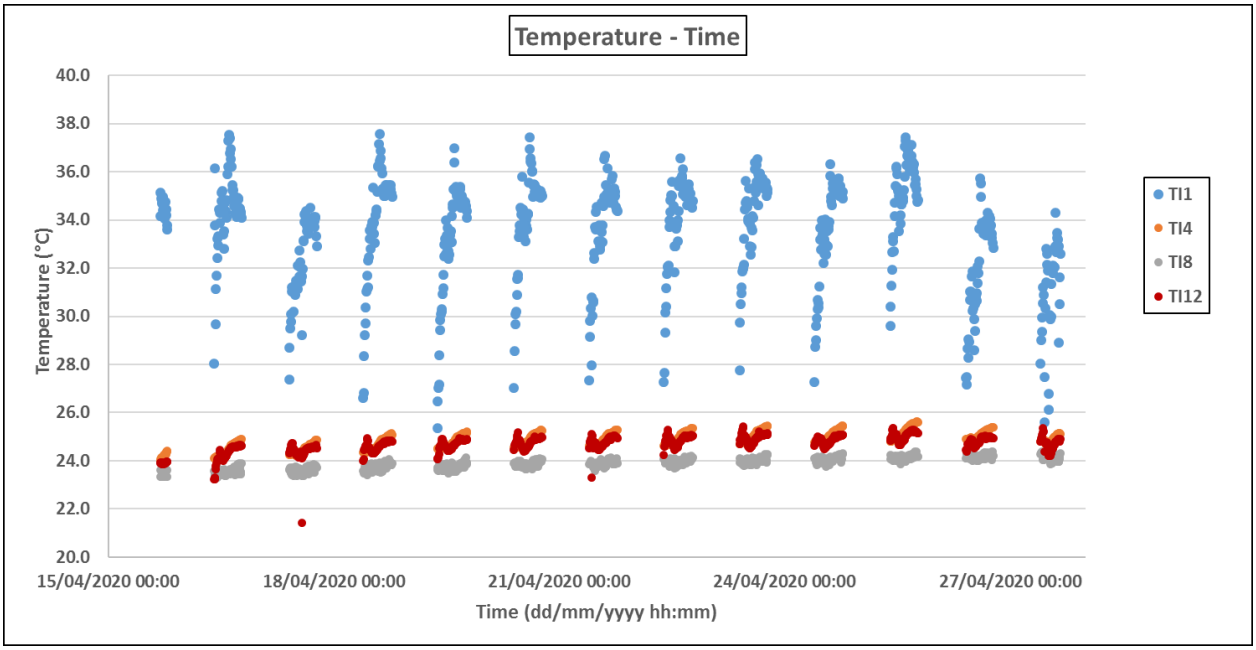


Figure 14: The figure above shows 13 days of performance. Temperature at TI12 is higher than TI8 because the thermal insulator suffered damage.

The graph of this experiment shows that in the first exchanger almost all the decrease in temperature occurs, reaching up to 92% of the total ΔT. It can even be observed that between the second and third wells there is an increase in air temperature of 0.8 ° C on average. This was because the insulation found in the connection between the second and third wells suffered a fault when it was covered with the earth from the excavation. For this test, the calculated COP was 1.6 with a ΔT of 8.9 ° C. The very low value for the COP in this test is due to the decrease in the diameter of the pipe compared to previous experiments and the speed obtained.

In the thermal disturbance that occurs in the soil around the down comer of the first well, it can be observed that an increase in temperature of up to 3.3 ° C occurs at the end of each day that the test lasted. The above is explained because, as shown in the previous graph, almost all the heat transfer of the experiment occurs in the first well, which leads to an increase in soil temperature at 15 cm from the wall of the tube of almost the double compared to previous experiments.

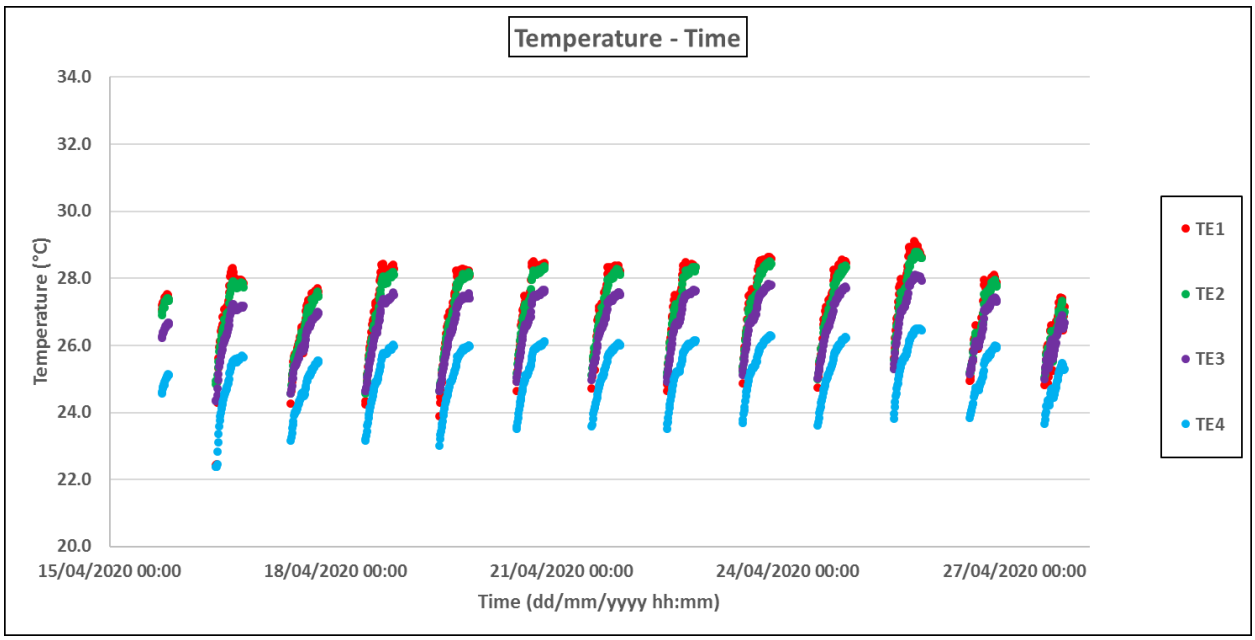


Figure 15: The figure above shows the higher thermal disturbance at 15 cm from the tube with an average value of 3.3 °C.

3.6 TEST 6

The sixth experiment was carried out between May 4 and 11, 2020. The 3-inch heat exchanger was used with a 15 cm separation between the downstream and upstream tubes. The air velocity inside the exchangers was 4.8 m ⁄ s and the total length was 18.2 meters. The average temperature at the entrance was 33.5 ° C, reaching up to 36.8 ° C on the hottest days.

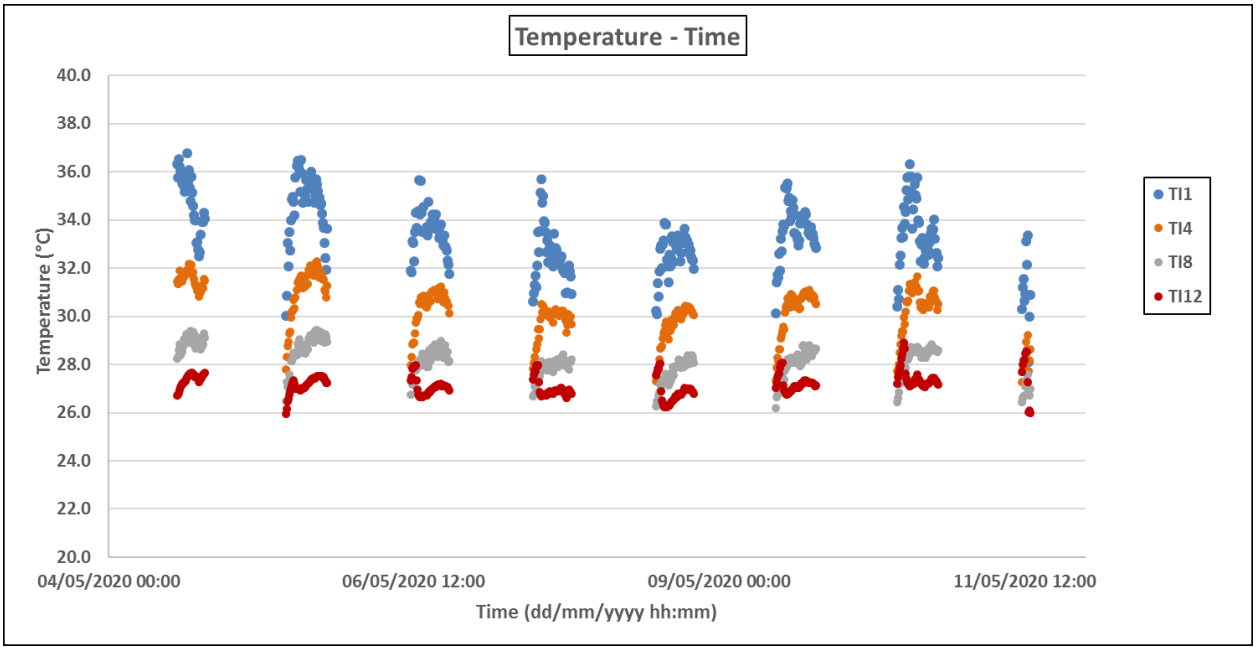


Figure 16: The figure above shows 8 days of performance with an outlet average temperature of 27.2 °C.

In the previous graph it can be seen that at the outlet of each well the air temperature decreased as it progressed inside the exchanger. In this way, at the exit of the third well there was an average temperature of 27.2 ° C, the worst of all the tests. The calculated COP was 5.7 for a ΔT of 6.3 ° C.

The radial disturbance for this test was 1.2 ° C recorded by the TE4 thermocouple. The graph 17 shows that the soil temperature before the thermal impact was 26 ° C. This is explained because the time that was allowed to pass between the installation of the exchangers in the wells and the first test was less compared to the other 2 groups of exchangers, therefore the thermal recovery of the soil after excavation was less.

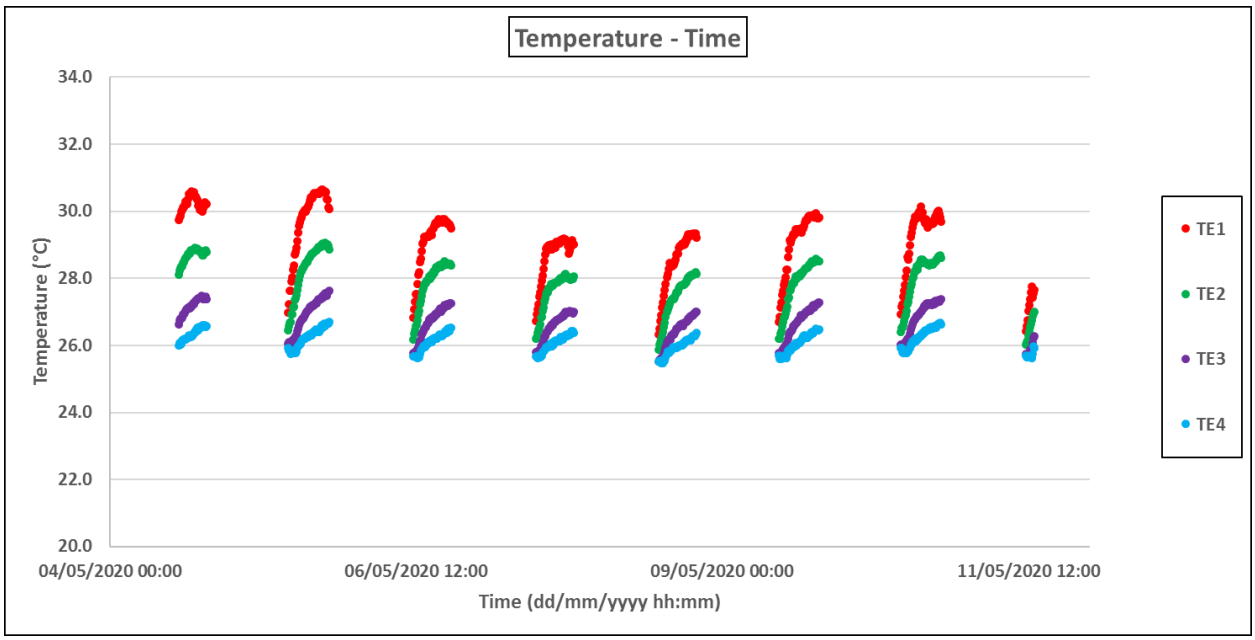


Figure 17: The figure above shows that thermal disturbance begins at 26 °C, as explained in previous paragraph.

To synthesize the data obtained, the following table shows a comparison between the experiments shown in this chapter.

Test #	Test duration	Pipe diameter	Spacing between pipes	Total lenght of the EAHE	Air speed	$\overline{T_i}$	$\overline{T_o}$	ΔT	COP	Thermal disturbance at 15 cm
1	2 h	3''	25 cm	11.8 m	5.4 $^{m}/_{s}$	34.1 °C	26.8 °C	7.3	7.3	1.5 °C
2	3 h	3''	25 cm	11.8 m	4.8 $^{m}/_{s}$	34.6 °C	27.1 °C	7.5	6.7	1.6 °C
3	3 h	3''	25 cm	18.2 m	4.8 $^{m}/_{s}$	34.5 °C	25.1 °C	9.4	8.5	0.8 °C
4	12 d	3''	25 cm	18.2 m	4.8 $^{m}/_{s}$	34.4 °C	26.6 °C	7.8	7.1	1.7 °C
5	13 d	2''	25 cm	18.2 m	2.2 $^{m}/_{s}$	33.6 °C	24.7 °C	8.9	1.6	3.3 °C
6	8 d	3''	15 cm	18.2 m	4.8 $^{m}/_{s}$	33.5 °C	27.2 °C	6.3	5.7	1.2 °C

Table 1: A resume with the results obtained in the tests.

3.7 DRILLING COST COMPARISON

The wells dug to install the heat exchangers were made with the help of a PREDATOR holder and extensions made of Schedule 40 steel tubular. The cost of the holder was $ 3,500.00 MXN, the steel tubular had a cost of $ 1,200.00 MXN, in inputs $ 1,000.00 was spent for the operation of the drilling rig and $ 9,000.00 MXN was spent on personnel to carry out the drilling. In total, $ 14,700.00 MXN was spent to be able to perform the 9 holes with an average depth of 2.8 meters deep.

Budgets were also requested from different companies dedicated to conducting soil studies and drilling wells. The companies were asked the cost of drilling a 10-meter-deep well with a diameter of 50 cm. Of the companies that sent their response, the average cost per drilling was $ 62,400.00 MXN. This represents up to 4 times the cost of drilling up to 9 shallower holes.

4. CONCLUSION

3 groups of EAHE were installed, each one of 3 exchangers connected in series and with different characteristics each. In each group, the total length and speed of the air inside the heat exchanger can be modified. By modifying the total length and air speed, the following conclusions were obtained.

Between tests 1 and 2, when changing the air velocity from 5.4 m / s to 4.8 m / s the change in outlet temperature is not significant. However, when increasing the total length of the exchanger from 11.8 m to 18.2 m and comparing experiments 2 and 3, a difference in the outlet temperature of 2 ° C is shown, in addition, the COP increases from 6.7 to 8.5 and the radial thermal impact it is lower, going from 1.6 ° C to 0.8 ° C.

The lowest heat exchanger outlet temperature of all experiments was achieved in run 5, with the 2-inch tubing. However, it was also the test where the lowest COP was calculated, due to the speed obtained and the diameter of the pipe.

Comparing the cost of drilling a single 10-meter deep well versus 3 wells no more than 3-meters deep, it is shown that by making several shallow wells, up to 75% of the cost of a single well can be saved. which is beneficial when comparing the investment that must be made when installing this type of ventilation system against compression air conditioning equipment.

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