# Solutions for Energy Conservation and Pollution Reduction: Earth-Air Heat Exchangers

Cătălin Teodosiu, Lidia Niculiță, and Raluca Teodosiu

***Abstract*—The aim of this work is to evaluate the capacity of earth-air heat exchanger (EAHX) systems to contribute to energy and pollution savings for heating and cooling of buildings. This is fulfilled by means of numerical simulations (dynamic regime) based on coupled model: "weather file/soil model/EAHX/ventilation system/building. Detailed results concerning EAHX efficiency, energy conservation and pollution reduction (in comparison with classical solutions for winter heating and summer cooling), are shown for three different Romanian regions for a single-family separate house.**

***Index Terms*—Earth-air heat exchanger, energy saving, greenhouse gas emission reduction, modeling, simulation, ventilation.**

## I. 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 (within EU and worldwide) associated to energy use in order to slow down climatic changes and therefore to limit the global warming [1]. 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 [2]. 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 more than 40% of total final energy consumption and 36% of EU $CO_2$ emissions [3]. 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.

As a result, for achieving the EU energy saving targets, the very low energy houses and passive houses technology will be an essential tool on this road [4], [5]. This field of action can significantly help to challenge recent pessimistic reports suggesting that current EU measures could achieve energy savings of only about 13% by 2020. In fact, following the European Commission's proposal in November 2008 for an update of the 2002 Energy Performance of Buildings Directive (EPBD), the Recast was adopted by the European Parliament and the Council of the EU on 19 May 2010 (European Directive 2010/31/EU). One of the highlights of the recast is a strengthening of the energy performance requirements of new as well as existing buildings across the EU. The timescales are mentioned in Article 9 of the Directive, which states that MS shall ensure that "by 31 December 2020, all new buildings are nearly zero-energy buildings and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings." The EPBD Recast definition of very low energy building was agreed to: "nearly zero energy building means a building that has a very high energy performance" and "the nearly zero or very low amount of energy required should to a very significant level be covered by energy from renewable source, including renewable energy produced on-site or nearby". In addition, it is worthwhile to mention that the ventilation system is indispensable in this case as these buildings are extremely well thermal insulated and air tightened.

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 [6]. Consequently, the objective of this study is to fulfill 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).

## II. Ground to Air Heat Exchanger System

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

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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" [7]):

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

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.

## III. Numerical Modeling

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 [8]-[13]. Most of these studies have focused on the heat transfer soil – pipe heat exchanger, taken carefully into account thermal inertia of the ground. In addition, there are also analysis focused on the effect of air velocity and its turbulence on the performance of the ground to air heat exchanger system. These works are mainly based on computational fluid dynamics approach [14]-[16].

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 TRaNsient SYstem Simulation Software Program - TRNSYS environment [17].

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 inter-connections are shown in Fig. 2.

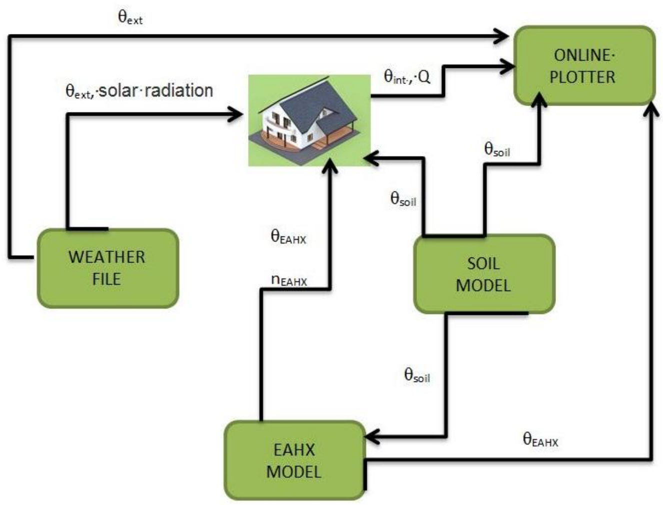



Fig. 2. Key of the numerical model.

Furthermore, we present below the characteristics of the main model components (weather data, building, soil, buried pipe model), as well as the main assumptions taken into consideration.

- 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 [17]. 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.) [18], [19]. Moreover, the following assumptions are taken into account: the soil is homogenous and the soil type does not change around and along the tube of the earth-air heat exchanger.

- 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. Furthermore, it is also assumed that the pipe material used is isotropic and homogeneous.

Finally, all thermophysical properties are considered constant and they are evaluated at an average temperature.

## IV. Case Study

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

### A. 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 Table I.

TABLE I: 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 [20]. Thermal resistance values for each envelope element are given in Table II (including also these values corrected by thermal bridges – specified between parentheses).

TABLE II: 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 20 ℃, summer 26 ℃.

The house described above has been considered located in three Romanian cities, corresponding to different climatic zones of the country (Fig. 3 and Fig. 4): Constanta, on the Black Sea coast - moderate continental climate with considerable maritime and some subtropical influences (minimum/maximum outside air temperature: -11,2 ℃/31,1 ℃ according to the Meteonorm weather database); Bucharest, capital – temperate humid continental climate (minimum/maximum outside air temperature: -15,4 ℃/35,4 ℃ according to the Meteonorm weather database); Iasi, in the North-East of Romania – pronounced continental climate, influenced by air masses of Eastern origin, with very cold winters and hot summers (minimum/maximum outside air temperature: -16,5 ℃/33,0 ℃ according to the Meteonorm weather database).

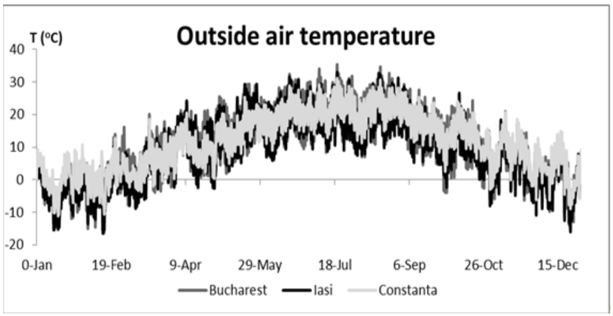



Fig. 3. External air temperature (Meteonorm weather database).

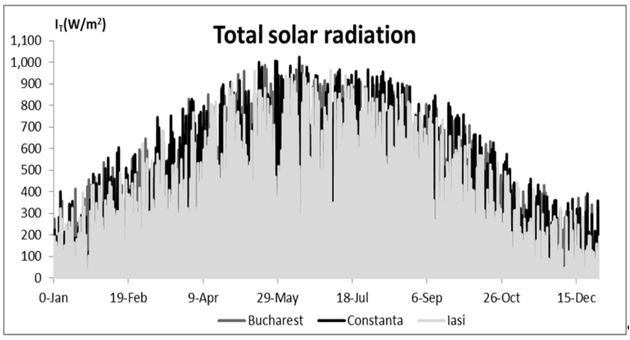



Fig. 4. Total solar radiation (Meteonorm weather database).

### B. 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 III presents the main thermal properties of the earth-air heat exchanger pipe.

TABLE III: EAHX Pipe Characteristics

| Density (kg/$m^3$) | Specific heat (J/kg K) | Thermal conductivity (W/m K) |
|---|---|---|
| 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 [21] 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.

## V. 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 IV, based on hourly time step simulations values.

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 IV: EAHX EFFICIENCY (%)

| Solution / City | Constanța, Bucharest, Iași |
|---|---|
| EAHX, D = 110 mm | 79.9 |
| EAHX, D = 160 mm | 88.9 |
| EAHX, D = 200 mm | 92.6 |
| EAHX, D = 400 mm | 97.5 |

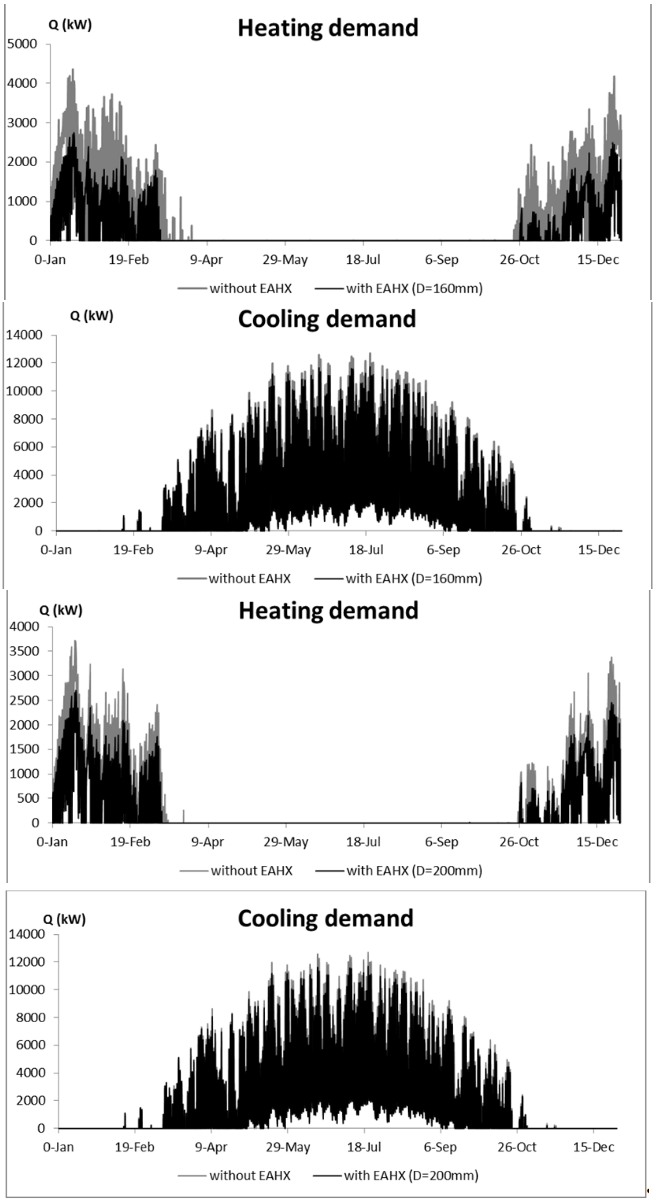



Fig. 5. Constanța (heating/cooling demand without/with EAHX).

Concerning the integration of the earth-air heat exchanger within the ventilation system, we show (Fig. 5- Fig. 7) the diminution of the winter heating power and summer cooling power for the cities taken into account. The comparisons are given for two diameters, 160 mm and 200 mm, usually recommended for single-family houses with floor area between 100-150 m$^2$.

Based on the previous results, we summarize in Table V the energy consumption values in various situations (without/with EAHX).

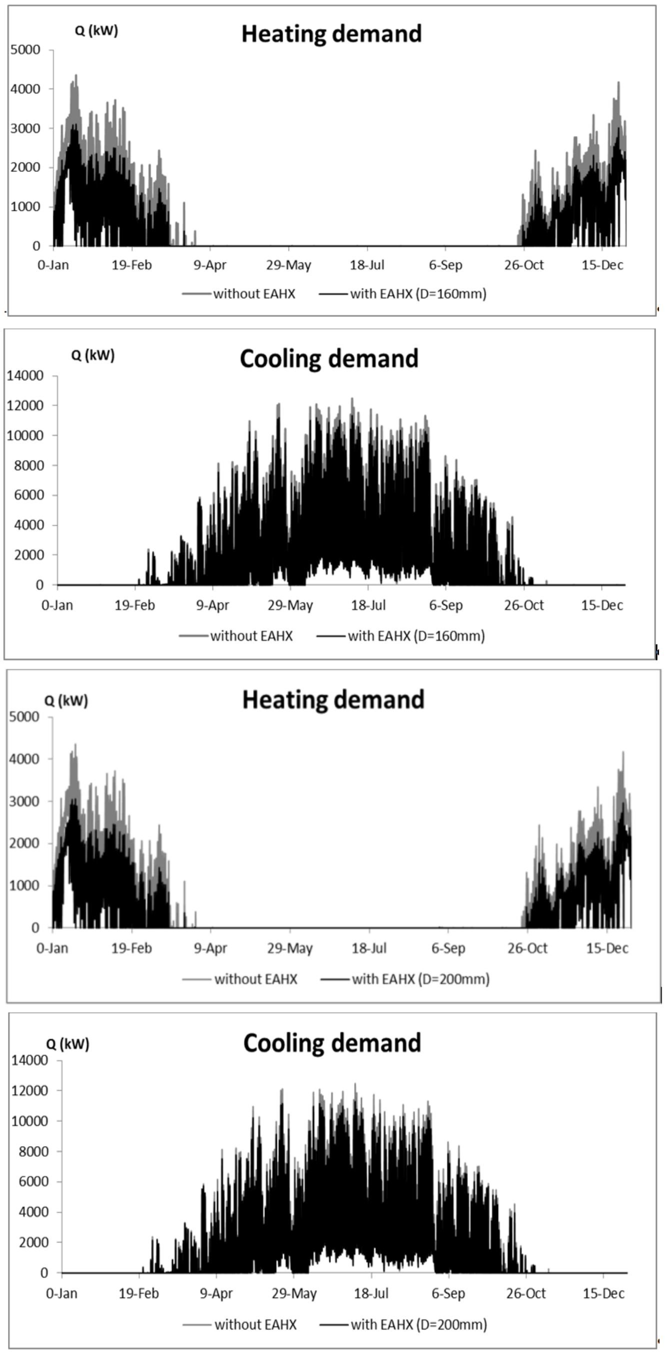
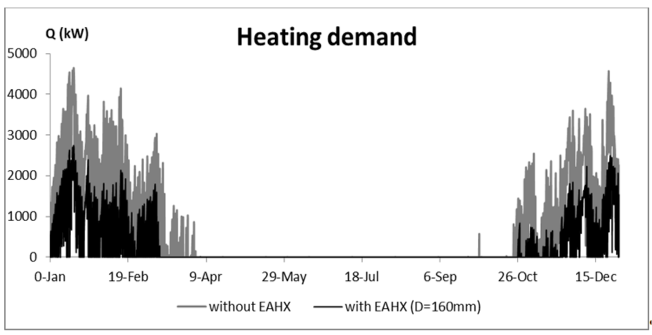



Fig. 6. Bucharest (heating/cooling demand without/with EAHX).



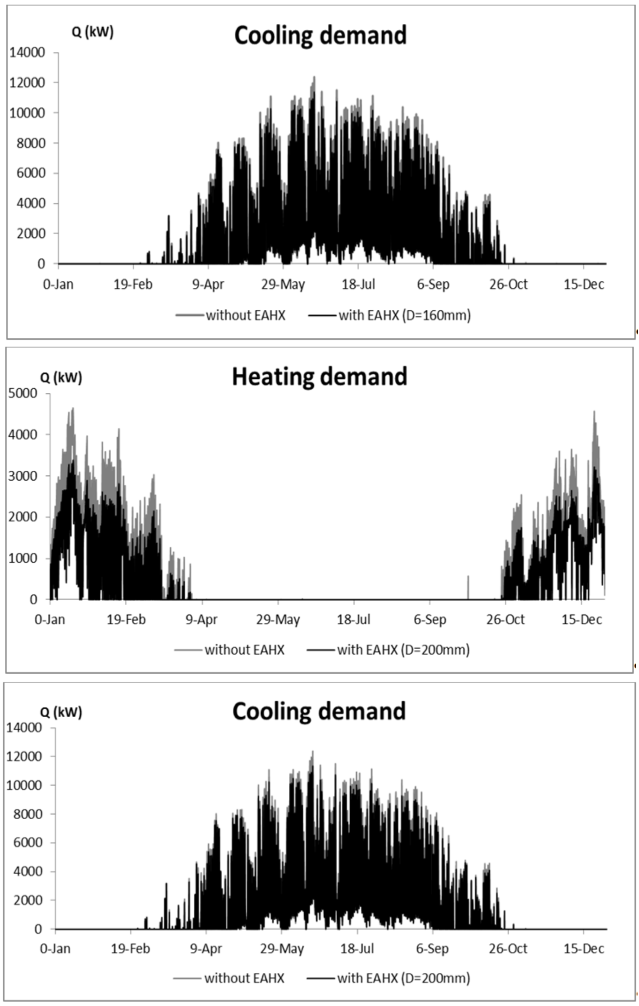



Fig. 7. Iași (heating/cooling demand without/with EAHX).

TABLE V: ENERGY CONSUMPTION (KWH/M$^2$, YEAR)

| Solution / City | Constanța | |
|---|---|---|
| | 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 | Iași | |
| | 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 |

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

Based on the values in Table V, 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).

TABLE VI: ENERGY SAVINGS (KWH/M$^2$, YEAR)

| Solution / City | Constanța | |
|---|---|---|
| | 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 | Iași | |
| | 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 |

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.

TABLE VII: HEATING AND COOLING ENERGY SAVINGS (MWH/YEAR)

| EAHX diameter/ solution | City | 110 (mm) | 160 (mm) | 200 (mm) | 400 (mm) |
|---|---|---|---|---|---|
| electric heating + cooling | Constanța | 1534 | 1704 | 1773 | 1866 |
| | Bucharest | 1922 | 2134 | 2221 | 2335 |
| | Iași | 2086 | 2305 | 2400 | 2528 |
| gas heating + cooling | Constanța | 1586 | 1762 | 1833 | 1929 |
| | Bucharest | 1994 | 2214 | 2305 | 2423 |
| | Iași | 2170 | 2398 | 2497 | 2630 |
| condensing gas technique heating + cooling | Constanța | 1445 | 1604 | 1669 | 1757 |
| | Bucharest | 1798 | 1996 | 2078 | 2184 |
| | Iași | 1941 | 2144 | 2232 | 2351 |
| liquid fuel heating + cooling | Constanța | 1644 | 1826 | 1900 | 2000 |
| | Bucharest | 2074 | 2303 | 2397 | 2520 |
| | Iași | 2264 | 2502 | 2604 | 2744 |
| wood heating + cooling | Constanța | 1958 | 2174 | 2263 | 2381 |
| | Bucharest | 2509 | 2785 | 2899 | 3048 |
| | Iași | 2770 | 3064 | 3190 | 3360 |
| wood gasification heating + cooling | Constanța | 1709 | 1897 | 1975 | 2078 |
| | Bucharest | 2164 | 2402 | 2500 | 2629 |
| | Iași | 2368 | 2617 | 2725 | 2871 |
| pellet heating + cooling | Constanța | 1644 | 1826 | 1900 | 2000 |
| | Bucharest | 2074 | 2303 | 2397 | 2520 |
| | Iași | 2264 | 2502 | 2604 | 2744 |

We estimated also heating and cooling energy savings (Table VII) as well as corresponding greenhouse gas emissions reductions (Table VIII) 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). We considered for each type of energy source (Table VII) 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.

The results in Table VIII are presented in terms of resulting $CO_2$ emissions per year, 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 [22].

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.

TABLE VIII: $CO_2$ 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 |

## VI. CONCLUSION

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.

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