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The potential of Earth-to-Air Heat Exchangers for reducing energy demand in Spanish dwellings

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Abstract. An earth-air heat exchanger (EAHX), also known as Provençal well or Canadian well, is a system for cooling and heating buildings using the ground as a heat sink/source. This study is dealing with earth-air heat exchanger (EAHX) implementation for Spanish dwellings. The objective is to assess the potential of this solution for HVAC energy savings and greenhouse gas emissions reductions. A numerical study is conducted to assess the thermal behavior of EAHX using the transient simulation tool TRNSYS. The simulations are carried out for typical Spanish single family detached home, taken into account three different climate regions. Detailed results are presented concerning EAHX thermal behavior and its benefits in terms of energy savings and anti pollution effects for fresh air pre-heating and pre-cooling within mechanical ventilation system of the house.

Key words

Earth-air heat exchanger, TRNSYS simulation, energy saving, passive cooling/heating, geothermal heat sinks.

1. Introduction

The buildings sector – i.e. residential and commercial buildings - is the largest user of energy and CO2 emitter in the EU and is responsible for about 40% of the EU's total final energy consumption and CO2 emissions. The sector has significant untapped potential for cost-effective energy savings which, if realized, would mean that in 2020 the EU would consume 11% less final energy. This in turn translates to a number of benefits, such as reduced energy needs, reduced import dependency and impact on climate, reduced energy bills, an increase in jobs and the encouragement of local development.

Consequently, EU has made efforts to find out solutions for decreasing the amount of GES associated to energy use in order to slow down climatic changes and therefore to limit the global warming. In fact, the major European Union (EU) objective is to increase the energy efficiency by 20% and to reduce the GES by 20 % until the year 2020. In line with this, according to The Energy End-Use Efficiency and Energy Services Directive (ESD 2006/32/EC), Member States (MS) must achieve a minimum annual energy savings target of 9% by the ninth year in the period from 2008 to 2016.

On the other hand, recent years have seen a rise in the number of air-conditioning systems in southern European countries. This creates considerable problems at peak load times, increasing the cost of electricity and disrupting the energy balance in those countries. Priority should be given to strategies which enhance the thermal performance of buildings during the summer period. To this end there should be further development of passive cooling techniques, primarily those that improve indoor climatic conditions and the microclimate around buildings.

In this perspective, the use of geothermal heat exchangers for heating and/or cooling of buildings has experienced lately a growing interest, principally because of its simplicity and also because it lead to important energy savings concerning fresh air supply within ventilation systems of buildings during all the year. It is worthwhile to mention that for very low energy houses (which will become the standard for all new buildings across the EU by 31 December 2020 according to European Directive 2010/31/EU), the ventilation system is indispensable as these buildings are extremely well thermal insulated and air tightened.

Consequently, the central idea of this study is to fulfil methodical numerical investigation in order to quantify energy and GES emissions savings, achieved by using earth-air heat exchangers added to ventilation systems for Spanish conditions (climate and typical dwelling built up according to national regulations).

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2. Case study. Thermal loads

The house taken into account is characteristic for the new dwellings built up in Spain nowadays (single-family separate house). The building has ground floor and one level. The total habitable area and total volume are 120 m^2 and 300 m^3, respectively. All the dimensions, materials and characteristics of the thermal envelope used on the simulation are extracted from Spanish regulation CTE HE1 [1] and are described in table 1.

Table I. – Thermal envelope.

	Orientation	Surface [m^2]	U [W/m^{2}K]
Exterior walls	N	37,50	0,642
	S	37,50	0,642
	E	39,80	0,642
	W	39,80	0,642
Windows	N	10,00	3,21
	S	18,75	3,21
	E	10,00	3,21
	W	10,00	3,21
Roof	-	120,00	0,496
Floor	-	80,00	0,612
Interior ground	-	80,00	2,191
Interior wall	-	65,70	2,376

Internal loads taken into consideration within the simulations are according to common occupation of the dwelling (5 persons, 690 W from equipment and 5 W/m^2 from lighting). Temperature set point of 25ºC for summer and 21ºC in winter is taken from national HVAC regulation "Reglamento de Instalaciones Térmicas en Edificios" RITE [2]. The annual thermal load calculated is 13.157kWh (109,64kWh/m^2) distribuited as follows: 3.620kWh for heating and 9.537kWh for cooling.

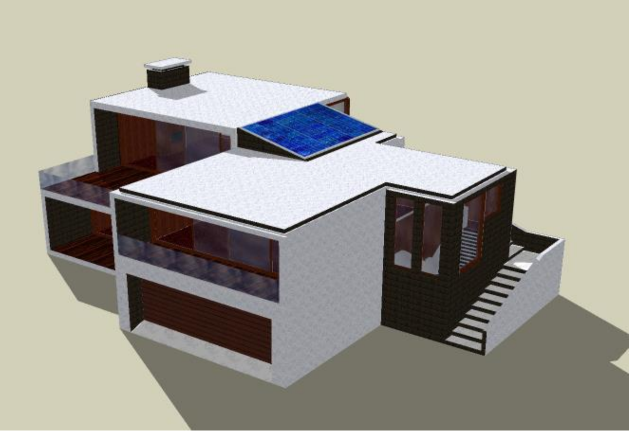


Fig. 1. Building considered. Designed by Ricardo Ribeiro.

The house described above has been considered located in Barcelona. The City is situated on the eastern coast of the Iberian Peninsula, so Atlantic west winds often arrive in Barcelona with low humidity, producing no rain. The proximity of the Atlantic, its latitude, and the relief, are the reasons why the summers are not as dry as in most other Mediterranean Basin locations. Barcelona and its metropolitan area has a Subtropical-Mediterranean climate (Köppen climate classification: Csa), with mild winters and warm summers. Its average annual temperature is 20 °C (68 °F) during the day and 11 °C (52 °F) at night.

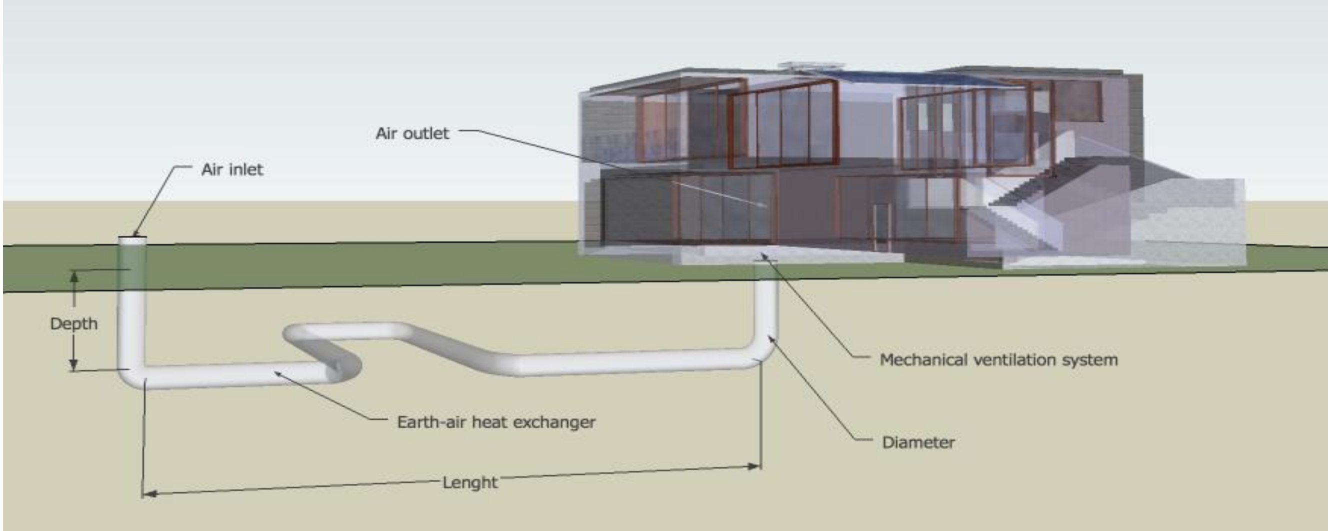


Fig. 2. Earth to air heat exchanger system coupled to the building.

3. EAHX system

The system functioning is based on outside air circulated through pipes buried in the ground (Fig. 2). The heat exchange takes place between the ground and the air inside the pipes: earth's average temperature at 2 meters depth is 17ºC all year round, while outside air temperature can range from 0.5-31ºC, if we refer to situations encountered in Spain. Their purpose is to provide some pre-conditioning of the air, either pre-heating in the winter or pre-cooling in the summer. Depending on working conditions (length, diameter, thermal conductivity and depth of the tube, air flow, soil characteristics, etc.), the air temperature difference within earth-air heat exchanger can reach 10-15ºC.

The fresh air flow rate of the house ventilation system is 165 m^3/h (meaning 0.54 renovations per hour). This is the minimum air flow value established in national regulation CTE HS3[1] in order to guarantee the indoor air quality. Pipe diameters taken into account during the simulations are 200 to 800 mm. Tubes mounting depth are 0.5 to 3.5m and the total lengths of the buried part of the system (the "active" heat transfer part) are 5 to 60 m (single pipe). These parameters have been chosen based on "rules of thumb" regarding the standard design of earth-air heat exchanger system for single-family houses up to 150 m^2 floor area. In fact, previous studies [3,4] showed that, for shorter circuits (25 to 40 m) the air temperature at the exit of the earth-air heat exchanger system does not approach the soil temperature, while bigger lengths do not lead to significant improvements of heat transfer.

Table II presents the main thermal properties of the earth–air heat exchanger pipe.

Table II. – EAHX characteristics.

Pipe thermal conductivity	0.12 W/mK
Pipe density	900kg/m^3
Fluid density	1.29 kg/m^3
Fluid specific heat	1000 J/kgK
Soil density	3200 kg/m^3
Soil thermal conductivity	2.5 W/mK
Soil specific heat	840 J/kgK

In fact, the thermal performance of earth-air heat exchangers can be theoretically appreciated by means of achieved heat transfer efficiency or "performance":

$$\eta = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{soil}} \qquad (1)$$

Where:
T_{inlet} is the inlet EAHX air temperature.
T_{outlet} is the outlet EAHX air temperature.
T_{soil} is the soil temperature.

It is worthwhile to mention that higher efficiency takes place in the summer. Moreover, the air is also dehumidified in the summer due to condensation that occurs on the inner surface of pipes. This helps also to improve thermal comfort and energy savings for air treatment in summer.

4. Dynamic simulation of the system behaviour

Numerical simulations were carried out using TRNSYS software [5]. TRNSYS is a modular simulation environment for the study transient low and renewable energy system.

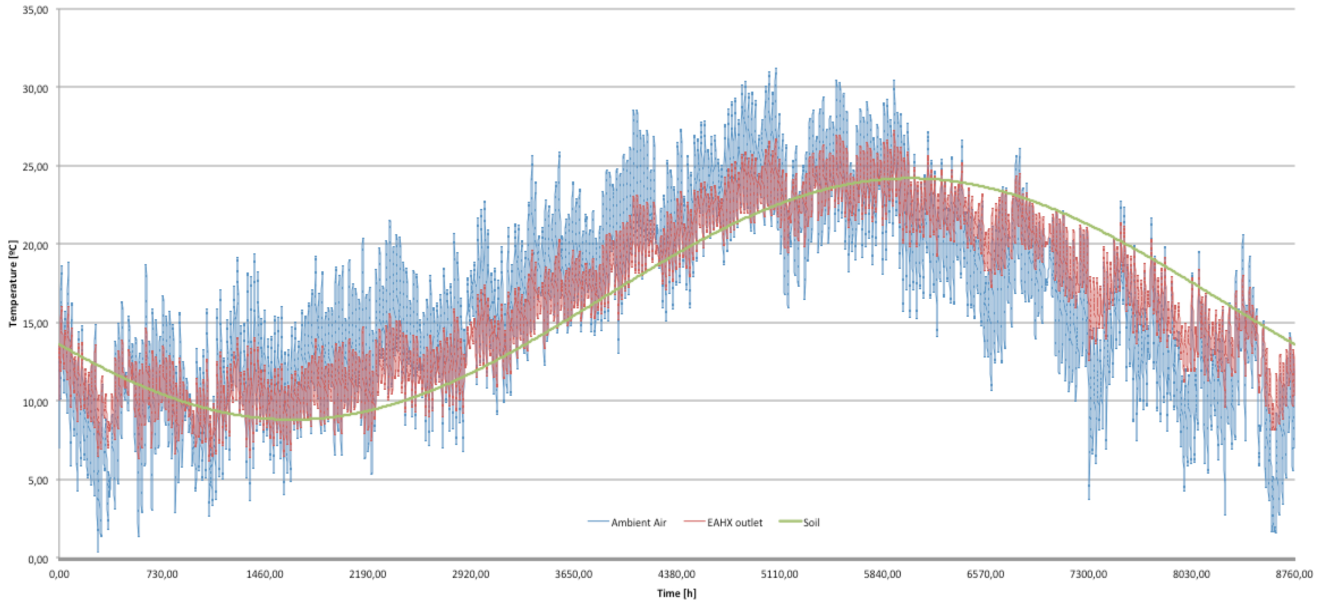


Fig. 3. Inlet air, outlet air and soil temperature obtained (pipe ∅400mm, pipe depth 2m, pipe length 40m, air flow rate 165m^3/h).

The simulation of earth-air heat exchanger also requires climatic data such ambient air temperature and relative humidity. Weather data for Spain locations have been generated using Meteonorm files provided within TRNSYS. Metenorm uses monthly average weather data for any location to generate Typical Metrological Year at small time steps.

Soil surface temperature and thermal properties determine the heat balance at the soil surface, which affects the subsurface soil temperature [6]. Soil thermal properties have been determined from Catalan Geological Institute (IGC). In Fig 3 it can be observed the annual evolution of the ambient air, EAHX outlet air and soil temperatures.

5. Results and discussion

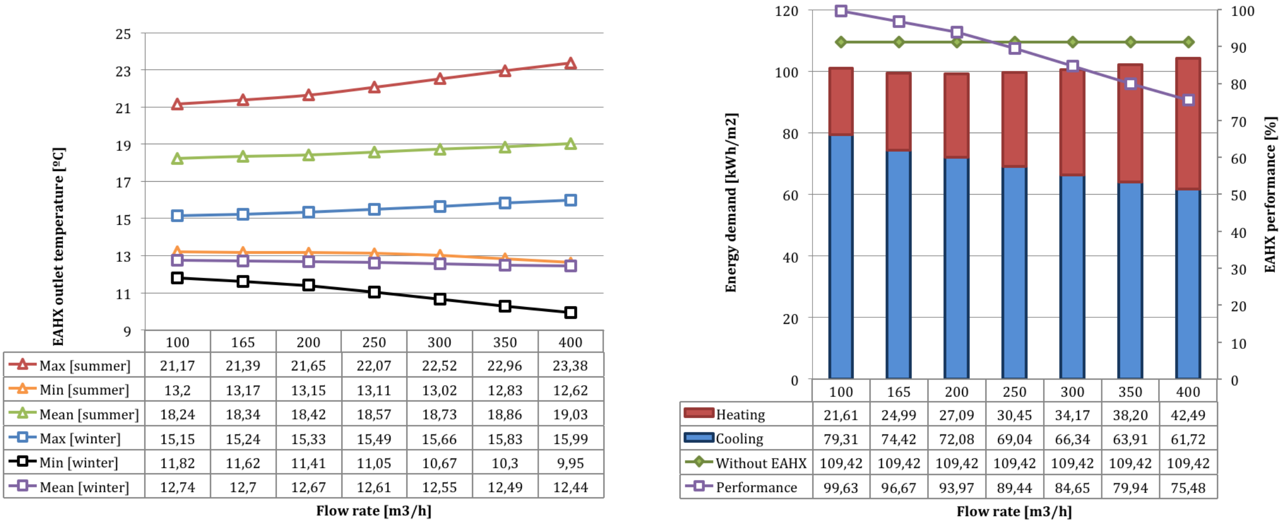
The thermal performance of an earth-air heat exchanger is affected by the pipe configuration, air velocity, burial depth and inlet air condition. In this study the effect of pipe configuration: length, diameter, burial depth and air flow have been evaluated. Ambient conditions for Barcelona have been used as input to the simulation programme. The simulation has been carried out for the whole year and for a 24 hour period. Figures 4 to 7 show the statistical variation of the pipe outlet air temperature and thermal performance for different scenarios.

Fig. 4 reveals an energy demand increase tendency when high flow rates are selected, mainly because of the excessive ventilation load. It also can be observed that cooling energy demand tends to decrease while heating demand, contrarily, tends to increase. This is due to the fact that heat transfer efficiency decrease with high air velocity. Consequently, it supposes a high ventilation load in winter and a low ventilation load in summer.

The thermal performance of earth-air heat exchanger can be improved by reducing the air flow to the very minimum. However, it must be take into account that a minimum flow rate value of $165m^3/h$ is necessary to guarantee the Spanish indoor air quality regulation compliance.

On the other hand, increasing the exchanger length is another way to improve the EAHX performance. Fig 5 shows a slight decrease in the energy demand when long pipes are installed. That's because of prolonged exchange surface leads to high heat transfer efficiency rates. However, bigger lengths do not lead to significant improvements of heat transfer efficiency.

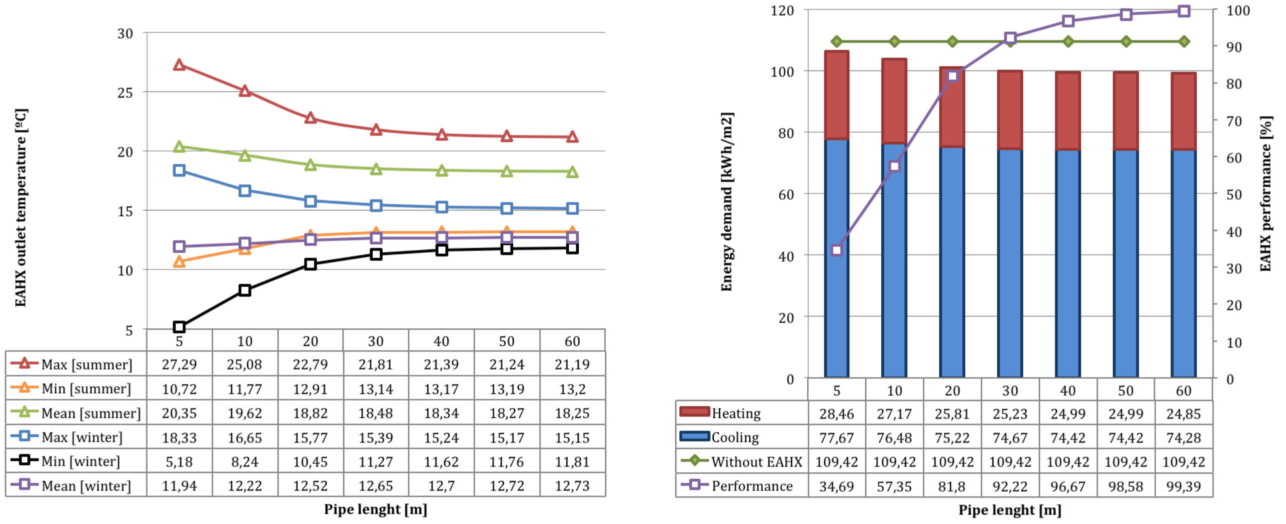
In the same way, increasing the exchanger depth is another solution to increase the system efficieny. In Fig 6 it can be observed that EAHX systems with deep pipes lead to low energy demand due to an increase in soil temperature stability associated with depth.



	100	165	200	250	300	350	400
Max [summer]	21,17	21,39	21,65	22,07	22,52	22,96	23,38
Min [summer]	13,2	13,17	13,15	13,11	13,02	12,83	12,62
Mean [summer]	18,24	18,34	18,42	18,57	18,73	18,86	19,03
Max [winter]	15,15	15,24	15,33	15,49	15,66	15,83	15,99
Min [winter]	11,82	11,62	11,41	11,05	10,67	10,3	9,95
Mean [winter]	12,74	12,7	12,67	12,61	12,55	12,49	12,44

	100	165	200	250	300	350	400
Heating	21,61	24,99	27,09	30,45	34,17	38,20	42,49
Cooling	79,31	74,42	72,08	69,04	66,34	63,91	61,72
Without EAHX	109,42	109,42	109,42	109,42	109,42	109,42	109,42
Performance	99,63	96,67	93,97	89,44	84,65	79,94	75,48

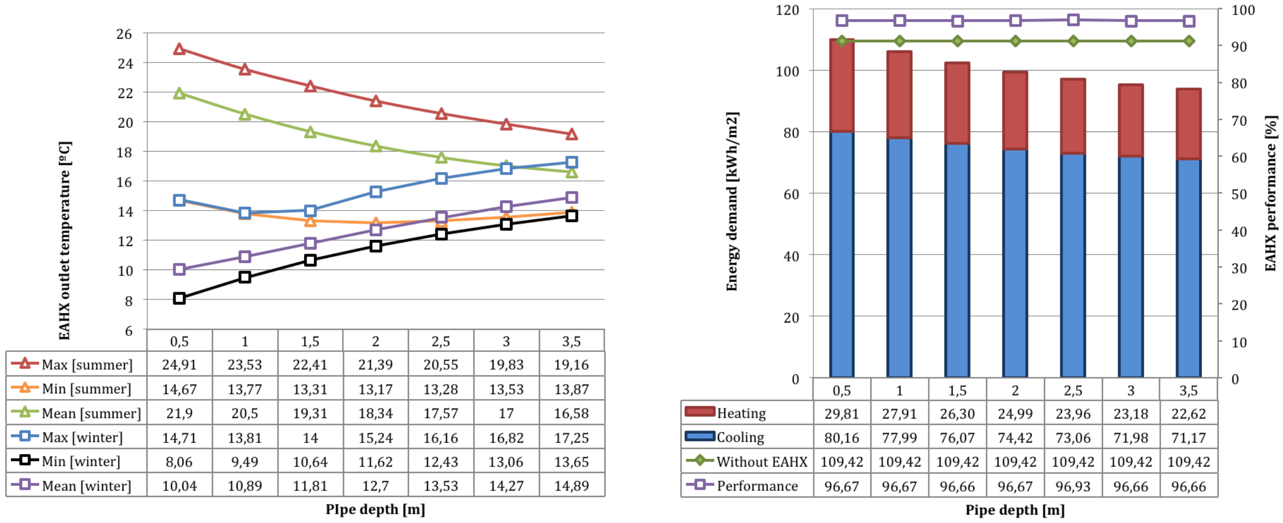
Fig. 4. EAHX outlet temperature and annual energy demand vs air flow rate (pipe ∅400mm, pipe depth 2m, pipe length 40m). T_{amb} max = 31,26ºC, T_{amb} min= 3,45ºC T_{amb} mean= 16,27ºC.



	5	10	20	30	40	50	60
Max [summer]	27,29	25,08	22,79	21,81	21,39	21,24	21,19
Min [summer]	10,72	11,77	12,91	13,14	13,17	13,19	13,2
Mean [summer]	20,35	19,62	18,82	18,48	18,34	18,27	18,25
Max [winter]	18,33	16,65	15,77	15,39	15,24	15,17	15,15
Min [winter]	5,18	8,24	10,45	11,27	11,62	11,76	11,81
Mean [winter]	11,94	12,22	12,52	12,65	12,7	12,72	12,73

	5	10	20	30	40	50	60
Heating	28,46	27,17	25,81	25,23	24,99	24,99	24,85
Cooling	77,67	76,48	75,22	74,67	74,42	74,42	74,28
Without EAHX	109,42	109,42	109,42	109,42	109,42	109,42	109,42
Performance	34,69	57,35	81,8	92,22	96,67	98,58	99,39

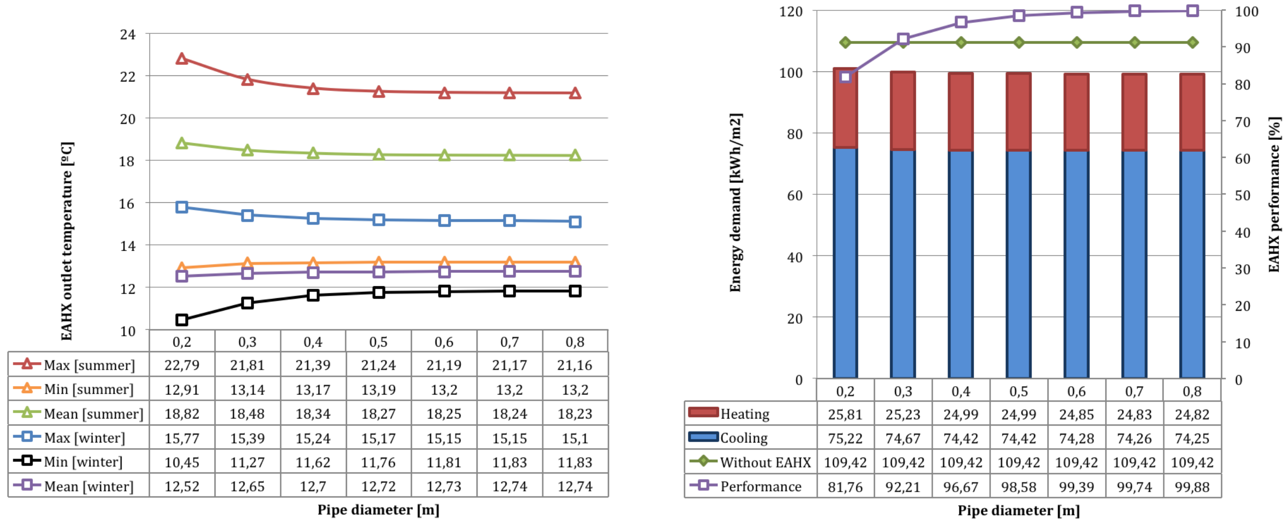
Fig. 5. EAHX outlet temperature and annual energy demand vs pipe lenght (pipe ∅400mm, pipe depth 2m, air flow rate $165m^3/h$). T_{amb} max = 31,26ºC, T_{amb} min= 3,45ºC T_{amb} mean= 16,27ºC.



	0,5	1	1,5	2	2,5	3	3,5
△ Max [summer]	24,91	23,53	22,41	21,39	20,55	19,83	19,16
△ Min [summer]	14,67	13,77	13,31	13,17	13,28	13,53	13,87
△ Mean [summer]	21,9	20,5	19,31	18,34	17,57	17	16,58
□ Max [winter]	14,71	13,81	14	15,24	16,16	16,82	17,25
□ Min [winter]	8,06	9,49	10,64	11,62	12,43	13,06	13,65
□ Mean [winter]	10,04	10,89	11,81	12,7	13,53	14,27	14,89

	0,5	1	1,5	2	2,5	3	3,5
🟥 Heating	29,81	27,91	26,30	24,99	23,96	23,18	22,62
🟦 Cooling	80,16	77,99	76,07	74,42	73,06	71,98	71,17
◆ Without EAHX	109,42	109,42	109,42	109,42	109,42	109,42	109,42
□ Performance	96,67	96,67	96,66	96,67	96,93	96,66	96,66

Fig. 6. EAHX outlet temperature and annual energy demand vs pipe depth (pipe ∅400mm, air flow rate 165m^3/h, pipe length 40m). T_{amb} max = 31,26ºC, T_{amb} min= 3,45ºC T_{amb} mean= 16,27ºC.



	0,2	0,3	0,4	0,5	0,6	0,7	0,8
△ Max [summer]	22,79	21,81	21,39	21,24	21,19	21,17	21,16
△ Min [summer]	12,91	13,14	13,17	13,19	13,2	13,2	13,2
△ Mean [summer]	18,82	18,48	18,34	18,27	18,25	18,24	18,23
□ Max [winter]	15,77	15,39	15,24	15,17	15,15	15,15	15,1
□ Min [winter]	10,45	11,27	11,62	11,76	11,81	11,83	11,83
□ Mean [winter]	12,52	12,65	12,7	12,72	12,73	12,74	12,74

	0,2	0,3	0,4	0,5	0,6	0,7	0,8
🟥 Heating	25,81	25,23	24,99	24,99	24,85	24,83	24,82
🟦 Cooling	75,22	74,67	74,42	74,42	74,28	74,26	74,25
◆ Without EAHX	109,42	109,42	109,42	109,42	109,42	109,42	109,42
□ Performance	81,76	92,21	96,67	98,58	99,39	99,74	99,88

Fig. 7. EAHX outlet temperature and annual energy demand vs pipe diameter (air flow rate 165m^3/h, pipe depth 2m, pipe length 40m). T_{amb} max = 31,26ºC, T_{amb} min= 3,45ºC T_{amb} mean= 16,27ºC.

Finally, Fig. 7 shows a no significant dependency between pipe diameter and energy demand. However, a slight decrease in the energy demand is observed when large diameters are selected.

The thermal behavior of the earth-air heat exchanger can be predicted by using its performance as shown above, based on equation (1). The annual mean earth-air heat exchanger efficiency for different situations is shown in purple line, based on hourly time step simulations values.

4. Conclusions

In this study, a transient thermal simulation is developed to assess the potential of EAHX for reducing the energy demand on Spanish dwellings.

The energy use for heating and cooling of buildings accounts for a significant percentage of energy consumption in Spain and Europe. The reductions in building energy consumption using passive and low energy systems for indoor environmental control have significant potential for reducing building energy consumption and the related CO_2 emissions. Earth-air heat exchanger utilizes soil temperature below the surface, which is lower than ambient temperature in summer and higher than ambient temperature in winter.

Thermal performance of EAHX has been established using the thermal simulation tool, to evaluate the potential of the system under Spain climatic condition.

The result of thermal analysis reveals significant improvement in the temperature of ventilation air supply in both summer and winter. Energy savings can reach roughly 900 kWh/year for heating (10,45%) and can even overcome 990 kWh/year for cooling (25,10%), with efficiency of 99,6%.

Different dimensions of earth-air heat exchanger have been evaluated with respects to outlet air temperatures, energy consumption and efficiency. Earth-air heat exchangers have the potential to reduce the rising trend of conventional mechanical cooling system use in buildings and the energy consumption of such systems. It is important however, to look at the application of the system with simple but effective control.

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