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Blowers energy consumption decrease in an extended aeration activated sludge process by cooling the suctioned air

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A R T I C L E I N F O

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Ground temperature
Air temperature
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A B S T R A C T

In order to reduce energy consumption of the blowers in extended aeration wastewater treatment plants, decreasing suctioned air temperature is planned. For this purpose, in a full-scale facility, a 16.0 m^3 cold room and an earth-air heat exchanger (EAHE) at a depth of 1.5 m (four parallel sections of 10.5 m followed by one of 9.1 m of PE DN 315 pipe) have been built. Temperatures of suctioned and ambient air and ground at four depths have been continuously controlled. The EAHE stands out in summer, decreasing air aspirated temperature an average of 4.0 °C, with point values up to 6.0 °C. This system enables a decrease in the instantaneous work of the blowers on 63.0 % of the days of the year, with average decreases up to 2.0 % and maximum of up 4.0 %. By the cold room instantaneous work is decreased 39.8 % of the days of the year, with average decreases up to 1.2 % and maximum of up to 3.3 %. Both systems are effective during the central hours of the day, with a wider range of hours for the EAHE, and are inefficient during the early morning. According to statistical analysis, the EAHE should be located at a depth where the earth's undisturbed temperature is reached, using several pipe segments to improve heat exchange and avoid excessive pressure loss in the air aspiration. Soil material round the EAHE with high thermal conductivity is essential to achieve a high heat transfer and avoid temporal performance degradation by thermal saturation of the ground

1. Introduction

In the last decade, wastewater treatment plants (WWTP) have been transformed into resource recovery facilities, rather than waste disposal systems [1]. Efficiency in wastewater treatment systems is one of the biggest challenges today, with treatments being developed that are not only effective in removing pollutants from the water, but also in reducing the energy footprint associated with these facilities.

Nowadays, activated sludge processes are by far the most used for wastewater treatment. For these facilities, energy consumption is related with the level of treatment and the size of the facility, varying between 0.41 and 0.78 kWh/m^3 [2], with 45 % to 75 % of the total energy cost, required for activated sludge aeration [3]. However, several authors suggest that energy use could be decreased up to 50 %, being aeration the process in which the various energy optimisation strategies are focused [4]. This aspect is of particular interest in extended aeration facilities, whose energy cost can be up to one-third-higher than in conventional activated sludge systems [5].

The search for effective energy saving strategies has increasingly attracted the attention of various researchers, seeking to optimise the relationship between energy and effluent quality. Furthermore, the new Directive (EU) 2024/3019 of the European Parliament and the Council concerning urban wastewater treatment promotes energy efficiency. In this sense, numerous studies have been carried out in recent decades. On the one hand, work is being done to adjust the oxygen supply to the needs of the system by means of different mechanisms [2,5,6]. Other strategies aim to decrease the pollutant concentration entering the biological process by diverting it to the sludge line, thus reducing the oxygen requirements in the activated sludge process [7]. An important aspect of energy optimisation is the use of more efficient equipment, correct sizing and development and implementation of strict maintenance plans [8].

Fine-pore diffusers are the most used technology for activated sludge process aeration, due to their advantageous aeration efficiency [2,3]. This technology aspirates air from the outside by means of blowers which compress it and supply it to the activated sludge through membrane diffusers, generating fine air bubbles.

The blowers are adiabatic machines used to supply large volumes of

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air at low pressure. For this equipment, as for an air compressor, the work done to supply the air required is directly proportional to the product of the pressure and the change in volume of the air supplied. Therefore, according to the laws of thermodynamics, the work required to compress air by the blowers will be directly proportional to the air temperature at the suction of the equipment [9]. Therefore, the colder the aspirated air is, the less work is required to supply it, and the less energy is consumed.

Although the energy saving due to supplying the blowers with the coldest air possible could not to be very significant, the large air requirements that must be continuously supplied to an activated sludge reactor make it important, mainly in warm areas, since outside temperatures can be extremely high at certain times of the year, in addition to the high percentages of humidity that usually occur in the area where the WWTPs are located. According to this, to ensure that the air suction to the WWTP blowers is as dry, cold and clean as possible, a cold room is usually built. The air enters the cold room from outside and from this cold room the blowers suction air.

An alternative to the cold room is the use of geothermal energy, a renewable energy that can be applied to provide heating and cooling [10,11]. Various alternatives have been developed to harness this energy source, being the earth-air heat exchanger (EAHE) an energy-efficient method to preheat and cold air in buildings [11–15]. From the mid-twentieth century this system was researched and implemented in the building sector, expanding significantly from the mid of the 1990s, mainly in cold areas [11]. There are two major types of EAHE systems, the open-loop and the closed-loop. Both are basically composed of one or more pipes buried in the ground in a horizontal or vertical position at a particular depth, with equipment for air conveyance through conduction in which heat exchange will take place [11, 16].

Since their introduction, various models have been developed for the design of the EAHE systems, being the length and diameter of the pipe, as well as its arrangement and the velocity of the supplied air, the most significant variables for their operation in building applications. Other less significant factors include the pipe material, with PVC being the most commonly used material [11].

Another variable to consider is the depth of the EAHE pipes location [11]. The subsurface layer of the soil experiences interactions with variable atmospherics conditions. So, with greater depth ground temperature becomes more stable to a depth at which remains almost constant throughout the year, because no interactions occur. This constant temperature is called earth's undisturbed temperature (EUT) [17]. The EUT remains lower than ambient air temperature in summer and vice versa [17]. Due to this, during summer months it is possible to cool air temperature using an EAHE system. The EUT depends on climatic conditions and is different according to the regions of the earth, so the depth at which the EUT is reached varies from one area to another, being described from 1.5 to 2.0 m [18] to 7.0 m or more [11].

In a WWTP, the most suitable EAHE system to implement is the open-loop, since blowers needs to aspirate air from outside to oxygenate the wastewater. Its building to cool the aspirated air by the blowers is simple, given the available space and the earthworks required prior to developing the various elements. The EAHE system can be located at certain depth within the soil subsurface layer without interference, due to the proximity of other installations or similar structures. Therefore, it is a viable and novel alternative to a cold room, since it can contribute to energy saving to a greater extent than the cold room, obtaining further progress in reducing the energy footprint associated with WWTPs.

The application of an EAHE system to suction air from the blowers of a WWTP will allow to decrease aspirated air temperature, when ambient air temperature is high. This will reduce the work required for air supply by the blowers and thus energy consumption. Aspirated air humidity will also vary due to heat exchange [13]. Based on this, this study is proposed with the aim of comparing the temperature variations suffered by the air aspirated by the blowers of an extended aeration WWTP, depending on the capture area (cold room or EAHE system) and its effect on the work carried out by the blowers. The air cooling capacity of the designed EAHE system and its improvement possibilities will also be assessed by applying a simple model that allows understanding the influence of the main design variables in specific applications for a WWTP.

2. Material and methods

2.1. Facility under study

The study has been realised in the Huétor Tájar-Villanueva Mesía WWTP (Granada, Spain), during a year. This is an extended aeration activated sludge facility for urban wastewater treatment with a capacity of up to 3850 m^3/d with a population equivalent of 16,370.

The WWTP has three positive displacements rotatory screw blowers (Robuschi, mod. WS65/2C-1F LP) with a capacity between 780 Nm^3/h (2945 rpm) and 1540 Nm^3/h (5415 rpm) and with a frequency inverter which operates between 30 and 50 Hz. The differential working pressure is 615 mbar and the electric motor power is 37 kW. These machines provide a constant air flow and variable pressure. They feed two grids of membrane diffusers submerged 5.25 m below the water surface and they are located in the same room, which keeps them isolated from outside.

The three blowers are connected by an air suction duct which can be fed from a cold room or via an EAHE-type chimney intake system (Fig. 1). In the outer area (north-facing) there are four intake chimneys connected to a PE pipe DN 315, with an enclosure (1.2 m^3) from which air is conducted through a PE pipe DN 315 to the embouchure, connecting with a 316 L and DN 304 stainless steel tube until its connection to the blowers. The suction pipes have a slope from the chimneys to the catch basin of 2.0 %, being the catch basin the lowest point, located on gravel base that serves for condensates drainage. The pipe connecting to the blowers also has a similar slope towards the catch basin. The pipes of the EAHE system have been placed at a depth of 1.5 m based on previous experiences of Bisoniya el at [18]. The installation was covered with a filling material, using compacted gravel, and there is no interference from the water table (located at 12.0–15.0 m. depth). The cold room, with a volume of 16.0 m^3 (1.0 m x 5.0 m x 3.2 m) connects to the outside through a window, located on the north-facing wall. The air in the cold room can be suctioned by the blowers, by means of a manual valve opening located in the pipe connecting to the intake duct.

2.2. Measuring equipment

For the development of the research, eight temperature meter (IyC, model PT100) have been placed associate with their corresponding transmitters (SEM 1605-P) with a measurement range between −200 to 450 $^\circ C \pm$ 0,3 %. Four of them were located on the ground, in the air intake area, at different depths (0.5 m, 1.5 m, 3.0 m y 5.0 m). In the air suction line, one is located in the interior, another in the cold room feeding the blowers. There is also an ambient air temperature and humidity meter (STATUS, mod SEM 160I) located close to the air suction area, on a wall, at a height of 2.0 m over the ground, without direct solar radiation (range for temperature −20 to 80 ± 0.5 °C, range for humidity 0.0 to 100.0 ± 0.3 %).

For the measurement of the flow rate of air supplied to the biological treatment, a mass flow meter with a range between 0.0 to 20.0 m/s with an accuracy of 0.4 % has been installed in the air outlet pipe from the blowers (Schmidt, mod. SS 20.500). A pressure sensor is also available in the same pipe with a range between −1.0 to 1.0 bar with an accuracy of 0.5 % (IFM-PN2599).

Data obtained are recorded in the WWTP control system (SCADA), including those from the complementary measuring equipment, defining data record every minute.

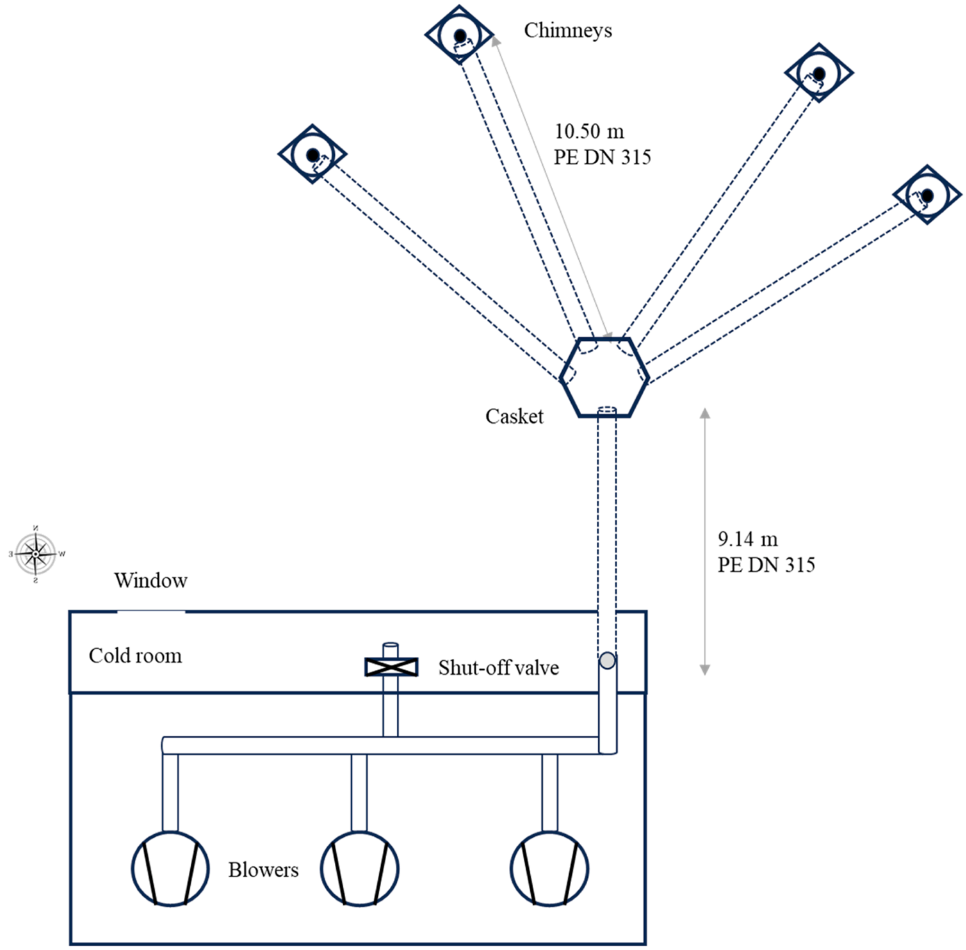

Fig. 1. Diagram of the open earth-air heat exchanger system used in the study.

2.4. Statistical analysis

Data obtained by continuous measurements were treated by the specific software Active Factory 9.2 (Wanderware) to remove outliers recorded during the measurement and to obtain daily mean values. For statistical analyses, the data compiled were analysed using the SPSS software package (IBM-SPSS v22). Pearson's correlation coefficients (PCCs) between the different air (ambient and after passing through the cold room and EAHE system) and ground temperatures were obtained to assess the degree of influence of each on the other. Correlations between the main variables which influence the performance of the EAHE system, and its operation parameters have also been obtained, before performing a multivariate statistical analysis in order to select the most influential variables and parameters.

Multivariate statistical analysis was performed using the CANOCO software (v4.5 for Windows, ScientiaPro, Budapest). A redundancy analysis (RDA) was carried out to assess the relationship between the main EAHE system variables and control parameters. The Monte Carlo permutation test, with 499 permutations, was used to assess the statistical significance of each variable or parameter in the canonical axes. CanoDraw was used for the graphical presentation of the results.

3. Results and discussion

3.1. Ambient temperature evolution and its influence in blowers energy consumption

In the WWTP location (Huétor Tájar, Andalusia-Spain), the inland mediterranean climate is predominant, with long summers and mild winters with large daily temperature ranges throughout the year.

For this study, temperature records started 8 November 2023, extending over a full year. Since the beginning of the period, ambient temperature experienced a downward trend. December was the coldest month, with minimum values of −2.8 °C on 27 December 2023 and with a monthly average of 8.3 °C. After December, the average temperature experienced an upward trend, reaching the highest temperatures in the month of July with a record of 47.2 °C on 29 July 2024. The highest average temperature was obtained in the month of August, with 30.7 °C. From this period onwards, the ambient temperature reverses its trend (Fig. 2).

Thermal amplitude in ambient temperature varied between 2.1 and 26.7 °C, with temperature generally dropping at night and minimums around dawn. The months with the highest temperatures were generally those with the greatest thermal amplitude and vice versa. The highest value was recorded in July and the lower in October, November and December with thermal amplitude below 5.0 °C. Independently of this behaviour, during the coldest months, significant thermal amplitudes higher than 20.0 °C, were also recorded (Fig. 3).

Taking into account that the work done by the blowers to compress air is directly proportional to aspirated air temperature [9], if the air is suctioned directly from outside, the effect of temperature on energy consumption will be significant, increasing especially during the summer months. The spring months also stand out, with maximum temperatures easily exceeding 30.0 °C.

Based on the results of the studied WWTP simulation, the actual oxygen requirements (AOR) at a wastewater temperature of 20 °C, ranged from a maximum of 173.9 kg O_2/h to a minimum of 15.7 kg O_2/h. These requirements are mainly dependent on the pollution

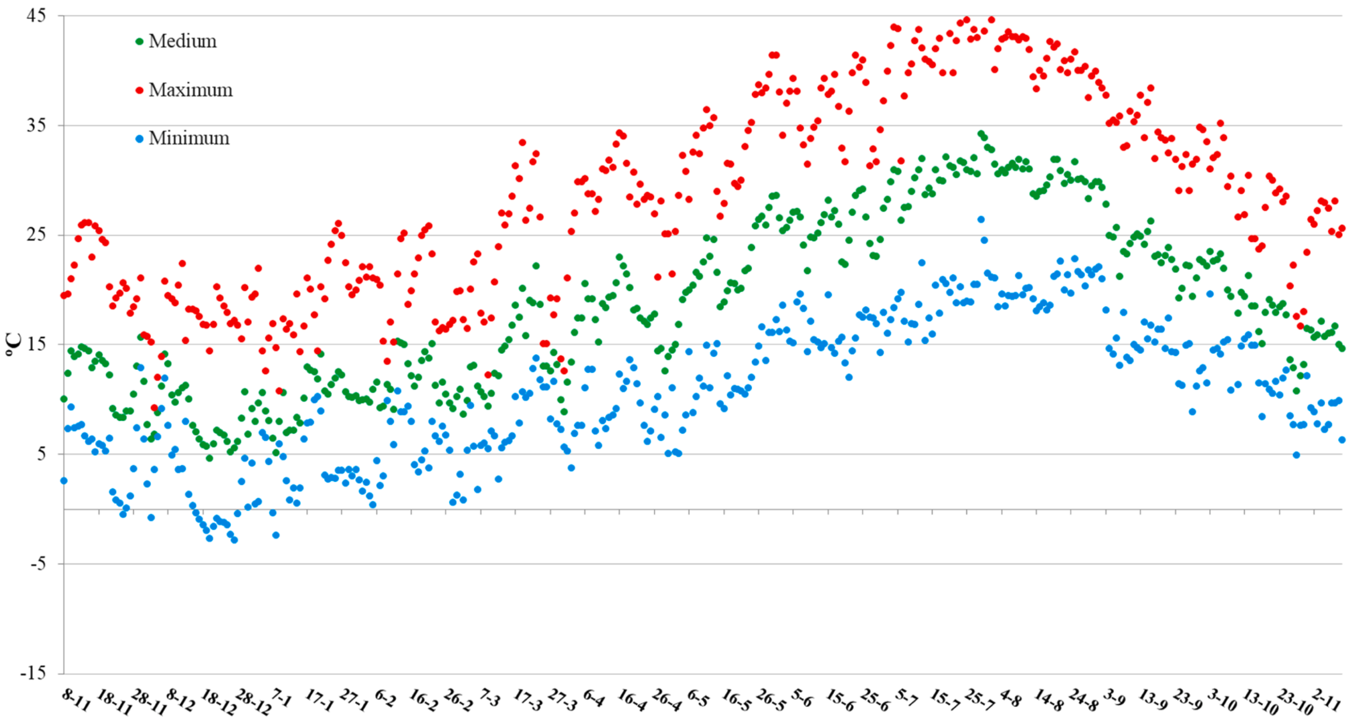

Fig. 2. Medium, maximum and minimum ambient temperature evolution.

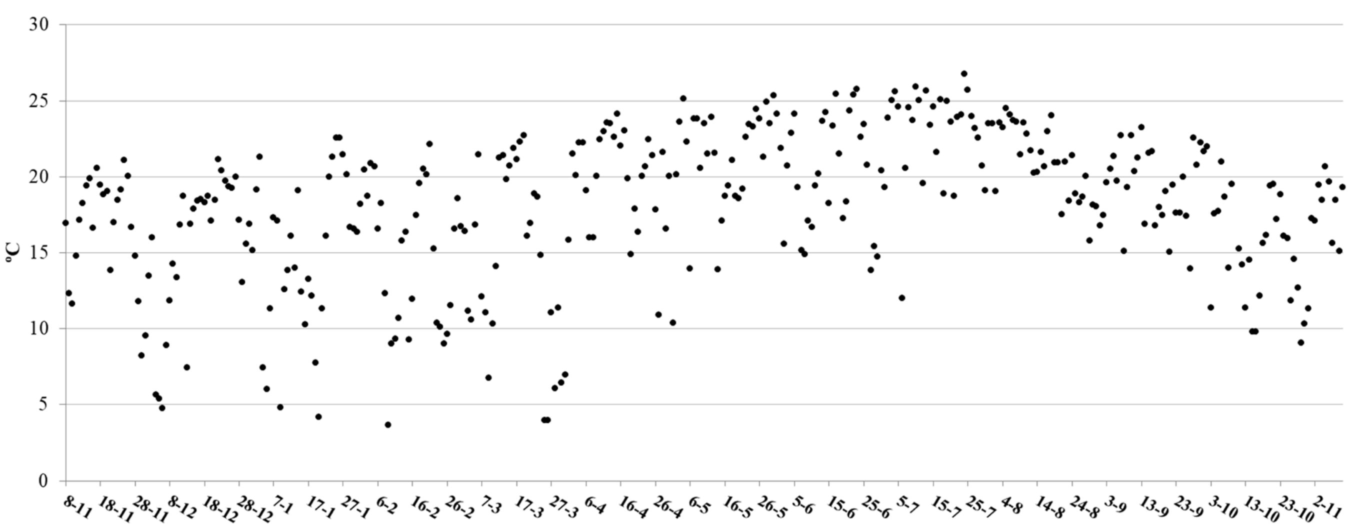

Fig. 3. Daily thermal amplitude evolution in ambient temperature.

concentration for both organic matter and nitrogen, also influencing other process variables such as cell retention time [19]. Based on this data, to define and measure all the aeration system, different variables that can affect oxygen transfer efficiency (OTE) must be considered [2, 3], which varied between 14.2 % and 17.8 %. Considering the mass ratio of oxygen in air (23.0 %) and the molecular weight of the air (28.96 g/mol), air requirements range from 184.5 kmol/h to 14.9 kmol/h. Considering the equation of state for ideal gases, it is possible to estimate instantaneous work variation of the blowers as a function of the ambient air temperature. With these premises, the instantaneous work carried out by the blowers, considering an ambient air temperature of 20.0 °C, will vary between a maximum of 120.8 kW and a minimum of 9.1 kW, with an average increase of 0.34 % for each degree Celsius of increase.

The ambient temperature is not the most influential factor in energy consumption, depending mainly on the pollutant concentration values, which fluctuate significantly for this WWTP, as indicated by the AOR values. However, considering that thermal amplitude for most of the days exceed 20.0 °C, increases in instantaneous work represent about 7.0 %, which has a significant impact on energy consumption. In addition, increases in ambient temperature also lead to an increase in the wastewater temperature, which will result in an increase in AOR values [19] and a decrease in OTE values [6], so the increases in instantaneous work will be greater.

Another factor to consider is relative humidity, whose maximum ranged from almost 100.0 % for the autumn months, winter and spring, until values around 60.0 % for summer months, with minimum values of about 40.0 percentage points less than the maximum, during the whole year. Relative humidity is influenced by the climate and the location of the WWTP in the bank of the Genil river (Granada-Spain). It has to be considered due to its influence on air density and the generation of water condensates which can affect the average life of the blowers.

3.2. Aspirated air temperature evolution

The air temperature in the suction points changed daily in line with ambient temperature, both in the cold room and after EAHE system (Fig. 4). Statistically significant correlation is observed in the analysis of PCCs (p-value < 0.01) between ambient temperature and temperatures in the cold room (PCC = 0.979) and EAHE system (PCC = 0.970), so that in both cases aspirated air temperature depended mainly on the ambient temperature.

Regardless of the positive correlation observed between average ambient temperature and the one of aspirated air, generally, air aspirated throughout the EAHE system cooled in certain periods of time, whereas cold room temperature was more similar to ambient temperature (Fig. 4). The cooling capacity of the EAHE system was more significant during the months from April to August, with an average monthly decrease up to 4.0 °C, with point values up to 6.0 °C. This cooling, although milder, was also observed between the months from December to March, while for the months from September to November, the air became warmer.

Considering the variation of the daily mass flow of aspirated air and its temperature, by using the equation of state of ideal gases, it is possible to define the instantaneous work required to compress the air in each circumstance. If the instantaneous work performed by suctioning air directly from the outside or from the cold room or EAHE system is compared, the improvement percentage due to the change in temperature can be obtained. For average temperatures, the improvement of the instantaneous work was more significant when using the EAHE system which was reduced on 63.0 % of the days throughout the year (Fig. 5). However, with the cold room the improvement occurred on only 39.8 % of the days. The most significant decreases using the EAHE system were obtained in the spring-summer season, reaching up to 2.0 % daily average in the instantaneous work decrease, whereas with the cold room the greatest decreases occurred during spring, with decreases of up to 1.2 %. During the autumn months collecting air from the outside was more appropriate since with the cold room and the EAHE system the air warmed up.

Ground temperature, which influences the heat transfer capacity through the EAHE system, shows a significant inertia [18]. Therefore, after the summer, ground temperature remains relatively high regarding ambient temperature, which experiences a drop during autumn so that air will be heated when passing through the EAHE system. This effect is reversed in spring.

If the same analysis is realised regarding maximum daily temperatures (Fig. 5), it is observed that for most days of the year, instantaneous work can be reduced with both types of collection (94.0 % of the days for both systems). However, during the daily hours with maximum ambient temperature, the EAHE system was more advantageous than the cold room only in the summer, with decreases in instantaneous work of up to 5.2 %, whereas the suction through the cold room allowed further decreasing in winter and spring, and even in part of autumn, reaching decreases up to 4.0 %.

Regarding minimum daily temperatures, for almost all days of the year, air was heated in the cold room, whereas on 14.5 % of the days throughout the year (May and June) the air could be cooled with the EAHE system (Fig. 5).

The hourly analysis shows that by means of the suction through the EAHE system, it was possible to reduce the instantaneous work during the central hours of the day, for all months of the year (Fig. 6). However, depending on the month, the time range varied, being wider for the month of July, with instantaneous work decreasing from by up to 4.0 % from 8:00 to 0:00, whereas in November, the EAHE system was only effective between 11:30 and 18:00, with maximum decreases in instantaneous work of 1.0 %. Air suction through the cold room was equally effective during the central hours of the day being more effective during the month of May between 9:30 and 21:00, with decreases of 3.3 % of instantaneous work, whereas in October it was only effective between 11:30 and 18:00 with maximum decreases of 1.0 %. For both systems, it was noteworthy that during the early morning hours the air got warmer, making them ineffective.

In general, the cold room is less efficient than the EAHE system in decreasing the instantaneous work of the blowers when compressing the air. Its characteristics are typical for these installations with a surface-mounted installation, so its walls are in direct contact with the exterior. Its orientation prevents direct sunlight, and air is suctioned from a shaded, north facing area. However, the cold room has a surface area of 27.0 m^2 that is in contact with the exterior, where the temperature is variable; while the EAHE system has a surface of 43.0 m^2 that contact the ground at a depth of 1.5 m with an almost constant temperature throughout the day.

The EAHE system for cooling has already proven effectiveness in building, mainly for warm climates [11–15] and, according to our results, it is also suitable to cool the air suctioned by the blowers in WWTP. However, air suction through the cold room is more effective than the EAHE system for a few hours a day, except in summer. This means that the two systems should not only be considered as alternatives, as they can be complementary through their individual application or combined, forming similar systems to the one studied by Lashgari et al. [16]. Thus, depending on the period of the year and the time zone, the suction point can be varied, considering that during the early morning hours it is more viable to collect directly from the outside during the whole year.

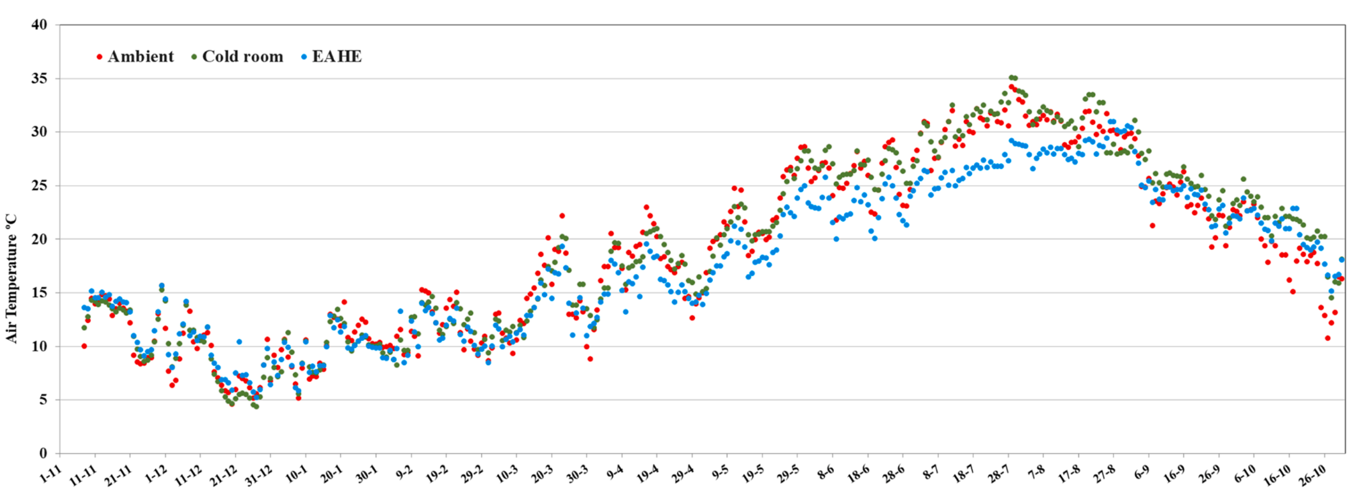

Fig. 4. Evolution of average air temperature values of ambient, suctioned air through cold room and suctioned air through the EAHE system.

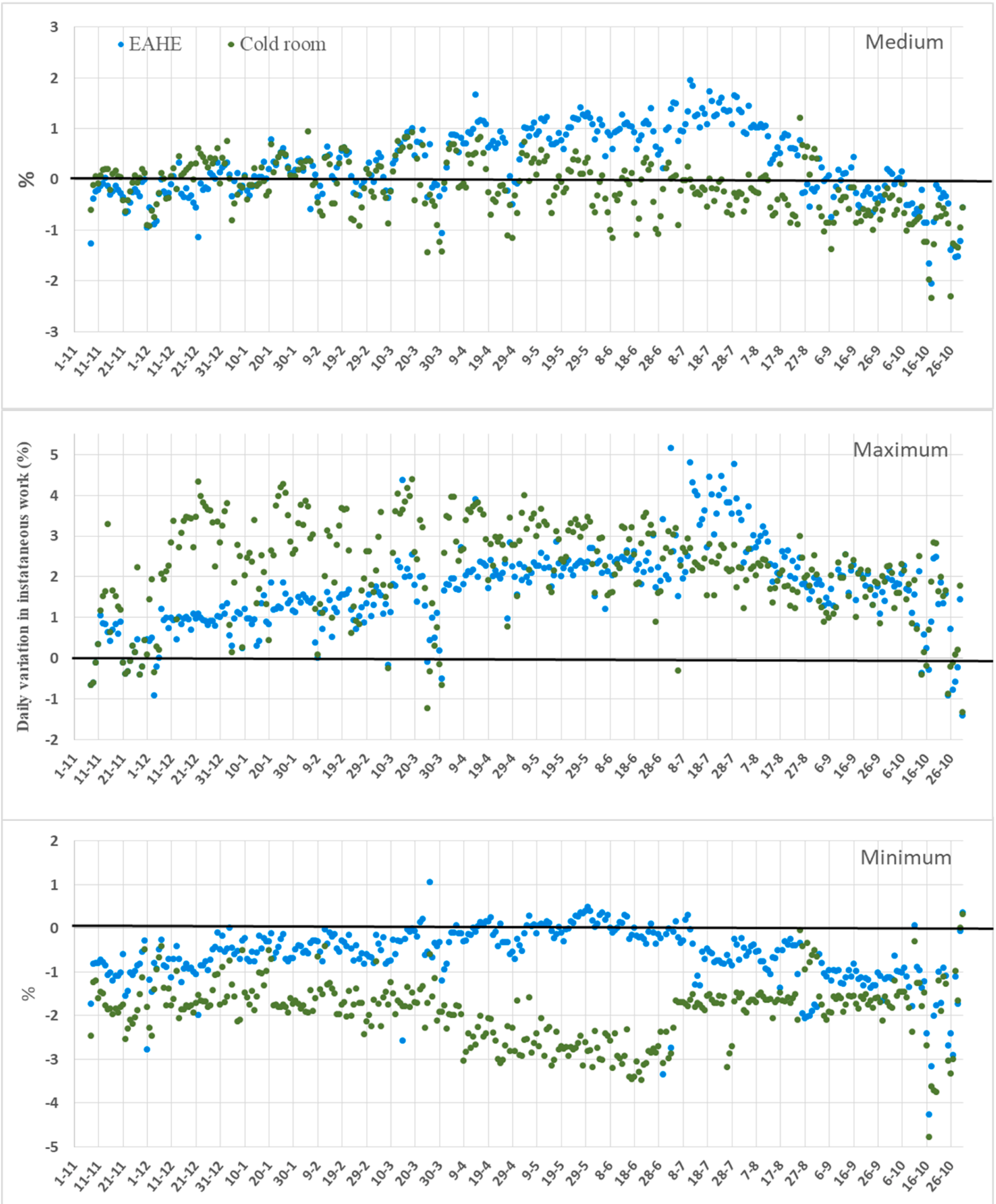

Fig. 5. Calculated percentage of daily variation in instantaneous work in air suction by the blowers depending on the air suction point (cold room or EAHE) at medium, maximum and minimum temperatures.

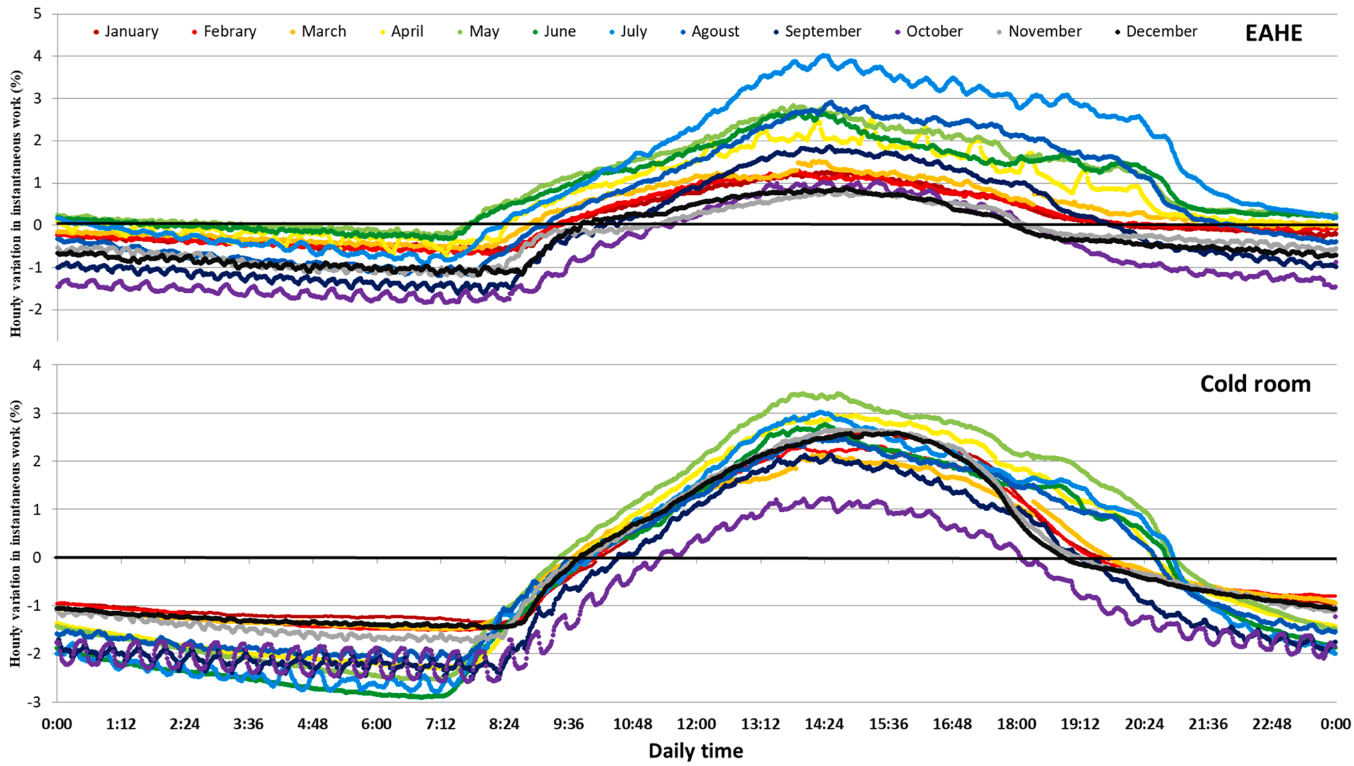

Fig. 6. Calculated percentage of hourly variation in the instantaneous work in air suction by the blowers depending on the air suction point (cold room or EAHE) at medium temperature.

Decreases in instantaneous work between 1.0 % and 4.0 % can be considered not very significant. However, its application in extended aeration WWTPs is relevant. These installations provide an effective response to water purification in small municipalities, but they require a continuous and large supply of air to provide oxygen to activated sludge, and linked to this, high energy consumption [5].

For the specific case of Huétor Tájar-Villanueva Mesía WWTP (Granada, Spain), during the experimental period the average energy consumption ranged between 1655.0 kWh/d and 2772.0 kWh/d, (0.43–0.72 kWh/m^3), depending mainly on the treated wastewater flow and pollutant loading. This is why energy optimisation in these installations is of great importance, thus low percentages of reduction in energy consumption mean large economic savings [4].

Air inputs ranging from 604.7 m^3/h and 1293.6 m^3/h were required during the experimental period, which has meant energy required for activated sludge aeration varied between 69.4 % and 79.9 % of the total energy consumption. These values are consistent with those typical for extended aeration facilities [2,3] and are within the medium range of theoretically calculated values. Saving between 1.0 % and 4.0 % of energy requirements for activated sludge aeration means a saving of between 11.4 kWh/d and 88.6 kWh/d, values which, as indicated above, are low but contribute to taking a step further in the energy optimization of these facilities. The installation of an EAHE system is simple and inexpensive, especially if done during the construction of the WWTP, taking the advantage of the earthworks already in place. In this scenario, the increase in the total cost is due to the price of the pipe already installed, so the payback time does not exceed the first year of operation. This estimate regarding energy savings can be extrapolatable to any extended aeration WWTP, as this technology is not recommended for facilities with a treatment capacity exceeding 5000 m^3/d. It should be noted that the extended aeration WWTP are small facilities, so the installation of the EAHE system in large WWTP will result in greater energy savings.

3.3. *Ground temperature evolution*

Ground temperature has experienced a temporal evolution analogous to ambient temperature for the four depths where measures were taken (Fig. 7), presenting a statistically significant positive correlation (p-value $<$ 0.01) according the PCCs analysis (PCC = 0.937, 0929, 0773 and 0.709 for 0.5 m, 1.5 m 3.0 m and 5.0 m respectively). Correlation is much more evident as depth decreases, being temperatures recorded at 0.5 and 1.5 m of depth and at 3.0 and 5.0 m of depth very similar, presenting statistically significant positive correlation between them (p-value $>$ 0.01) according to PCCs analysis (PCC = 0.993, 0.994 respectively).

Due to this behaviour, ground temperature reached its minimum values during January, standing out a minimum of 10.0 °C at 1.5 m depth, whereas maximum values were reached during August, reaching 29.7 °C at 0.5 m depth. Both at 0.5 m and 1.5 m ground temperatures were more extreme, with a variation between the maximum and minimum annual average temperature of almost 20.0 °C. Whereas at 3.0 m and especially at 5.0 m, the annual thermal oscillation has been lower, with 11.7 °C and 9.4 °C respectively. Another remarkable aspect about ground temperature was daily thermal amplitude, which had averaged 0.35 $\pm$ 0.17 °C for depths of 0.5 m and 1.5 m, whereas for depths of 3.0 m and 5.0 m the daily average thermal oscillation was 0.13 $\pm$ 0.07 °C and 0.11 $\pm$ 0.05 °C, respectively.

Several studies have shown that ground temperature fluctuations decrease rapidly with increasing depth and become negligible at 3–5 m depth [15]. Other studies showed that daily and annual variations in ground temperature do not penetrate deeper than 0.5 and 4.0 m respectively [20]. This behaviour is similar to that observed in our study, so the evolution of the temperature in the ground where the EAHE system has been located is the usual one.

Based on the temperature values recorded at the different depths analysed, two layers can be considered, one of them with a depth of about 2.0 m, whose temperature will be more influenced by the ambient

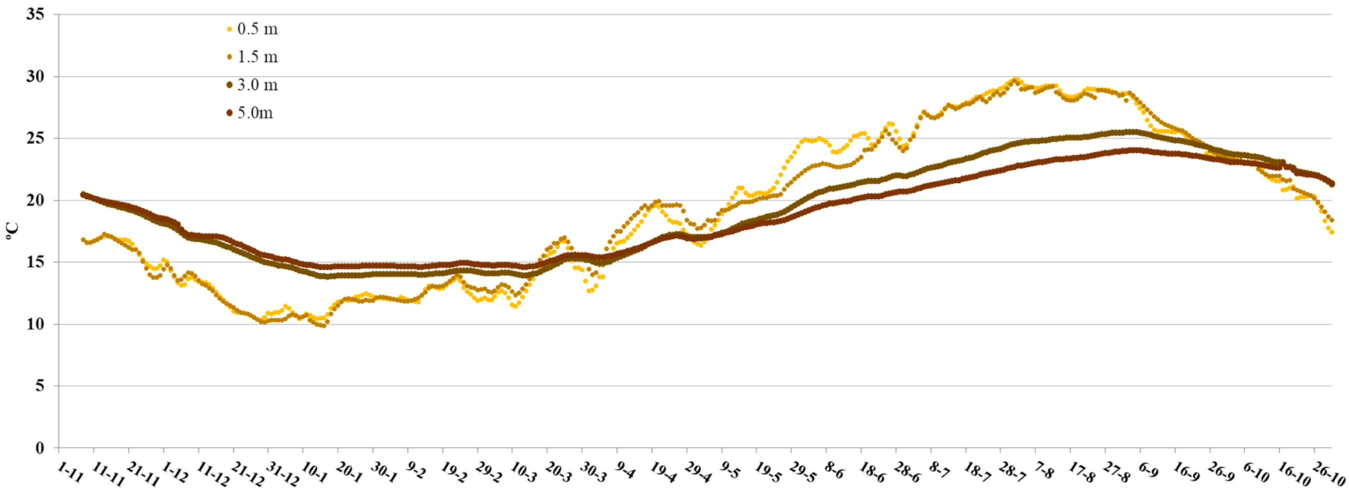

Fig. 7. Ground temperature evolution at four different depths.

air temperature, and another that would reach 5.0 m of depth, less influenced, but which is still affected by the ambient temperature according to the PCCs analysis. This means that in the study area, the maximum depth monitored does not correspond to the EUT zone.

Bisoniya et al. [18] considered that EUT was reached at a depth of about 1.5–2.0 m in studies released in a particular locality of India. However, Bisoniya [13] indicates that the EUT can be estimated as the average value of the annual ambient air temperature, which has been 18.8 °C for the location of the WWTP, a slightly lower value than the annual average reached at the maximum depth analysed (18.9 °C). This indicates that in the studied area, the EUT is reached at a depth of >5.0 m, although it is close.

Ground is a complex system that consists of a subsurface layer, experiencing interactions with variable atmospheric conditions (solar radiation, rainfall, air temperature), and a deeper layer having no such interactions, so that the ground temperature becomes more stable with depth until reaching the EUT [17]. The thickness of different layers in ground, based on temperature, depends on the soil material type and its thermophysical properties such as thermal conductivity, thermal diffusivity, density, heat capacity [15,21]. Other properties such as ground moisture, the water table level and the nature of the materials are also relevant parameters that will influence the depth at which the EUT is reached [21].

The thermal conductivity of the soil is responsible for the surface temperature penetration inside the earth. Derbel and Kanoun [22] observed that ground temperature becomes more stable and less influenced by ambient temperature, as depth increases. According to, thermal soil properties their results reveal that the higher the soil conductivity the higher the temperature rise when the depth increases. In addition, the ground temperature is more stable at greater depth if thermal conductivity is higher. In our case, the EAHE system was covered with a filling material, using compacted gravel, a mixture of materials whose thermal conductivity is 0.95 W/ m K. Compared to other materials and soil types, the thermal conductivity of our soil can be considered medium-low [22,23] which will influence the penetration of heat from the soil surface to deeper layers. This implies that the influence of ambient temperature will be greater in the shallower layers and will decrease with increasing depth. The use of filler materials with a lower thermal conductivity would limit the effect of ambient temperature on ground temperature, thus allowing more stable and close values to the EUT at lower depths and vice versa.

Another aspect that has not been analysed in the study is ground moisture, which affects significantly ground thermal conductivity [14, 21]. In this sense, Lin et al., [10] observed that the performance of an EAHE system increased up to 40.0 % with saturated ground compared to dry ground, which is due to the greater thermal conductivity at a higher ground moisture [21]. However, the greater the thermal conductivity of soil, the greater the heat exchange with the ambient air, which can affect to ground temperature and thus, the effectiveness of the EAHE systems. Therefore, the effect of ground moisture on the effectiveness of EAHE systems applied to cool the air aspirated by the blowers of a WWTP, must be further analysed.

With the EAHE system at 1.5 m depth it has been possible to cool the air suctioned by the blowers of a WWTP. However, given the behaviour of ground temperature at depths larger than 1.5 m, locating the EAHE system at large depth would increase the cooling capacity, thus further decreasing the instantaneous work required by blowers. Wu et al. [24] evaluated the thermal performance of an EAHE system considering pipes located at 1.6 m and 3.2 m depth for cooling operations, obtaining a lower air temperature at a depth of 3.2 m, so that at a greater depth the heat exchange potential of EAHE system increases.

The comparison between ground temperature at different depths and ambient temperature (Fig. 8) shows that from May to August average ground temperature at any depth is lower than average ambient temperature. This will cool the air suctioned for blowers by passing it through the ground using an EAHE system, being more effective at larger depth [13]. The month with the greatest differences between ambient temperature and ground temperature was July, with average values of difference of 2.8 °C, 3.0 °C, 7.2 °C and 8.8 °C for depths of 1.0 m, 1.5 m, 3.0 m and 5.0 m respectively. This shows greatest efficiency when working at depths of up to 5.0 m. A similar circumstance is observed in August, although the differences vary between 1.5 °C and 2.0 °C lower, as well as in June, with differences between 1.0 °C and 3.0 °C lower. Since daily thermal amplitude has been minimal for all the depths analysed while for the ambient temperature it is considerable, the possibilities to cool the air suctioned by the blowers can also be extended to other months such as April, with average values varying between 0.7 °C and 1.6 °C. A similar situation happens in March and September (Fig. 8). The opposite is observed during autumn and winter months, when average ground temperatures are higher than average ambient temperature.

3.4. *Estimation of the aspirated air temperature through an EAHE system at different depth*

Bisoniya [13] described a formula for estimating the air outlet temperature after an EAHE system considering that, heat is released or absorbed by the air flows through the pipe by convection, and from the ground to pipe walls and vice versa by conduction. The water table in the area where the EAHE system is located is at 12.0–15.0 m depth, so it

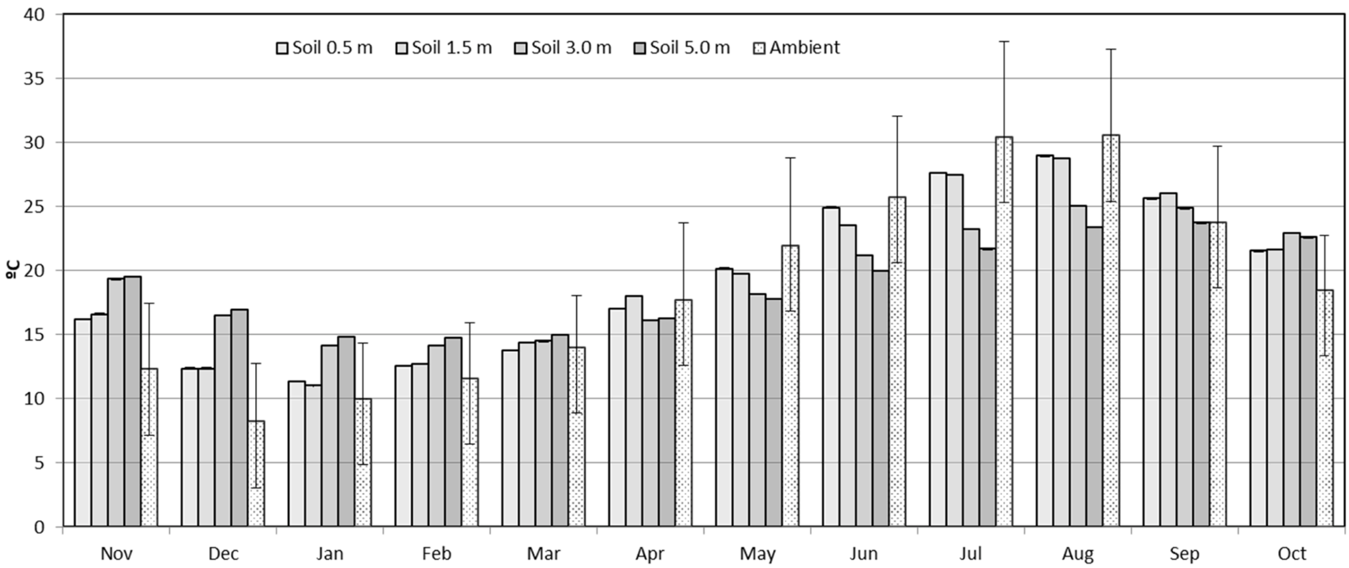

Fig. 8. Monthly average ground (four different depth) and ambient temperature. Bars represent thermal amplitude values.

does not interfere with the heat transfer phenomena between the ground and the EAHE system. Therefore, the model can be considered valid for the experimental system.

For the definition of the formula, it is assumed that the contact between the pipe walls and the ground is perfect and that the thermal conductivity of the ground is much higher compared to the surface resistance, so that wall pipe temperature (T_{wall}) is considered equal to ground temperature. Under these conditions the air temperature at outlet of an EAHE system (T_{out}) can be obtained by the following expression:

$$T_{out} = T_{wall} + (T_{in} - T_{wall}) x e^{-NTU}$$

The number of transfer units (*NTU*) is a dimensionless value defined as the number of transfer units, which corresponds to the following expression [11], where $-G_t L$ is the total thermal conduction of a given length (L) of heat exchanger, $\dot{m}$ is the mass flow rate of air (kg/s) and C_P is the specific heat of air (J/kg K).

$$NTU = \frac{-G_t L}{\dot{m} \times C_p}$$

$-G_t L$, (W/K) can be obtained according the following expression where it is considered the thermal resistance due to conduction mode of heat transfer for cylindrical disturbed soil thickness that surrounded the pipe, R_s (K/W), the thermal resistance due to conduction mode of heat transfer between the inner pipe wall and outer surface of wall surface, R_p (K/W) and the thermal resistance due to convection mode of heat transfer between circulating air and inner pipe wall surface, R_c (K/W) [11].

$$G_t L = \frac{1}{R_c + R_p + R_S}$$

To calculate the three necessary thermal resistances, it must be known the thermal conductivity of disturbed soil k_S (W/m K), the thermal conductivity of pipe material k_p (W/m K), the pipe outer radius r_0 (m), the pipe inner radius r_i (m), the radius of the outer surface of disturbed soil r_s (m) with is considered equal to the radius of pipe, the length of the pipe (m) and the convective heat transfer coefficient between air and pipe wall h (W/m^2 K), according the following expressions [11]:

$$R_s = \frac{1}{2\pi L k_s} ln\frac{r_s}{r_0} \quad R_p = \frac{1}{2\pi L k_p} ln\frac{r_0}{r_i} \quad R_C = \frac{1}{2\pi r_i L h}$$

h will depend on the diameter of the pipe *D,* on the thermal conductivity of air *K* (W/ m K) and on Nusselt number *Nu*, defined for a turbulent flow in a pipe with smooth internal surface.

$$h = \frac{K \times N_u}{D}$$

The flow rate of aspirated air by the blowers is dependent on the oxygen requirements of the biological process and during the experimental period the average values have varied between 1293.6 m^3/h and 604.7 m^3/h. This causes variations in the turbulence inside the pipes, so that for the first sections the Reynolds number ranged between 1.2×10^4 and 3.0×10^4, while in the final section it ranged between 4.9×10^4 and 1.2×10^5. The Prandtl number was more stable, and ranged between 0.67 and 0.73. Given that the EAHE system has been built with PE pipe with a smooth internal surface, the formulas described by Bisoniya [13] and based in the correlation of "*Nu*" given by De Paepe and Janssens [25] are applicable for the system under analysis.

For the four 10.5 m long pipe sections, *NTU* values have ranged between 1.1 and 1.7, so according to De Paepe and Janssens [25], the effectiveness of the studied system varied between 64.0 and 81.0 %. However, for the 9.14 m long pipe section, *NTU* values have ranged between 0.08 and 0.15, with an effectiveness varying between 8.0 and 14.0 %. Under these operating conditions, the annual average temperature calculated after the EAHE system at 1.5 m depth was 19.2 ± 6.5 °C, whereas the real annual average value has been 17.9 ± 6.9 °C.

The modelled temperature values at the EAHE system outlet obtained with the simple model applied are more stable and slightly higher than the real values with the system located at 1.5 m depth (Fig. 9). The model is more accurate in periods when the EAHE system cools (spring-summer), with an average error of 3.9 ± 2.8 % while in periods when the average ground temperature is higher than the average ambient temperature, the model is less accurate. Sofyan et al. [15] used a commercial model to compare different types of EAHE systems applied for air cooling. Calibration of the model with experimental data also showed slightly higher values than real ones, albeit with an error around 1.0 %. The model used is more sophisticated, thus reducing the error between real and modelled data. Bisoniya [13] established several premises that allow the simplification of the model, highlighting that the temperature of the pipe wall is equal to ground temperature, assuming perfect soil-pipe contact. These premises lead to a greater error between the modelled and real values, despite which mathematical expressions offer an estimated value close to the real value, which is suitable for our purposes. Several researchers have developed more sophisticated

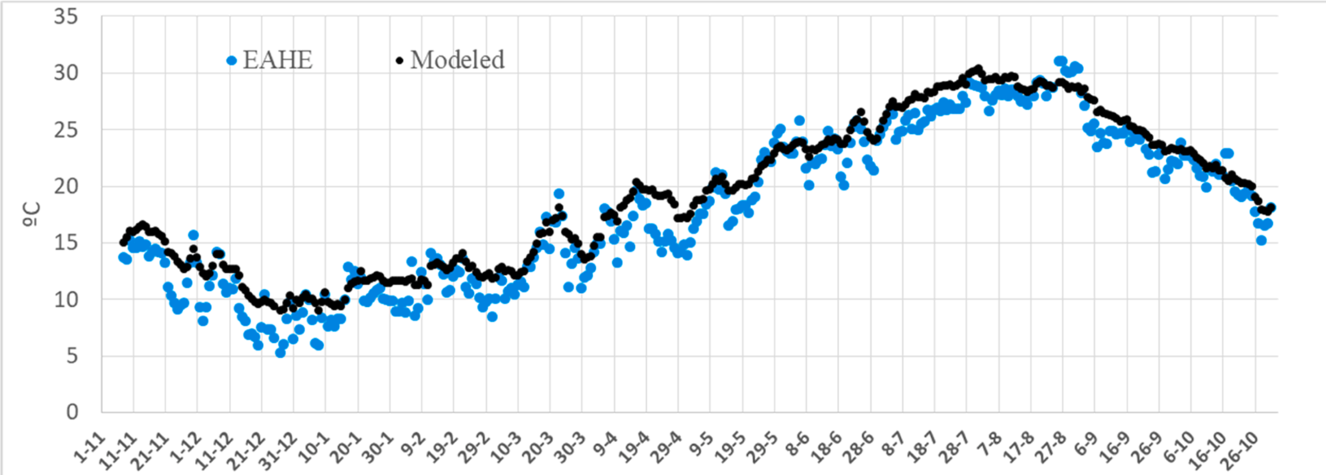

Fig. 9. Comparison of outlet air temperature values from the EAHE system modelled with the formulas described by Bisoniya (2015) and the values measured *in situ*.

models to define the behaviour of an EAHE system, using computational fluid dynamics or 3D physical models [26,27]. The use of these tools would reduce the margin of error and allow more precise control over the behaviour of the EAHE system applied in WWTP to cool the air supplied to the blowers, which could represent a substantial improvement in both the design and operation of this type of installation.

Based on the results obtained, assessing achievable temperature in the aspirated air by the blowers through the EAHE system is considered, in case of having used a larger depth for the location of the pipes, for which, as described above, lower and more stable temperatures have been recorded throughout the year. The calculation is also carried out considering the hypothetical EUT for the area where the study was carried out, according to the considerations of Bisoniya [13].

According to the estimation carried out as ground depth increases, a further decrease in temperature is achieved, as well as temperature stabilisation with milder maximums and higher minimums. At a depth of 1.5 m, the annual estimated average value of T_{out} is 19.2 ± 6.5 °C, with maximum temperatures of 30.4 °C and minimum temperatures of 9.1 °C (Fig. 9). If the system is located at a depth of 5.0 m, ground temperature decreases with an annual estimated average value of T_{out} being 18.9 ± 3.7 °C, with maximums of 24.5 °C and minimums of 13.3 °C and, if *EUT* is considered, annual estimated average value of T_{out} reached is 18.9 ± 1.9 °C, with maximums of 22.9 °C and minimums of 15.4 °C.

Based on the average values obtained by estimation, with EAHE system at a depth of 1.5 m air is cooled on 45.4 % of the days of the year, reaching up to a maximum of 2.0 % of instantaneous work decrease. With a depth of 5.0 m, cooling is reached on 48.5 % of the days, with an instantaneous work savings of up to a maximum of 4.7 %, whereas, if EAHE system is located at a depth in which EUT is reached, air will be cooled 50.0 % of the days of the year, with decreases of the instantaneous work up to a maximum of 6.1 % (Fig. 10). For all circumstances, the months from May to August are the most suitable for air suction through the EAHE system, where an average saving in instantaneous work can be achieved ranging from 0.5 % to 0.8 % for a depth of 1.5 m,

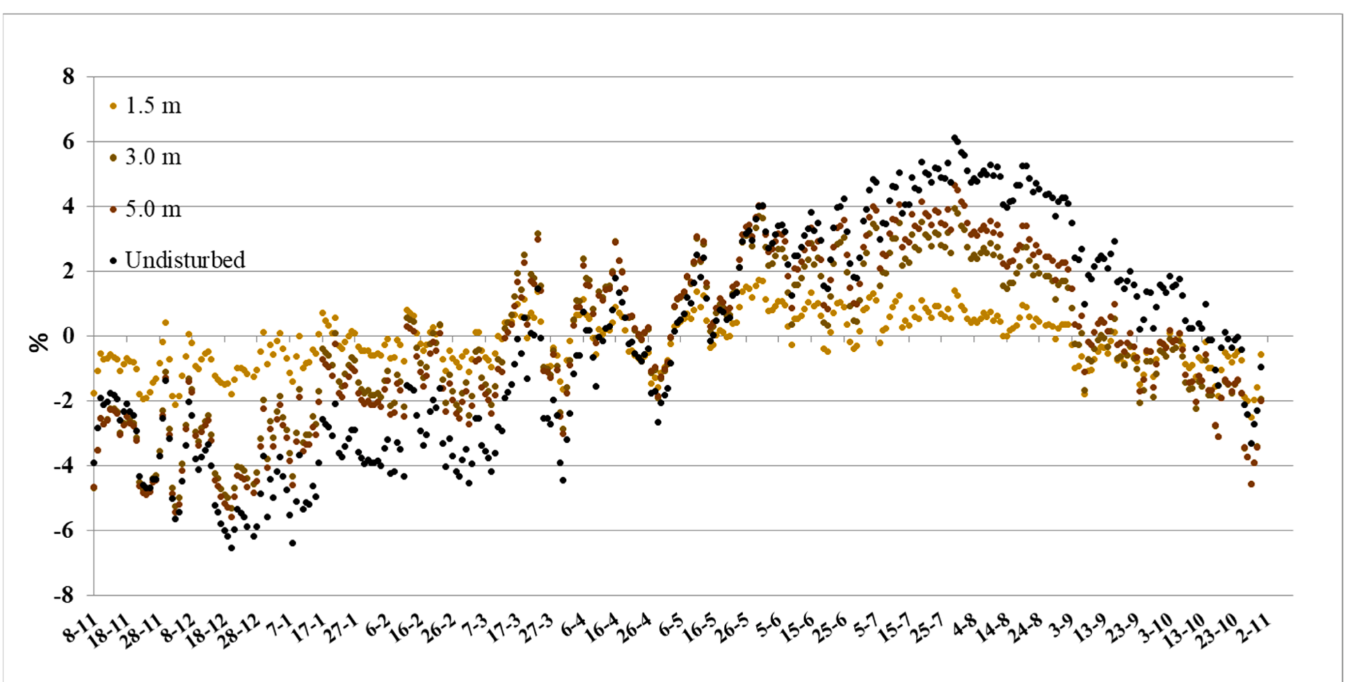

Fig. 10. Clculated percentage of daily variations in the instantaneous work in air suction by the blowers depending on the outlet air temperature values from the EAHE system modelled in function of installation depth.

increasing to values between 1.8 % to 3.5 % if the depth used is 5.0 m. In addition, the increased depth at the location of the pipes would allow the application of the system during April and September (Fig. 10).

If the estimated temperature values are compared with the real ones, with the EAHE system located at a depth of 1.5 m (Section 3.2), it can be seen that for the real values the number of days in which the temperature decrease is higher, which could also be extended to the rest of the depths analysed. These results show that it is possible to increase the period of the year in which the application of the EAHE system allows the suctioned air to be cooled, while at the same time increasing energy savings. Under these circumstances, EAHE system is a better option than air suction through the cold room.

3.5. Defining the most influential variables on the effectiveness of the EAHE system

EAHE system functioning will depend on different variables, notably its dimensions and characteristics. Dimensions are defined by r_i, the length of the pipe (L) and the number of parallel segments of pipe. The characteristics are defined by the thickness of the pipe (r_o-r_i) and k_p. With respect to soil, the main variables considered have been T_{wall}, mainly defined by the depth where the EAHE system is located, and k_s. These variables will be fixed once the EAHE system is builded, remaining $\dot{m}$ as the only modificable variable, which will depend on air flow rate of air supplied to the system (Q_{air}) and air density, which will be influenced by the ambient temperature (T_{in}) and relative humidity.

To define the degree of importance of the different variables on parameters such as NTU, the effectiveness of the EAHE system (ε) as defined by Bisoniya [13], T_{out} or the difference between T_{in} and T_{out}, have been assigned values based on the operating characteristics recorded during the study period, for the time at which the system is able to cool effectively. Other variables such as the number of parallel segments of pipe, k_p, r_o-r_i and k_s have not been modified during the study, so values consistent with the type of installation and materials usually applied have been assigned to them.

Once values of the variables were defined, PCCs were used to assess the existence of statistical correlations (Table 1), in order to select the most influential variables and parameters. Through the analysis, a statistically significant correlation between EAHE dimensions and all parameters analysed is observed, with L being particularly noteworthy. The higher the value of L, NTU, ε and T_{in} - T_{out} increase, whereas T_{out} decreases, being inverse for r_i and r_o-r_i.

The number of parallel segments of pipe has proven to be the most influential variable in the system, showing statistically significant correlation (p-value< 0.01) with all the analyzed parameters. k_p and k_s have also proven to be influential variables in the system, with a particular impact on NUT and ε. T_{wall} and T_{in}, show a positive statistically significant correlation with T_{out} and therefore inversely proportional to T_{in} - T_{out}. Q_{air} shows statistically significant correlation with all the parameter studied, standing out the negative correlation with NTU and ε, whereas relative humidity is not a significant influential variable.

An RDA was performed to evaluate the influence of the main EAHE variables on the NTU, ε and aspirated air temperature. The model represented 79.2 % of the variance on the first axis and 99.9 % of the cumulative variance on the second axis. All analysed variables presented p-values lower than 0.002. The RDAs results are represented on a diplot diagram (Fig. 11).

RDA shows that the most influential variable is the number of parallel segments of pipe, and as reflected in PCCs it has a directly proportional effect on NTU and ε, which results in a significant decrease of T_{out} when increasing the number of segments of pipe. This variable is related to L, the third most significant variable according to RDA, which shows the same statistical behaviour. Both variables have been analysed separately to assess the influence of each one on heat transfer and its greater or lesser importance. Computational fluid dynamic simulation studies applied to EAHE system reveal that the decrease of air temperature is directly proportional to increasing pipe length [15,26]. Obviously, the longer the pipe the bigger surface of contact for heat exchange with ground. Now, the increase in the length of the pipe can be achieved in two ways, by selecting a long tube or by increasing the number of

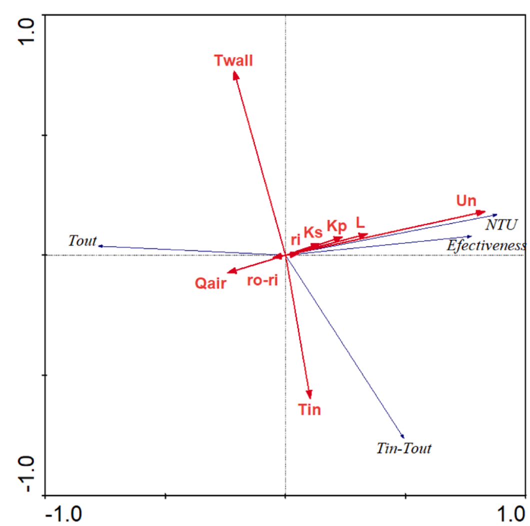

Fig. 11. RDA ordination diagrams (diplots) showing the relation between the main EAHE system variables and the effectiveness of the system, T_{out} and the difference between T_{in} and T_{out}.

Table 1
Pearson correlation coefficient between main process variables and EAHE system parameters.

	NTU	ε	T_{out} (ºC)	T_{in} - T_{out} (ºC)
Humidity (%)	-0.002	-0.002	0.001	-0.001
Q_{air} (m^3/L)	-0.184	-0.163	0.081	-0.109
r_i (m)	0.044	0.062	-0.030	0.041
r_o-r_i (m)	-0.044	-0.052	0.260	-0.035
L (m)	0.313	0.305	-0.151	0.205
Pipes segments units	0.713	0.774	-0.383	0.519
T_{wall} (ºC)	0.003	0.002	0.840	-0.508
T_{in} (ºC)	0.004	0.004	0.675	-0.023
k_s (W/m K)	0.143	0.107	-0.053	0.072
k_p (W/m K)	0.233	0.186	-0.092	0.125

Significant correlation with p-value < 0.01 Significant correlation with p-value < 0.05

parallel segments of pipe. In both circumstances, the contact surface area is increased, but increasing the number of segments which work in parallel also decreases the airflow velocity for the same operating air flow rate.

Another way to increase the contact surface area is to increase the pipe cross-section. In this regard, Sofyan et al. [15], working with computational fluid dynamic simulation, observed that the increase of r_i was directly proportional to the decrease in T_{out}, although it did not decrease significantly. However, Ahman and Prakash [26], working too with computational fluid dynamic simulation studies, observed that the temperature drop in the large r_i is less than in the smaller ones. Our results show a very similar r_i to that observed by Sofyan et al. [15], showing itself according to the multivariable analysis (Fig. 10) as a variable with little influence on *NTU* and ε. Ahman and Prakash analysis [26] considers three different r_i, maintaining air velocity, which implies that Q_{air} increases if r_i increase, which reduces convective heat transfer. The increase in Q_{air}, leading to a reduction in the time air molecules spend flowing inside the pipe, prolongs the heat exchange process between the air and the pipe surface so insufficiently [27].

In our study, RDA shows that Q_{air} has an inversely proportional effect on *NTU* and ε, so an increase in Q_{air} implies an increase in T_{out}. Therefore, the effect that Q_{air} has on convective heat transfer implies that the number of parallel segments of pipe is the most influential variable of the EAHE system, since not only does it increase the surface area, but it also decreases Q_{air} while decrease the statistical significance of r_i, although it should not be disregarder.

Another important aspect when selecting the dimensions of the elements of an EAHE system located in a WWTP is the pressure drop in the aspiration of blowers. *L* has a linear influence on pressure drop and the r_i and Q_{air} has a combined effect on pressure drop, so that the increase of Q_{air} and decrease of r_i results in increase in pressure drop. The increase of pressure drop in the aspiration of blowers would limits the energy benefit obtained from lowering the captured air temperature, so it is crucial to select the appropriate dimensions of the EAHE system elements to achieve maximum heat transfer without excessively increasing pressure drop.

Q_{air} will depend on the aeration needs of the biological reactor and its mode of operation, and the maximum pipe length is needed to promote heat exchange. So, a longer pipe divided in several parallel segments is suitable to improve heat exchange and avoid an excessive pressure drop. Similar conclusions have been reached by Bisoniya [13], which proposes the use of several tubes to descend in length and air flow as a more suitable alternative. The selection of r_i will be more focused on avoiding high pressure drop given its lesser influence on heat exchange.

With respect to the characteristics of the pipe, k_p show a similar statistical behavior to the number of parallel segments of pipe, *L* or r_i, although with low significance according to the multivariable analysis (Fig. 10). Nevertheless, the selection of a suitable pipe material is important to achieve a good performance. In our study, polyethylene pipe with a k_p of 0.38 W/m K was used, however most of the studies used PVC [11]. To compare, the use of PE for our EAHE system and under our operation conditions showed a ε value of 0.87, while if PVC ($k_p = 0.16$ W/m K) is used, ε is reduced to 0.76. The use of other plastic material such as high-density polyethylene ($k_p = 0.42$ W/m K) can increase ε to 0.88 and the use of metal pipe would significantly increase efficiency. However, when selecting the material of pipe, not only k_p is considered, but also other factors such as its effect on internal air friction, its mechanical strength, and especially its cost are important.

The thickness of the pipe is the variable with the least influence on the effectiveness of the EAHE system, according to the multivariable analysis (Fig. 10). Its effect is inversely related to that of the variables that define the system dimensions or k_p, so that greater thickness results in lower effectiveness. Under our operation conditions, a 10.0 % variation in pipe thickness results in a 0.7 % variation in effectiveness, hence its low significance. These results show that although the effect of pipe thickness should not be disregarded, its selection should be based on other criteria.

Soil thermal properties greatly influence the performance of EAHE system [28]. One of the properties to highlight, and which have been included in our model is k_s, which define the ground ability to conduct heat. The statistical analysis shows k_s as a variable with a directly proportional influence on effectiveness, with statistical significant differences (p-value < 0.01), although according to the multivariable analysis its influence on overall effectiveness is medium (Fig. 10).

The EAHE system was covered with compacted gravel with *ks* of 0.95 W/ m K obtaining, under our operation conditions, a ε value of 0.87. If k_s value is modified downwards, for example a value of 0.5 W/ m K is assigned, ε drops to 0.79, while if it is increased to a value of 2.0 W/ m K ε rises to 0.93. These variations in effectiveness based in k_s are significant and must be taken into account, mainly in a WWTP, since its characteristics allows the selection of the type of material used to cover the EAHE system.

Now, just as the positive effect of k_s on the effectiveness of an EAHE system is well known [23,28], so is the directly proportional effect that this variable has on the heat transferred to the outer soil layer [23].

Another aspect to consider in an EAHE system regarding k_s is that air temperature inside the pipe is affected not only by k_s but also by the time duration of continuous operation. Due to continuous dissipation of heat from the air inside the pipe to the soil, the drop in air temperature obtained in an EAHE system is affected by time duration for which the system is put into use, mainly with longer period of continuous operation. This happens since continuous heat dissipation for longer periods from air inside the pipe to soil results into higher soil temperature. So, the cooling potential of EAHE system gets deteriorated during continuous running of the EAHE system mainly due to derating of subsoil and the EAHE pipe under identical flow and climatic conditions [23]. This influence of the operating time is of great importance in EAHE system located in WWTP which operate continuously for 24 h, at least during the period in which the system is effective in cooling the air (spring-summer).

The effect of operating time on the cooling potential of EAHE system will be conditioned by *ks* [23]. Penetration of heat from EAHE system pipe to adjacent soil layers is much faster for soil with higher k_s. Substantial amount of heat transferred from air inside the pipe to the soil is effectively penetrated in the subsequent soil layer and therefore lesser rise in soil temperature will be observed for soil layers in the immediate vicinity of the pipe surface for soil with higher k_s. So, maximum deterioration in the thermal performance of EAHE system during continuous operation is observed for soil of least k_s.

In our experiments, the EAHE system was covered with compacted gravel with *ks* of 0.95 W/ m K, a value which can be considered medium-low according the values of other types of materials [22,23]. So, thermal saturation with performance degradation can be expected after a certain period of continuous operation. However, the air thermal amplitude of temperature during periods of higher temperatures (summer) exhibits the greatest values (Fig. 2) with temperature generally dropping at night and minimums around dawn. This circumstance makes the EAHE system ineffective at cooling the air during the night, which would limit its daily operating hours (Fig. 8), a period in which the cooling capacity of the system could be recovered (Fig. 5).

T_{in} has a directly proportional and statistically significant effect on T_{in} - T_{out} and according to the PCC analysis it presents a positive statistically significant effect on T_{out}. However the multivariable analysis its effect on T_{out} is limits, due to the influence of other variables. This variable cannot be controlled and defines whether or not the use of the EAHE system is appropriate.

An EAHE system mounted in a soil with higher k_s gives better thermal performance even after prolonged continuous operation, due to rapid dissipation of heat from the soil layers located in the immediate vicinity of the EAHE pipe to the soil layers located away from the soil pipe interface in the radial direction [23]. This increases the relevance of k_s when building a new EAHE system in WWTP, making it more than appropriate to use for filling and covering the system materials with high k_s.

The moisture content of soil greatly affects its k_s [14,21]. The voids in the soil get filled with water, which subsequently increase the bridging between the soil particles thus, improving k_s. In this sense, in an unsaturated ground, the thermal efficiency improved with infiltration of rain water. This is of little use in a semi-arid area with an annual pluviometry of 400 mm and with significant rain events on only 16.0 % of the days of the year, infrequent in the period of time in which the EAHE system is most useful. However, water is abundant in WWTPs, some of which, properly treated, can be applied to increase soil moisture in the area where the EAHE system is located. This would increase the effectiveness of the EAHE system and mitigate performance degradation by thermal saturation, regardless of the soil thermal properties. This application requires further analysis, also assessing the effect it would have on the evolution of ground temperature with depth.

According to multivariable analysis T_{wall} was the second most influential variable which indirectly affect to T_{in} - T_{out} and according to the PCC analysis it presents a positive statistically significant effect on T_{out}. Therefore, it is suitable to locate EAHE system as deep as possible, to approach the *EUT* and that the air presents a long journey through the EAHE system.

4. Conclusions

To reduce energy consumption of the blowers used in the extended aeration activated sludge WWTP, aspirated air temperature is decreased as a result of using a cold room or a full-scale EAHE system, located at a depth of 1.5 m.

Both forms of collection have proven to be effective in cooling the air. The EAHE system stands out for the period of higher ambient temperature, as it can decrease the aspirated air temperature an average of 4 °C, with point values up to 6 °C. With the EAHE system located at a depth of 1.5 m, instantaneous work of the blowers is decreased 63.0 % of the days of the year, with average decreases up to 2.0 % and maximum of up to 4.0 %. By collection through the cold room instantaneous work of the blowers is decreased 39.8 % of the days of the year, with average decreases up to 1.2 % and maximum of up to 3.3 %. Both systems are effective during the central hours of the day, with a wider range of hours for the EAHE system, and are ineffective during the early morning hours. During most of the year, except summer, the cold room suction is more effective against peak temperatures.

According to the statistical analysis carried out, among all the variables in the EAHE system, T_{wall} and L are the most decisive, being convenient the use of several pipe segments to improve heat exchange while avoiding excessive pressure loss in the air aspiration. In addition, to ensure maximum air cooling, the location of the pipes that form the EAHE system should be located at a depth where the EUT is reached. Soil material round the EAHE system with high k_s is essential to achieve both a high heat transfer and avoid temporal performance degradation by thermal saturation of the ground. The selection of a pipe material with high k_p and low thickness helps to achieve a good performance.

CRediT authorship contribution statement

V. Morillas: Writing – original draft, Investigation, Formal analysis. **A. Monteoliva-García:** Methodology, Investigation, Formal analysis, Data curation. **J.I. Pérez:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **M.A. Gómez:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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