Earth-Air Heat Exchangers (EAHE): Energetic Exergetic Analysis

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Abstract - EAHE is an air-soil exchanger buried under the ground that permits the use of shallow ground temperatures to decrease building's heating and cooling demands. Exergy analysis, which results from combining both the first and second law of thermodynamics, helps to analyze the performance of the EAHE at its reversible limit and to estimate the departure from this limit. An exergetic analysis will be carried out on the experimental EAHE installed at Illkirch-Graffenstaden campus of University of Strasbourg. The objective is to assess the system and identify the parts that dissipates energy the most to optimize the system. The experimental EAHE and the measurements taken are presented in the analysis and finally the derived results are analyzed.

Nomenclature

Cp	specific heat capacity $\left(J/_{kgK}\right)$
COP	coefficient of performance
D	diameter (m)
$\dot{E}x$	exergy rate (W)
h	specific enthalpy $\left(J/_{kg}\right)$
L	length (m)
$\dot{m}$	mass flow rate $\left(kg/_{s}\right)$
P	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
R	gas constant $\left(J/_{kgK}\right)$
T	temperature (K)
U	velocity $(m/_{s})$
$\dot{W}$	work rate (W)
η	efficiency
λ	thermal conductivity $(W/_{mK})$
ρ	density $\left(kg/_{m^3}\right)$
ψ	specific flow exergy $\left(J/_{kg}\right)$
ω	humidity ratio $\left(kg_{vapor}/_{kg_{dry\ air}}\right)$

Subscripts

a	air
av	average
d	destroyed
ex	exergetic
in	inner
i	inlet
mec	mechanical
n	referring to any location
o	outlet
sat	saturation
tot	total
v	vapor
w	wall
0	reference value

1. Introduction

To facilitate the energy transition, it is necessary to develop sustainable energy technologies. The Earth Air Heat Exchanger (EAHE) is such technology, which can reduce energy consumption of a building significantly by decreasing buildings heating and cooling demands. EAHE is an air-soil exchanger composed of a pipe buried under the ground and a fan deriving the air inside it. EAHE permits the use of shallow ground temperatures by heat exchange between the air and the soil surrounding the pipe. Where during winter shallow ground temperatures are higher than ambient temperatures and the opposite is true during summer which can preheat or precool the air before entering the building.

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As an energy system, EAHE requires energy analysis to size the system according to the needs and surrounding conditions. Also, using energy analysis the performance of the system can be determined by calculating the Coefficient Of Performance (COP). On another side, EAHE is also governed by the second law of thermodynamics which impacts the performance of the system. By combining the second law with the energy analysis, exergy equation results. Exergy is defined as the maximum amount of work that can be produced by a stream or system as it is brought into equilibrium with a reference environment. Exergy analysis can be used to analyze the system at the reversible limit and to identify the sources of irreversibility in the system by determining the exergy destroyed in each component of the system. Finally, the exergetic efficiency can be determined to give a more realistic assessment of the capabilities of the system than using normal energy efficiency.

Exergy analysis methods have been applied by different authors in scientific literature [1, 2, 3, 4, 5, 6, 7]. In some of these articles, the exergy analysis was not applied to EAHE while in others, the analysis did not consider all the parameters affecting the results. Some of them didn’t consider the effect of pressure variation inside the pipe and others considered constant soil temperature along the pipe when calculating exergy of heat transfer. To the best of the authors knowledge, none of these studies considers temperature, pressure, humidity and the control volume boundary temperature variations at the same time.

In the present study, energy and exergy analyses were applied to an experimental EAHE at ICUBE University of Strasbourg, France. The aim was to determine the performance of the system from both perceptions using pressure, humidity and temperature measurements and considering variable control volume boundary temperature when calculating exergy of heat transfer. Irreversibility sources in the EAHE were identified for possible enhancement of the system.

2. Experimental Setup

The experimental EAHE is located at IUT Robert Schuman, University of Strasbourg, Illkirch, France (48° 31' 50.1" N, 7° 44' 17.4" E). The system is composed of a polyethylene pipe buried under the ground up to a depth of 1.2 m with a total length of 29 m ranging from a depth of 0.73 m to 1.2 m. The air is circulated in the pipe using a fan installed at the outlet, and at the inlet, an air filter is added to trap dust. At the exit, the pipe has a vertical part again to drive air to the surface. From now on, “pipe” is referred to the horizontal part. The characteristics of the pipe used are given in Table 1.

Horizontally, the EAHE pipe was divided into three sections where each section is coated by a different type of coating soils; (1) sand, (2) sand-bent: a mix between sand and bentonite (3%), and (3) initial natural earth soil. More details about the study of the effect of using different coating soils, can be found in the articles published by Cuny et al. [8, 9, 10] as this is not the scope of this paper.

Parameter	*Total length*	*Outer diameter*	*Inner diameter*	*Thermal conductivity*
Symbol	L_{tot}	D_{out}	D_{in}	λ_{pipe}
Values	29	0.20	0.17	0.50
Unit	m	m	m	$W.m^{-1}.K^{-1}$

Table 1: *Pipe characteristics.*

Each section of the EAHE is associated with a vertical cross-section at its middle in which soil moisture and temperatures at different points are measured. The location of each sensor in the cross-section is represented in the scheme presented in Figure 1. In addition, temperature and relative humidity of air were measured after the filter at the inlet and before the fan at the outlet of the pipe. Velocity and differential pressure of air flow were also measured at different locations in the pipe. The velocity at the inlet of the pipe was measured as being $U_{air} = 2.4\ m/s$. Measured and deduced values of the pressure are shown in Table 2.

Location	*Inlet*	*After filter*	*Before fan*	*After fan (outlet)*
Differential pressure (Pa)	-0.07	-0.34	-0.67	-0.08
Absolute pressure (Pa)	102152	102126	102093	102152

Table 2. *Pressure measurements.*

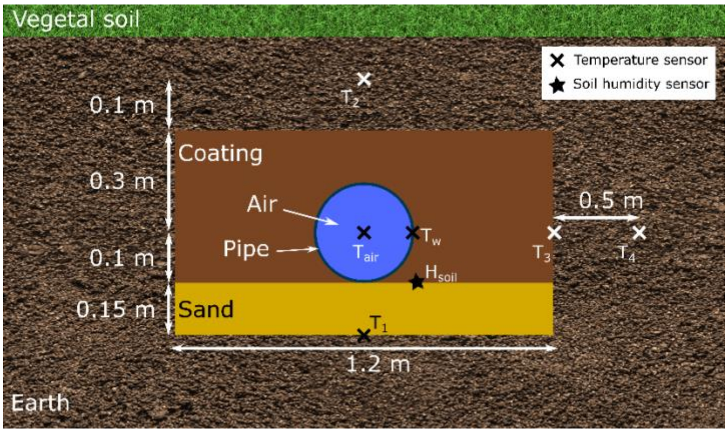

Figure 1: *System layers and positions of sensors.*

3. Analysis methods

3.1. Energy Calculation

Considering the whole of the air in the pipe as the control volume, the energy balance for the pipe alone becomes;

$$\dot{Q} + \dot{m}(h_i - h_o) = 0 \tag{1}$$

The enthalpy of the inlet and exit air were calculated depending on the temperature and humidity ratio. The mass flow rate $\dot{m}$ is considered constant and calculated as follows;

$$\dot{m} = \rho_{air}(T_{av}) \cdot \pi \left(\frac{D_{in}}{2}\right)^2 \cdot U_{air} \tag{2}$$

Where $\rho_{air}(T_{av})$ is the density of dry air at an average temperature, T_{av}, which is calculated by finding the average value between inlet and outlet temperatures at each timestep during the period studied, and then averaging that value over time.

3.2. Exergy Calculation

The general exergy equation states that the net exergy rate transfer by heat, work and mass, balances the net rate of exergy destroyed in the system;

$$\dot{E}x_i - \dot{E}x_o = \dot{E}x_{d,EAHE} \tag{3}$$

Considering the same control volume as for the energy equation, and substituting each exergy rate term by its corresponding formula, (3) becomes;

$$\left(1 - \frac{T_0}{T_w}\right)\dot{Q} + \dot{W}_{mec} + \dot{m}\psi_i - \dot{m}\psi_o = \dot{E}x_{d,EAHE} \tag{4}$$

Where T_0 is the reference temperature, which is the temperature of the environment chosen, and T_w is the tube wall temperature which is calculated as a function average of the three wall temperature measurements recorded along the tube. $\dot{W}_{mec}$ is the mechanical power delivered by the fan. ψ_i and ψ_o are the specific flow exergies which are determined using the humid air flow exergy formulated by Dincer and Sahin [11];

$$\psi_n = \left(C_{p,a} + \omega_n \cdot C_{p,v}\right)(T_n - T_0) - T_0 \cdot \left(C_{p,a} + \omega_n \cdot C_{p,v}\right) \cdot ln\left(\frac{T_n}{T_0}\right) + T_0 \cdot (R_a + \omega_n \cdot R_v) \cdot ln\left(\frac{P_n}{P_0}\right) + T_0 \cdot (R_a + \omega_n \cdot R_v) \cdot ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega_n}\right) + T_0 \cdot 1.6078 \cdot \omega_n \cdot R_a \cdot ln\left(\frac{\omega_n}{\omega_0}\right) \tag{5}$$

Such that n is any point along the flow, T_0, P_0 and ω_0 are the reference values of the temperature, pressure and humidity ratios respectively.

3.3. Restricted Dead State

Exergy is evaluated according to a reference state (dead state) which is usually the environment around the system which interacts with it but does not change its intensive properties upon this interaction. In the case of the EAHE it is sufficient to consider a restricted dead state as the chemical interactions between the system and the environment are not considered. The restricted dead state in this case is the surrounding ambient air. As the temperature, pressure and humidity of the ambient air are variable, an average values of temperature and humidity ratio of the month (or two months if period considered is in between), in which the analysis is carried out, are considered as reference values (T_0, ω_0) of the restricted dead state. The reference pressure (P_0) was taken as the standard sea level atmospheric pressure 101325 Pa. The restricted dead state was similarly defined in other studies [4, 12].

3.4. Performance Assessment

From energetic point of view, the performance can be assessed by determining the Coefficient of Performance (COP) which is the heat gained/lost by the system divided by the total consumed power;

$$COP = \frac{|\dot{Q}|}{\dot{W}_{mec}} \tag{6}$$

While from an exergetic point of view, the exergetic efficiency is calculated which shows the performance of the system according to its capabilities. The exergetic efficiency of the whole EAHE system is given by;

$$\eta_{ex} = \frac{\dot{E}x_o}{\dot{E}x_i} = 1 - \frac{\dot{E}x_{d,EAHE}}{\dot{E}x_i} \tag{7}$$

$\dot{E}x_{d,EAHE}$ is calculated from (4) and $\dot{E}x_i$ depends on the situation where it includes $\dot{E}x_{mass,i}$ in all situations, $\dot{E}x_{heat}$ only in heating case and $\dot{W}_{mec}$ if the fan acts on the control volume.

4. Results

4.1. Temperature and Heat Transfer

Figure 2 shows the temperature measured at the inlet and outlet of the pipe during the cooling period in the hottest week of 2018 (1^{st} to 8^{th} of August). The graph shows how the air is cooled inside the pipe during hot days where it shows the temperature decrease between the inlet and the outlet where the difference reached around 11 °C on some days. The variation of the inlet and outlet temperatures also shows how the EAHE stabilizes air temperature variations which is strongly required when cooling a building. Most of the nights, the ambient temperature drops to a value below the temperature of the soil at the depth of the EAHE, in this case, the EAHE is by-passed and the analysis of the data is only considered when the system is cooling the air.

The heat transfer calculated using equation (1) is shown in Figure 3. The figure shows the variation of heat released by the air as it passes through the pipe. The absolute value, $|\dot{Q}|$, increases during the day until it reaches a maximum at noon and then starts to decrease as ambient air temperature decreases during the day. Obviously, the absolute value of the heat rate, $|\dot{Q}|$, is higher when the inlet air temperature is higher as that increases the temperature difference between inlet and outlet air flows. During the chosen week, the maximum value of $|\dot{Q}|$ is about 1188W reached on 4th of August. Totally, the EAHE provided about 65 kWh of heat energy during the studied period.

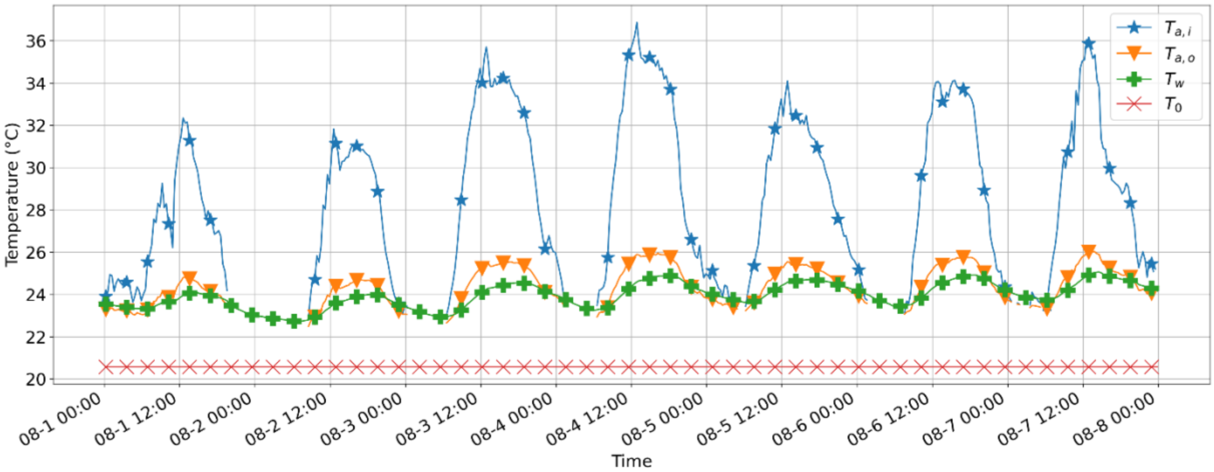

Figure 2: *Measured temperatures (°C) at the inlet and outlet of the pipe compared to the estimated reference temperature during hottest week of 2018 (1st to 7th of August).*

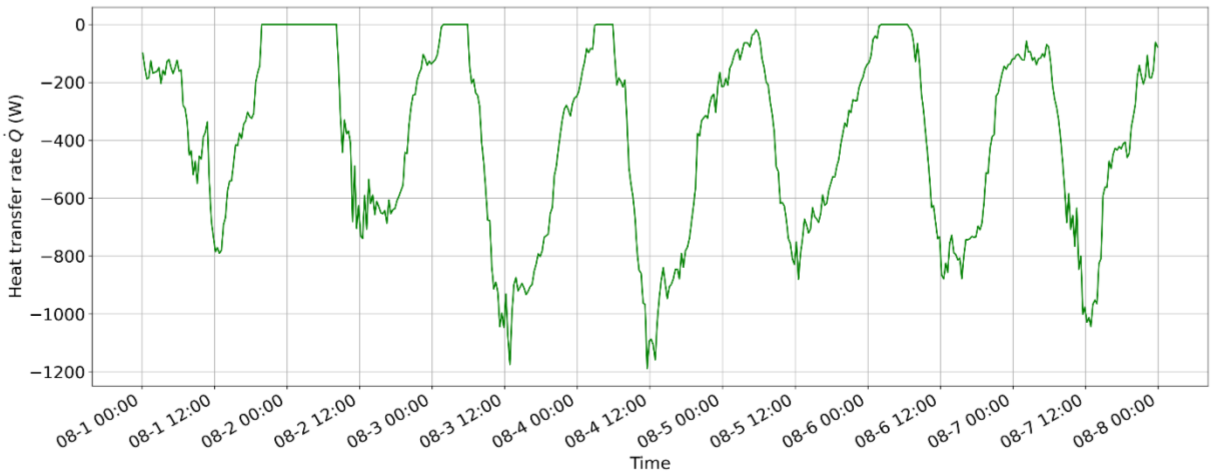

Figure 3: *Heat transfer rate gained by the air as passing in the pipe in between the filter and the pipe during the analysis period.*

4.2. Exergy Rates

Figure 4 shows the variation of exergy rates entering and exiting the whole EAHE system. The specific exergy rates are multiplied by the mass flow rate to obtain the mass flow exergy values shown in the figure. The graph shows that the exergy rate of the air flow decreases as it crosses the EAHE due to its cooling. Cooling effect is also shown by the negative values of exergy rate of heat transfer where its absolute value variation is proportional to the difference between inlet and outlet air temperature variation. It is noticed also that the exergy destruction rate is proportional to this temperature difference. The exergy rate of the work of the fan is not related to temperature and is the same as the value of that work rate so it is constant at $\dot{W}_{mec} = 31.2\ W$ all the time.

Figure 5 shows the share of exergy destruction between the filter, pipe and fan of the EAHE. Obviously, most of exergy is being destroyed at the level of the fan and the lowest destruction is at the level of the filter or for some durations in the pipe. Exergy destruction rate in the fan is almost constant because it is mainly dependent on the pressure difference of air between inlet and outlet of the fan which was assumed to be constant. Despite this pressure difference is also assumed constant between inlet and outlet of the filter, there is still a slight variation in the exergy destruction rate in the filter because it is also affected by the humidity ratio which was measured in ambient atmosphere and after the filter because the filter could trap some of that water content. Exergy destruction rate inside the pipe varies the most due to its dependence on exergy exchanged by the air flow which is mainly related to the temperature variations between inlet and outlet of the pipe.

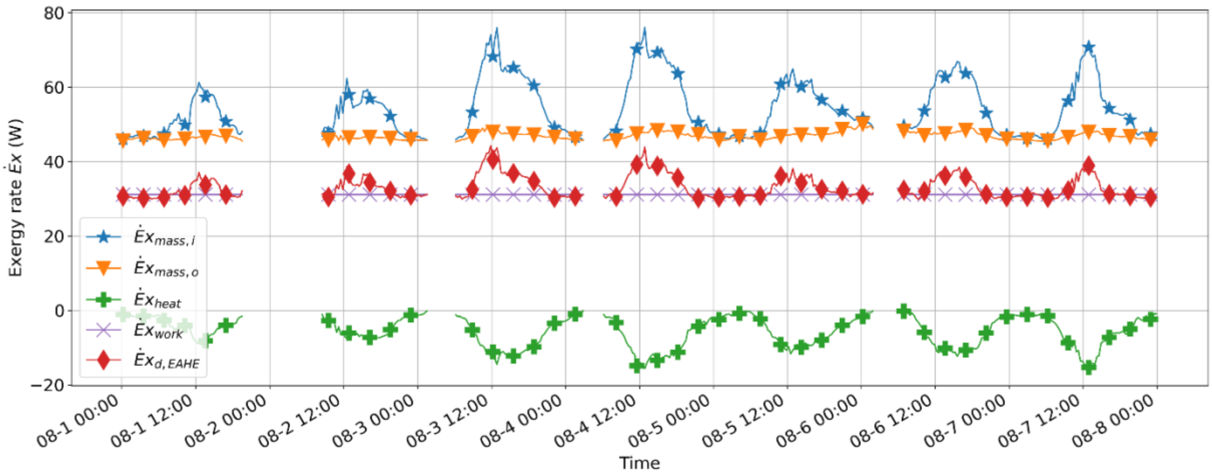

Figure 4: *Exergy rates transferred to or from the system during the analysis period.*

4.3. Performance Assessment

The Coefficient Of Performance (COP) of the system varies depending on the heat transfer rate variation which changes with ambient temperature. Figure *6* shows this variation where COP reaches a maximum value of about 38 which coincides with the highest heat rate recorded on the 4th of August at noon. The minimum value of COP is 0, reached when the inlet and outlet measured temperatures are equal on 4th of August after midnight. In general, COP increases during the day and reaches its maximum at noon as the ambient temperature sharply increases compared to soil temperature which barely changes during this duration. The opposite happens when the COP decreases and reaches its minimum during the rest of the day. COP variation is higher when day-night ambient temperature variation is higher.

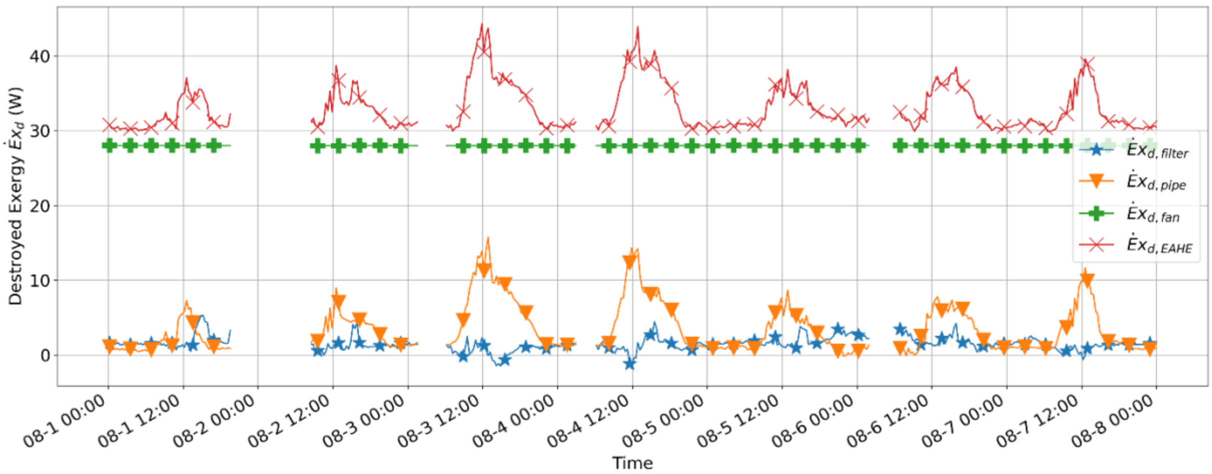

Figure 5: *Exergy destroyed in each component of the system during the analysis period.*

Figure *6* also shows the variation of the exergetic efficiency which was formulated in equation (*7*). The variation in exergetic efficiency is lower because it is more related to the variation of the inlet mass flow exergy rate and the destroyed exergy rate that are strongly related and thus compensate between one another resulting in a more stable outcome. The exergetic efficiency varies between around 57.5% and 63.8% which is about 61% on average.

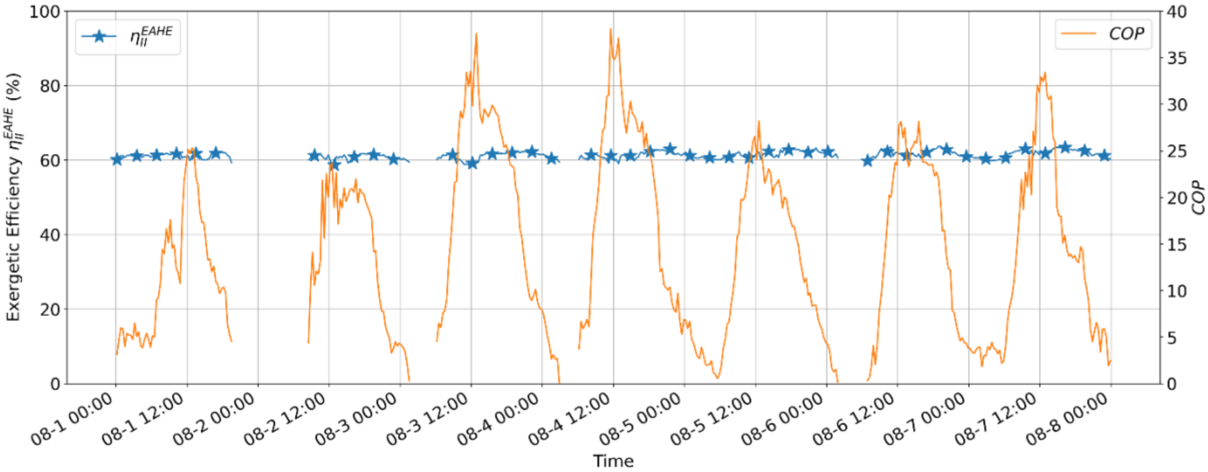

Figure 6: *Performance assessment of the EAHE showing the variation of the COP and the exergetic efficiency of the system during hottest week of 2018.*

5. Conclusion

Energetic and exergetic analyses were performed on an experimental EAHE site in the North-East of France to determine the efficiency of the system from both perceptions. The calculations were performed using pressure, humidity and temperature measurements and considering variable control volume boundary temperature when calculating exergy rate of heat transfer. The analyses were carried out during a cooling period of 2018.

Results showed that about 63 kWh of heat was removed from the air to cool it using around 4.4 kWh of electricity during the analysis period. The COP of the system depends mainly on the outside air temperature. Its variation is consequently very important: from 0 to 38. This energetic analysis confirmed that the system can decrease the cooling expenses using free geothermal energy by pre-cooling the air supplied to a building.

On the other hand, the total exergetic efficiency of the whole EAHE system is quite stable all along the analysis period. It varies between around 57.5% and 63.8% with an average of about 61%. By exergy destruction of different components, it was found that exergy is mostly destroyed in the fan while the lowest destruction was mainly in the filter. This resulted in lower exegetic efficiency in the fan than other components. Therefore, the fan should mainly be improved to lower the exergy destruction rate in the system and thus to increase the efficiency of the whole system.

Moreover, the exergy analysis showed that exergy is strongly related to the environment where the variations in temperature, humidity and pressure of air in the ambient environment strongly affect the values of heat and flow exergies and thus exergy destruction and exergetic efficiency. Therefore, the system performance is dependent on the weather in the location where it is being used and its profitability should be studied carefully in each location.

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