Thermoeconomic design of an earth to air heat exchanger used to preheat ventilation air in low energy buildings

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Abstract: Geothermal energy is one of the renewable sources of energy that can generate electricity and heat with a low impact on the environment. An important percent of the primary energy consumption is used to provide buildings heating and cooling. Thermal energy demand for buildings is driven by population growth and climatic conditions. For these reasons new solutions had to be found in the dwellings sector and the passive house concept has proved to be very efficient. A passive house can be equipped with geothermal systems such as heat pumps and earth to air heat exchangers. The paper presents the description and the design of an earth to air heat exchanger installed to preheat and cool the ventilation air for a passive house built within "Politehnica" University of Bucharest.

Key-Words: geothermal energy, earth to air heat exchanger, energy consumption reduction, passive house, heat recovery, heat transfer, thermoeconomic optimization

1 Introduction

The depletion of the classic fuels reserves and more intense utilization of the renewable energies led to the development of new technologies. Geothermal energy is classified as a renewable source of energy for electricity production and buildings heating.

Nowadays, in Europe the building sector is responsible for about 40% of the total primary energy consumption. One interesting solution for "payable" energy reduction is the utilization of the great thermal potential of the ground. The intensity of the thermal energy increases with depth. At 1.5 – 4 m depth, superficial layers of the earth contain large quantities of heat. An earth to air heat exchanger is a surface geothermal system able to exploit these resources.

A passive house, which is a low energy house, has to fulfill two important requirements: heating energy consumption must be lower than 15 kWh/m^2/year and total primary energy consumption must be under 120 kWh/m^2/year [1]. These conditions can be accomplished only by a combination between a special type of architecture, a south orientation, a compact shape, high tightness and a HVAC system based on renewable sources of energy (heat pumps, solar collectors, hot water tanks, fan-coils units, earth to air heat exchangers).

Energy demand for space heating of this type of building has been reduced by ca. 80% compared with conventional buildings [2]. The building costs of a passive house do not exceed the costs of a usual house by more than 16% [3]. In Germany, where the Passive House Institute from Darmstadt is conducting research in this field, over 7,000 units were built [4]. Other European countries such as Sweden, France and Austria developed their projects with the help of German experience. In Europe, the existence of over 20,000 passive houses by 2010 is estimated [5] and their number is growing.

The efficiency of an earth to air heat exchanger (EAHX) system depends on the climate of the location. For continental areas like Romania, the difference between the soil temperature and the outside air temperature is higher than 10°C. This fact makes the EAHX the suitable solution for preheating the ventilation air, during winter and cooling it during the summer. In European countries, the earth to air heat exchanger (EAHX) is also known as earth tubes, earth cooling tubes, earth warming tubes or "puit canadien".

Even if the passive house concept was formalized 15 years ago by the Passive House Institute from Darmstadt, in Romania it is still new. A new project is developed by the "Politehnica" University of Bucharest. Two passive houses having a surface of 180 m^2 each are under construction in the campus of the university. One of these houses will be equipped with an earth to air heat exchanger, used to preheat/cool the ventilation air.

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2 Description of the Earth to Air Heat Exchanger (EAHX)

An earth to air heat exchanger is a system which increases the interior temperature of the building during winter and it is also able to decrease it during summer, by using the thermal potential of the ground.

Throughout a year, the outside air temperature in Bucharest ranges from -15°C to 40°C, while soil temperature has a lower range, only from 4°C to 18°C. The ground contains heat that can be captured and transported through the pipes inside the building.

There are two different types of earth to air heat exchangers: the first one with the air flowing inside the tube and a second one with brine. A brine-ground heat exchanger operates in the same mode as the traditional type and it is another possibility to preheat the ventilation air in polluted areas. The water circulating inside the tube using a pump absorbs heat from the ground and then it enters a water-air heat exchanger. Inside the heat exchanger, the energy accumulated by water is delivered to the ventilation air. For an EAHX of this type, the length of the thermal channel is usually half of the air volume flow [6].

The investigated earth to air to air heat exchanger is placed near one of the two passive houses of the “Politehnica” University of Bucharest. During the winter, the air passes through the underground collector by using a fan. In this way, the low temperature of the air which enters the house is increased. During summer, the system uses the coolness of the ground to lower the temperature of the fresh air. The quality of the fresh air depends on the inlet air location. The exterior air intake will be placed at 1 m height on a 10 cm concrete socle away from the car parking areas. Other important elements such as a lattice, a hat and a filter protect the earth channels from insects, birds, rodents or dust.

The ground thermal channel represents the most important part of the system because it assures the energy change between soil and air. The tube should be placed at 1-2 m depth to reduce the influence of the outside environment as much as possible [7]. The criteria for choosing the pipes referred to mechanical strength, durability, tightness, thermal conductivity and impermeability. The collector network can be made up of one ground loop or several tubes connected in parallel [8]. The configuration of the network depends on the size of the available surface.

The walls of the pipes are treated in order to reduce microbial growth that could pollute the fresh air. Studies concerning air pollution were conducted and they showed that the concentration of a possible harmful growth of bacteria could even be decreased due to the air flowing [8].

The range of materials used to make the thermal tubes is quite large: concrete, sandstone, cast iron, polyethylene or polypropylene [8]. The material chosen for the pipe of the analyzed EAHX is a type of polyethylene with a high thermal conductivity. This material fulfills the environmental requests, it does not release toxic gas and it has low roughness.

Radioactive gas exists in higher or lower concentrations in any type of soil and in any area. The risk of lung cancer increases for the people living in the buildings located in high concentration radon (radioactive gas) areas. The investigated EAHX is tight enough and the radon does not get inside.

While the air is passing through the tube, water vapors condense on the inner surface, turning into small drops. The condensation process is important and it is taken into consideration for two reasons: if the water remains inside the channels, a perturbation of airflow appears and the quality of the air is affected by growth of bacteria and fungi. There are two possibilities to remove the condensed water. For a building with a basement, the condensed water is collected by a siphon placed at the lowest point of the installation. A brine to air heat exchanger also needs a siphon to remove the drops of water.

The scheme presented in fig. 1 is typical for a house without a basement like "Politehnica house". A condensation tower was built at the lowest point of the earth to air heat exchanger, close to the wall. The condensed moisture is removed by a condensation pump.

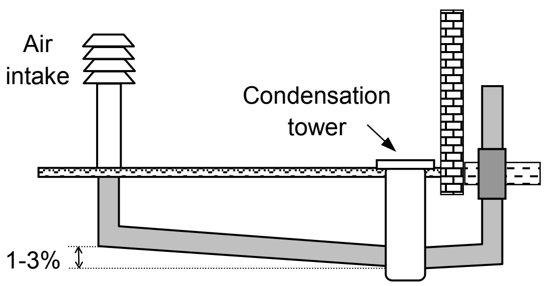

Fig. 1: Method used to remove condensed moisture

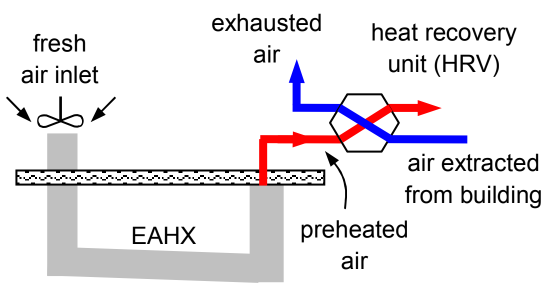

Fig. 2: Scheme of the EAHX-HRV system

For this type of building the underground pipe is installed at an angle of 1-3% so that the condensate could flow to the place where is collected.

Since the house is ventilated with fresh air, the heating load during winter becomes higher. To reduce energy consumption for heating, the air is preheated in two steps: first in the ground heat exchanger and second in a heat recovery unit (HRV) which can save even more than 90% from the energy of exhausted air (fig. 2).

The heat recovery ventilation system consists in a plate heat exchanger and two fans. The fans are identical, synchronized so that the basic ventilation conditions to be fulfilled. Inside the PHE, the exhausted air transfer heat to the supply air. The two air streams must be equal and in counter-flow. The utilization of a HRV system brings energy gains and improves also the quality of the interior air.

3 Theoretical model of the EAHX

This work presents the algorithm for calculation of optimum value for the length of the pipe integrated in an EAHX. The model is divided in two parts.

The first part of the algorithm is based on a common method included in many applications used in the heat exchangers field. The parameters from the following numerical application are characteristic for the studied earth to air heat exchanger.

All the input parameters used for theoretical study are presented in table 1. A high density polyethylene pipe was selected as thermal tube. The pipe is buried below the freezing point of the ground, in our case at 2 m deep.

Table 1: Input parameters of the theoretical model

Dimension / property	Symbol	Value	Unit
Pipe characteristics			
Wall tightness	δ	7,8	mm
Pipe diameter (exterior)	D_e	200	mm
Wall roughness	r	$1{,}5\cdot10^{-3}$	mm
Thermal conductivity	λ	0,28	W/(m·K)
Volumetric flow rate	V_a	165	m^3/h
Soil temperature	t_s	5	ºC
Tube inlet air temperature	$t_{a,i}$	-15	ºC

We made the assumption that the soil temperature, t_s, is constant during heating period. Its value depending on depth is obtained from a diagram specific for each climate zone.

The considered volumetric flow rate of the air was obtained following the ventilation needs of the house, according to a 0.5 changes/hour.

The tube inlet air temperature, the same as the outside temperature, is set at the minimum calculation temperature of -15 °C, typical for the month with the lowest outside air temperatures.

The value of the tube outlet air temperature ($t_{a,o}$) is found by using the expression of the tube thermal efficiency:

$$\varepsilon = \frac{t_{a,o} - t_{a,i}}{t_s - t_{a,i}} \quad (1)$$

This is a very important input parameter and it takes into consideration both the air temperatures and the soil temperature. The first step of the algorithm is to settle its value at 0.85 (the recommended average value for the HRV used in passive houses).

To evaluate the heat exchange rate, we must first determine the thermophysical properties of the air in the tube, at the temperature average value.

The convective heat transfer coefficient α is calculated as a function of the air thermal conductivity (λ_a) and the inner pipe diameter (D_i), with the classical expression:

$$\alpha = \frac{Nu_a \cdot \lambda_a}{D_i} \text{ [W/(m}^2\text{.K)] (2),}$$

where the Nusselt number of the air (Nu_a) is done by the Gnielinski expression [9], as a function of the Reynolds and Prandtl numbers:

$$Nu_a = 0{,}0214(\mathrm{Re}_a^{\;0,8} - 100) \cdot \mathrm{Pr}_a^{\;0,4} \quad (3)$$

The velocity of the air in typical applications usually ranges between 1 and 3 m/s. In this case it is about 1,72 m/s and assures a turbulent flow.

The next step, which should be followed to determine the heat transfer between soil and air, is to calculate the linear thermal resistances R_{cd}, R_{cv}:

$$R_{cd} = \frac{1}{2\pi\lambda} \ln \frac{D_e}{D_i}, \quad R_{cv} = \frac{1}{\pi D_i \alpha} \quad \text{[m.K/W]} \ (4)$$

R_{cd} is the thermal resistance due to conduction heat transfer between the inner surface of the pipe and its outer surface;

R_{cv} is the thermal resistance specific to the convective heat transfer between the pipe wall (its inner surface) and the air flowing inside;

If the values of the thermal resistances are known, the overall heat transfer coefficient can be estimated:

$$k_s = \left[\pi D_i \left(R_{cd} + R_{cv}\right)\right]^{-1} \ \text{[W/(m}^2\text{.K)]} \ (5)$$

The heat flux delivered by the ground is the heat gain by the air (or heat loss during summer):

$$\dot{Q} = k_s \cdot S \cdot \Delta t_m = c_{pa} \cdot \dot{m}_a \cdot (t_{a,o} - t_{a,i}) \quad (6)$$

where Δt_m is the logarithmic mean temperature difference between air and soil, c_{pa} is the air specific heat and $\dot{m}_a$ is mass flow rate of air.

From equation (6), the heat transfer surface (S) is obtained and also the pipe length derived from it:

$$L = \frac{S}{\pi D_i} \ \text{[m]} \ (7)$$

In the second part of the work, the thermal efficiency of the pipe varies between 0.5 and 0.99. While the ground and air temperature at the EAHX inlet are maintained constant, the air temperature at EAHX outlet changes according to the thermal efficiency of the pipe.

The pipe length ranges from 11.5 m to 76 m as its thermal efficiency rises (fig. 3). As it was expected, an earth to air heat exchanger is more efficient if the length of the tube is longer. The air temperature at the EAHX outlet is growing with the increasing of the pipe length as it can be seen in fig. 4.

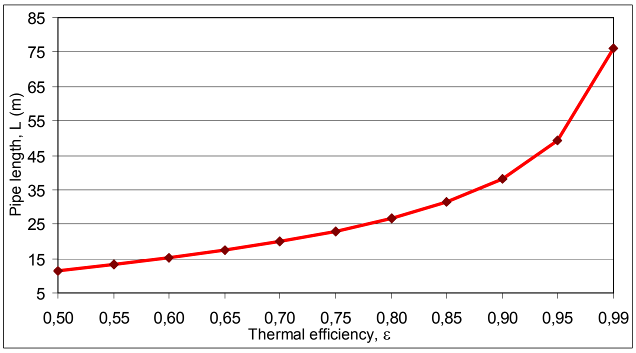

Fig. 3: The influence of the thermal efficiency on the pipe length

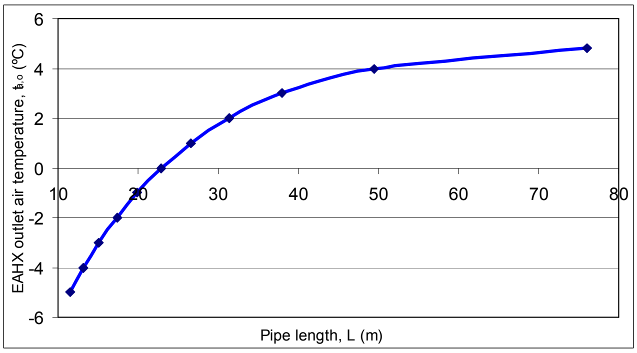

Fig. 4: The influence of the pipe length on the air temperature at the EAHX outlet

The temperature of the preheated fresh air from the pipe outlet is raised by an HRV system described above. The outgoing exhausted air ($t_{a,e}$) has 20°C and it contains a substantial amount of heat that is transferred to the fresh air in the HRV system.

The temperature at the HRV unit outlet depends on its thermal efficiency. According to the information delivered by the manufacturer of the utilized heat recovery unit, the thermal efficiency is of 91% [10]. From the thermal efficiency equation:

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$$\varepsilon_R = \frac{t_R - t_{a,o}}{t_{a,e} - t_{a,o}} \text{ , (8)}$$

the temperature of the air at the heat recovery unit outlet (t_R) is obtained.

Not only the outlet temperature of the EAHX depends on the pipe length but also the temperature at the outlet of the HRV unit. The air temperature reaches higher values because the heat transferred from the ground increases with the tube length. Fig. 5 illustrates the variation of the air temperature at the HRV unit outlet according to the tube length.

To meet the interior comfort conditions, the fresh air is further heated by electrical resistances.

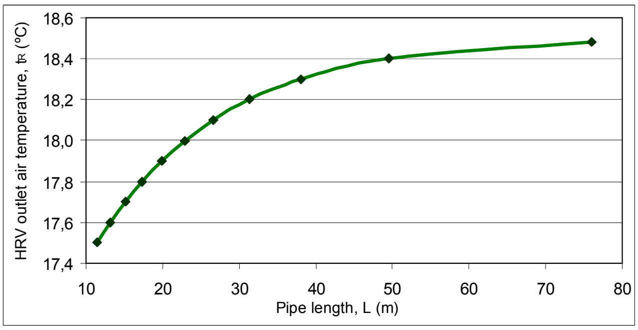

Fig. 5: The influence of the pipe length on the temperature at HRV unit outlet

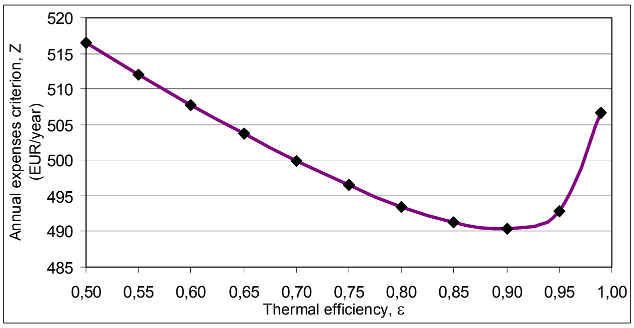

Fig. 6: Variation of the annual expenses as a function of the tube thermal efficiency

In order to find the optimum length of the tube, the following annual expenses criterion is used:

$Z = c \cdot I + C$ [€/year] (9)

where: c is the economical efficiency coefficient, I represents the investment cost and C is the annual operating costs.

The investment refers to drilling costs and the acquiring cost of the EAHX. The operating cost takes into account the power consumption of the air fan, the HRV unit ventilators and the electrical resistances.

The point where the EAHX operates optimally is the one corresponding to the lowest value of the annual expenses. As the fig. 6 presents, this value is reached for a tube thermal efficiency of about 90%. An optimal pipe length of 38 m corresponds to this point.

Considering the calculated length of the tube and the available land surface, the configuration of the EAHX pipe from the passive house from the "Politehnica" University of Bucharest is the one presented in the fig. 7.

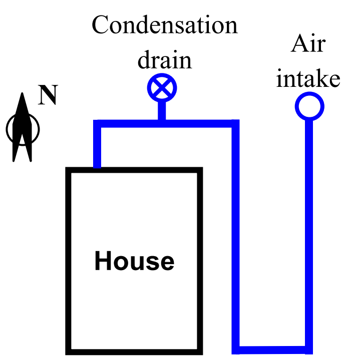

Fig. 7: Configuration of the EAHX tube from the "Politehnica house"

(a) (b)

Fig. 8: Installation of the EAHX tube
a) main side with fresh air intake; b) short side with condensation drain and house connection

To benefit of the heat regeneration of the ground provided by sun, the main side of the tube is buried on the east side of the building in an unshaded area. In the fig. 8a a picture from the installation of the main side of the

EAHX is presented. In the background the air intake can bee seen. The fig. 8b presents the short side of the ground heat exchanger with the house connection in the foreground and the condensation drain in the center view.

The future work intends to study the variation of air temperature at the EAHX exit and the construction of a forecast chart for the prediction of the additional heat need, depending on climatic conditions during the year.

4 Conclusion

Inside the campus of "Politehnica" University of Bucharest two low energy houses which are intended for passive house certification, are under construction. To reduce the primary energy consumption for heating and cooling the ventilation air, one of these houses is equipped with an earth to air heat exchanger (EAHX).

An algorithm for the EAHX tube length sizing is purposed. The first part of this work serves in sizing the geothermal system, starting with the tube parameters, the earth and outside air temperature. For proper sizing of the tube length, the extreme values for the two temperatures were considered. The calculation tool consists in usual equations typical for a heat exchanger sizing.

In the second part, economic aspects are taken into consideration. The EAHX is a complex system which has to be considered as a whole. After preheating in the EAHX tube, the ventilation air gets to the satisfactory temperature due to the other two systems connected to this device: a heat recovery unit and electrical resistances. In order to apply the economical criterion, all energy consumptions are taken into account. The calculation reveals that not only the outlet EAHX air temperature depends on the pipe length but also the electrical energy consumption of the air fan, the HRV unit and the electrical resistances.

The optimization calculation in order to determine the EAHX tube length was developed as a function of the tube thermal efficiency. As the thermal efficiency increases, the tube length has an exponential increase. This evolution has an important influence to the air temperature at the EAHX outlet that registers a significant growth. The air temperature at the heat recovery unit outlet has also a slight increase.

The point where the EAHX optimally operates is the one corresponding to the lowest value of the annual expenses. This value is reached for a tube thermal efficiency of about 90%. An optimal pipe length of 38 m corresponds to this point.

Taking into account the calculated length of the tube and the available land surface, a configuration in a single loop was chosen. The main side of the tube is buried on the east side of the building in an unshaded area, to benefit of the ground heat regeneration provided by sun.

Acknowledgements

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