Utilization of Earth-air heat exchangers in Energy and pollution savings for Romanian dwellings

RALUCA TEODOSIU, LIDIA NICULIȚĂ, CĂTĂLIN TEODOSIU
Thermo-Hydraulic and Protection of the Atmosphere Systems Department
Faculty of Building Services and Equipment, Technical University of Civil Engineering
Lacul Tei Bvd., no. 122 – 124, RO 020396, sector 2 , Bucharest,
Tel.: +40 21 242.12.08, Fax: +40 21 242.07.81
ROMANIA
ralucahohota@yahoo.com   www.utcb.ro

Abstract: This study is dealing with earth-air heat exchanger (EAHX) implementation for Romanian dwellings. The objective is to assess the potential of this solution for ventilation energy savings and greenhouse gas emissions reductions. Numerical transient coupled model (single-pipe EAHX – ventilation system – building) is developed using Trnsys as simulation tool. The simulations are carried out for typical Romanian single-family detached home, taken into account three different climate regions. For each case, 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.

1 Introduction

The energetic sector, including private households and tertiary field, generates 80% of European Union (EU) total greenhouse gas emissions (GES), being practically the main cause of climatic changes and atmospheric pollution.

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, it is well known that buildings are responsible for 40% of energy consumption and 36% of EU CO_2 emissions. Furthermore, EU documents estimate even more energy consumption due to ventilation and cooling of houses in South Europe. Therefore measures to improve energy efficiency in this sector have a strong leverage effect.

In this perspective, the use of geothermal heat exchangers for heating and/or cooling of buildings has experienced lately a growing interest. Among these equipments, the earth-air heat exchangers (EAHXs) represent the simplest technical solution. Despite its simplicity (in fact, this is an advantage from all points of view: execution, maintenance, payback, etc.), earth-air heat exchangers 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 Romanian conditions (climate and typical dwelling built up according to national standards).

2 Ground to air heat exchanger

The system functioning is based on outside air circulated through pipes buried in the ground (Fig.1). The heat exchange takes place between the ground and the air inside the pipes: earth's temperature varies from 2-3 meters depth within 5…15ºC all year round, while outside air

temperature can range from -20…40ºC, if we refer to situations encountered in Romania. In consequence, at the end of the buried pipes, heat transfer leads to air heating or cooling, depending on the season. Depending on working conditions (length, diameter, thermal conductivity and depth of the tube, air flow, soil characteristics, etc.), the air temperature difference in/out earth-air heat exchanger can reach 10…15ºC.
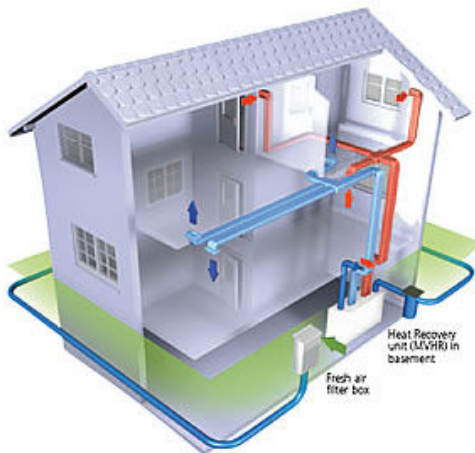

Fig.1. Earth-air heat exchanger system (REHAU)

In fact, the thermal performance of earth-air heat exchangers can be theoretically appreciated by means of achieved heat transfer efficiency (or "temperature ratio" [1]):

$$\eta = (T_i - T_o) / (T_i - T_S) \qquad (1)$$

where:
T_i – inlet EAHX air temperature (outside air temperature)
T_o – outlet EAHX air temperature
T_S – 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.

3 Numerical models

In order to thorough investigate the behavior of the ground to air heat exchanger; numerical modeling is the most relevant research tool. Therefore, there are numerous studies dealing recently with this subject [2-6]. Most of these studies have focused on the heat

transfer soil – pipe heat exchanger, taken carefully into account thermal inertia of the ground.

On the other hand, there is several simulation tools that can be used for modeling and simulation of the phenomena related to the earth-air heat exchanger thermal conduct: Design Builder + Energy Plus, Pleiades + Comfie, Trnsys, eQuest (DOE-2), Voltra, WTK2, WKM, etc. Among these, by far the best known and used specialized software is Trnsys [7].

In fact, Trnsys is flexible, modular software designed to simulate the energy performance of dynamical systems. It is commercially available since 1975. Nowadays, Trnsys has become a reference worldwide in the field of simulation of buildings and systems behavior in dynamic regime. Some 50 families of components ("types"), available in standard library, allow simulating, in transient conditions: buildings (mono or multi zonal), the simplest as the most complex heating and cooling systems, innovative building services and equipment systems, etc. Other components can couple the simulation with the weather, building occupancy (scenario concerning internal loads), use of different forms of energy, and generate the desired outcomes.

As a result, we developed comprehensive Trnsys simulation models in dynamic regime for coupling building- ventilation (with earth-air heat exchanger system). The main components of these models and their connections are shown in Fig. 2.
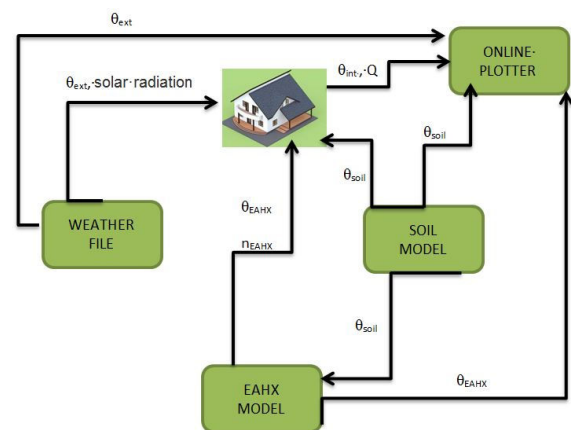

Fig.2. Key of the numerical model.

Furthermore, we present below the characteristics of the main model components: weather data, building, soil, buried pipe model.

- Weather data, based on "weather file" has the following major objective: reading weather data at regular intervals from a data file, conversion to a desired system of units and processing solar radiation data to obtain tilted surface radiation and the angle of incidence for an arbitrary number of

surfaces. In our study we used the file with weather data for 3 Romanian cities (these data contain the outdoor temperature, humidity and solar radiation - direct, diffuse and global).

- Building, component for the house thermal behavior modeling contents non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume; the balance equation takes mainly into account convective heat flux to the air node, coupling between zones by means of air mass flow, radioactive heat flux to the walls and windows [7]. The walls are modeled using transfer function technique (response factors).

- Soil, is the model component which describes the vertical distribution of ground temperature considering the annual mean temperature of the surface, the amplitude of the soil annual surface temperature, thermal diffusivity of the soil. These values can be found in the literature depending on the nature of the soil (dry sand, wet sand, dry loam, wet loam, etc.) [8, 9].

- Buried pipe model for air to soil heat transfer (the buried pipe is surrounded by a 3-dimensional finite difference conduction network). The proposed model is developed particularly for building energy transient simulations, thus the following hypothesis have been made: only conduction heat transfer is taken into account; the influence of moisture transfer or ground water flows are neglected; ground thermal properties are considered homogenous in the vicinity of the pipe. Axial heat transfer in the soil along the pipe is neglected and the conductive heat transfer is also neglected inside the pipe.

4 Case study

We introduce in this section the main characteristics of our case study.

4.1. Building

The house taken into account is characteristic for the new dwellings built up in Romania nowadays (single-family separate house). The building has ground floor and two levels (total floor area and total volume are 120 m^2 and 324 m^3, respectively). Other geometrical characteristics are shown in Table1.

Table 1. Envelope elements surfaces (m^2)

Windows (N, S, E, W)	Walls (N, S, E, W)	Roof (horizontal)	Floor on ground
35.84	119.04	60.00	60.00

Envelope thermal insulation of the house is according to national technical regulations [10]. Thermal resistance values for each envelope element are given in Table 2 (including also these values corrected by thermal bridges – specified between brackets).

Table 2. Envelope thermal resistances (m^{2}K/W)

Windows	Walls	Roof	Floor on ground
0.787	3.369 (2.527)	5.263 (5.105)	6.622 (5.430)

Internal loads taken into consideration within the simulations are according to common occupation of the dwelling (3 persons, 420 W from equipment and lighting, 5 W/m^2).

Temperature set points are as follows: winter 20ºC, summer 26ºC.

The house described above has been considered located in three Romanian cities, corresponding to different climatic zones of the country: Constanta, on the Black Sea coast - moderate continental climate with considerable maritime and some subtropical influences; Bucharest, capital – temperate humid continental climate; Iasi, in the North-East of Romania − pronounced continental climate, influenced by air masses of Eastern origin, with very cold winters and hot summers.

4.2. Earth-air heat exchanger system

The fresh air flow rate of the house ventilation system is 162 m^3/h (meaning 0,5 h^{-1}).

Table 3 presents the main thermal properties of the earth-air heat exchanger pipe.

Table 3. Pipe characteristics

Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
900	2900	0.12

Pipe diameters taken into account during the simulations are: 110, 160, 200 and 400 mm.

Tubes mounting depth is 2 m and the total length of the buried part of the system (the "active" heat transfer part) is 40 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 [11] showed that, for shorter circuits (25…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.

5   Results

The thermal behavior of the earth-air heat exchanger can be predicted by using its efficiency as shown above, based on equation (1). The annual mean earth-air heat exchanger efficiency for different situations is shown in Table 4, based on hourly time step simulations values.

Table 4. EAHX efficiency (%)

Solution / City	Constanţa, Bucharest, Iaşi
EAHX, D = 110 mm	79.9
EAHX, D = 160 mm	88.9
EAHX, D = 200 mm	92.6
EAHX, D = 400 mm	97.5

It is worthwhile to notice that the outside air temperature annual variation (depending on the zone climate) has not any influence, in this case, on the earth-air heat exchanger annual effectiveness. This happens because the air temperature after passing the earth-air heat exchanger is approaching the ground temperature – basically the same, regardless the climate.

Table 5. Energy consumption (kWh/m^2,year)

Solution / City	Constanţa	
	heating	cooling
without EAHX	30.03	143.91
EAHX, D = 110 mm	21.79	130.27
EAHX, D = 160 mm	20.88	128.75
EAHX, D = 200 mm	20.52	128.1
EAHX, D = 400 mm	20.02	127.31

Solution / City	Bucharest	
	heating	cooling
without EAHX	40.98	126.26
EAHX, D = 110 mm	29.57	112.43
EAHX, D = 160 mm	28.32	110.88
EAHX, D = 200 mm	27.81	110.25
EAHX, D = 400 mm	27.13	109.43

Solution / City	Iaşi	
	heating	cooling
without EAHX	50.31	114.01
EAHX, D = 110 mm	36.73	101.74
EAHX, D = 160 mm	35.55	100.66
EAHX, D = 200 mm	34.93	100.11
EAHX, D = 400 mm	34.13	99.37

Concerning the integration of the earth-air heat exchanger within the ventilation system, Table 5 summarizes energy consumption values in various situations (without/with earth-air heat exchanger – EAHX).

Energy savings achieved by introducing the earth-air heat exchanger within the mechanical ventilation system of the dwelling are highlighted in Table 6.

Table 6. Energy savings (kWh/m^2,year)

Solution / City	Constanţa	
	heating	cooling
EAHX, D = 110 mm	8.24	13.65
EAHX, D = 160 mm	9.15	15.16
EAHX, D = 200 mm	9.51	15.81
EAHX, D = 400 mm	10.01	16.61

Solution / City	Bucharest	
	heating	cooling
EAHX, D = 110 mm	11.41	13.84
EAHX, D = 160 mm	12.66	15.38
EAHX, D = 200 mm	13.17	16.01
EAHX, D = 400 mm	13.85	16.83

Solution / City	Iaşi	
	heating	cooling
EAHX, D = 110 mm	13.58	12.27
EAHX, D = 160 mm	14.76	13.35
EAHX, D = 200 mm	15.38	13.90
EAHX, D = 400 mm	16.17	14.64

Based on the values in Table 5, it is found that by using the earth-air heat exchanger within the mechanical ventilation system of the house, energy savings for heating are between 8…16 kWh/m^2,year. This means overall 960…1920 kWh/year heating savings for the house taken into account, with 120 m^2 total floor area. On the other hand, the analysis of the results clearly reveals the climate influence. For this reason, the cutbacks are most important for the house located in Iasi, while the lowest energy heating reductions occur at Constanta (winter with obvious marine influence).

Concerning summer situation, cooling energy savings are between 12…17 kWh/m^2, year, which means for the house total floor area of 120 m^2, total economy for cooling of 1440…2040 kWh/year. This time, as expected due to weather conditions, more substantial savings are attained in Constanta and Bucharest.

Based on heating and cooling energy savings (Table 6), we estimated also corresponding greenhouse gas emissions reductions in comparison with the classical solution, house without earth-air heat exchanger, equipped with gas fired boiler and direct expansion air conditioning plant (electrical mechanical compression cooling system).

The computations are presented in terms of resulting CO_2 emissions per year (Table 7), taken into account specific factors to convert "kWh" into "CO_2 emissions" and "kg of carbon dioxide equivalent" for different heating energy sources and electrical mechanical compression cooling [12]. Moreover, we considered for each type of energy source its acknowledged efficiency as follows: electric heating 1, gas heating 0.95, condensing gas technique heating 1.1, liquid fuel heating 0.9, wood heating 0.7, wood gasification heating 0.85, pellet heating 0.9 and electrical mechanical compression cooling 3.

Table 7. CO_2 emissions savings (kg/year)

EAHX diameter/ solution	City	110 (mm)	160 (mm)	200 (mm)	400 (mm)
electric heating + cooling	Constanța	271	300	313	329
	Bucharest	356	396	412	433
	Iași	402	445	463	488
gas heating + cooling	Constanța	262	291	303	319
	Bucharest	345	383	399	419
	Iași	388	430	448	472
condensing gas technique heating + cooling	Constanța	233	259	270	284
	Bucharest	305	338	352	370
	Iași	342	378	394	415
liquid fuel heating + cooling	Constanța	346	384	400	420
	Bucharest	460	511	532	559
	Iași	523	579	603	635
wood heating + cooling	Constanța	100	111	116	122
	Bucharest	120	133	139	146
	Iași	126	139	145	153
wood gasification heating + cooling	Constanța	91	101	105	111
	Bucharest	108	120	125	131
	Iași	112	123	128	135
pellet heating + cooling	Constanța	89	98	102	108
	Bucharest	105	116	121	127
	Iași	108	119	124	130

Depending on the heating and cooling solution efficiency, and the nature of the energy used (how "clean" is it), we salvage between 89 and 635 kg of CO_2 emissions per year.

6 Conclusions

The developed model allows describing in unsteady conditions the functioning of earth-air heat exchanger and their coupling with building ventilation systems.

The results make available the contribution and efficiency of this solution to cover the buildings energy consumption for heating and cooling of fresh air. Moreover, case studies taken into consideration for three Romanian climates demonstrate that earth-air heat exchangers can be used as feasible (and inexpensive) complement to conventional heating or air conditioning systems for pretreatment (heating or cooling) of the air within ventilation systems. Energy gains can reach roughly 2000 kWh/year for heating under severe winter conditions and can even overcome 2000 kWh/year for cooling in continental climate (with or without some maritime influences).

In addition, greenhouse gas emissions can be equally reduced. CO_2 emissions savings can attain more than half a ton/year in some circumstances (e.g. when liquid fuel fired boilers are employed for heating and direct expansion air conditioning - electrical mechanical compression for cooling). Further, it is worthwhile to draw the attention to the fact that the use of earth-air heat exchangers implies no chemicals, compressors, burners or other complicated and polluting equipments. The earth-air heat exchanger system needs only fans (already required for the mechanical ventilation system).

Finally, it is worthwhile to mention, as one of the main perspective of this study and its results, the analysis of condensation phenomena inside the buried pipes of the earth-air heat exchanger system. Consequently, the dehumidifying process of humid air that takes naturally place through the earth-air heat exchanger system in the summer can play a significant role in reducing the latent cooling load of buildings. On the other hand, this subject is of particular concern in the case of requirements for acceptable indoor air quality for very high occupant density buildings.

References:
[1] J. Pfafferott, Evaluation of earth-to-air heat exchangers with a standardized method to calculate energy efficiency, *Energy and Buildings*, Vol.35, 2003, pp. 971-983.
[2] P. Hollmuller, *Utilisation des échangeurs air-sol pour le chauffage et le rafraîchissement des bâtiments*, Ph. D. thesis, Université de Genève, 2002.

[3] M. De Paepe, A. Janssens, Thermo-hydraulic design of earth-air heat exchangers, *Energy and Buildings*, Vol. 35, No. 4, 2003, pp. 389-397.

[4] M.K. Ghosal, G.N. Tiwari, Modeling and parametric studies for thermal performance of an earth to air heat exchanger integrated with a greenhouse, *Energy conversion and management*, Vol. 47, No. 13-14, 2006, pp. 1779-1798.

[5] V. Bădescu, Simple and accurate model for the ground heat exchanger of a passive house, *Renewable Energy*, Vol. 32, No. 5, 2007, pp. 845-855

[6] S. Thiers, *Bilans énergétiques et environnementaux de bâtiments á énergie positive*, Ph. D. thesis, Ecole Nationale Supérieure des Mines de Paris, 2008.

[7] S.A. Klein et al., *TRNSYS Version 14.2. User manual*, Solar Energy Laboratory – University of Wisconsin, 1996.

[8] R. Wagner, S. Beisel, A. Spieler, K. Vajen, Measurement, modeling and simulation of an earth-to-air heat exchanger in Marburg (Germany), *In Proceedings of ISES Europe Solar Congress*, Copenhagen, Denmark, 2000.

[9] P. Duchaufour, *Introduction á la science du sol*, Dunod – Paris, 2001.

[10] R. Hohotă, I. Colda, D. Enache, M. Găvan, R. Enache, Etude numérique des „puits canadiens" pour la diminution des consommations énergétiques liées à la ventilation des bâtiments, *In Proceedings of IBPSA France*, Lyon, France, 2008.

[11] *** Order No. 2513/22.11.2010 of Romanian Ministry of Regional Development and Toursim (MDRT) approving the amendment of technical regulation C107/2005 (Thermo-technical calculation of buildings' construction elements).

[12] *** Building energy performance calculation methodology, Romanian Ministry of Regional Development and Toursim (MDRT):, MC 001/2 – 2006.