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# Earth-air heat exchangers in the Belgian climate : Analysis of the potential with a 3D modelling technique

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## SYNOPSIS

Earth-air heat exchangers can be used to reduce energy consumption in building ventilation systems. The idea is to pre-heat air in winter and pre-cool air in summer using the thermal capacity of the soil. To do this concrete and plastic tubes are put underground, through which the ventilation air is drawn.

In this paper a 3D unstructured finite volume model is derived, which allows evaluating the earth-air heat exchanger. The model solves conduction through the soil and the convection from air to the tube wall. The air ground-surface heat transfer is described by the heat flux through convection and solar radiation.

The model is used to study the performance of the earth-air heat exchanger in the Belgian climate.

It is shown that in summer the air can be cooled with about 9 °C at sufficient depth (3m) and tubes of about 50 m. In winter heating of 7 °C can be realised. It is also shown that a good control strategy is important.

## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | area [m$^2$] |
| $c_p$ | heat capacity [J kg$^{-1}$ K$^{-1}$] |
| $d$ | tube diameter [m] |
| $h$ | convection coefficient [W m$^{-2}$ K$^{-1}$] |
| $L$ | tube length [m] |
| $\dot{m}$ | mass flow rate [kg/s] |

| | |
|---|---|
| $Nu$ | Nussselt number [-] |
| $Pr$ | Prandtle number [-] |
| $\dot{q}$ | heat flux [W/m²] |
| $Re$ | Reynolds number [-] |
| $t$ | time [s] |
| $T$ | temperature [K] |
| $u$ | wind speed [m/s] |
| $a$ | time constant [1/s] |
| $l$ | thermal conductivity [W $m^{-1}$ $K^{-1}$] |
| $\rho$ | density [kg/m³] |

# 1 INTRODUCTION

In order to reduce energy consumption of buildings, several passive techniques are nowadays being introduced in HVAC-installations. In most cases solar energy is directly or indirectly used to supply heat or electrical energy. Sometimes solar gains inside the building are avoided to keep down the size of the air-conditioning unit.

The soil absorbs heat from the sun and thus accumulates heat in summer. In winter the heat is released to the surrounding structures and air. Furthermore, the soil has a big thermal inertia. Because of the aforementioned phenomena the temperature of the soil (at a sufficient depth) is lower than the surrounding air in summer and warmer in winter. This effect can be used to supply a building with energy. One of the interesting techniques is to put tubes into the ground, through which air is drawn (see Figure 1). These systems are called earth-air heat exchangers.

In several European countries this technique is used for private houses and office buildings. Recent examples are found in Germany [1] and Switzerland [2]. In Belgium only two buildings exist where an earth-air heat exchanger is used. The first one is the Zenit-house, a private house [3], the second one is the Oxfam building in Ghent, an office building [4] in which several advanced passive technologies are used. In both cases no special care was taken

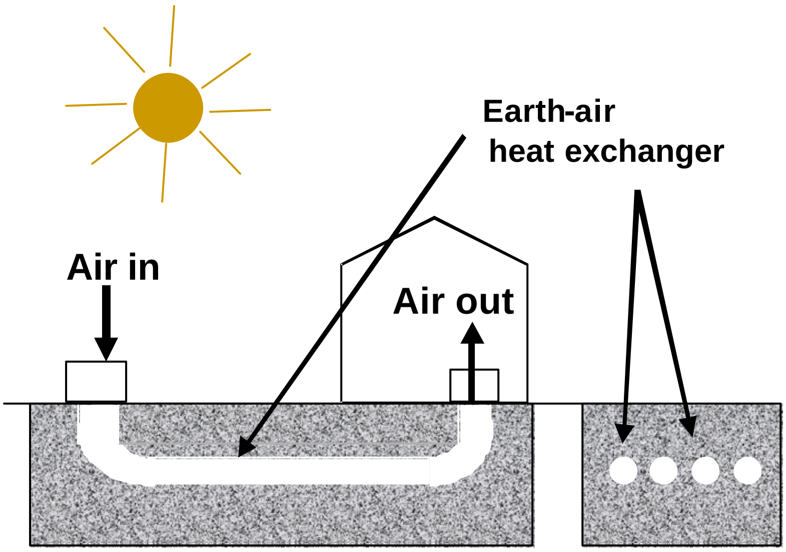

Figure 1 : Schematic of earth-air heat exchanger

for the design of the ground tube. In the Zenit-house one tube is used at a depth of 0.6 m. In the Oxfam building also one tube is used, put at a depth of 0.5 m. Therefore the thermal performance is not good.

At this moment two new office buildings are under construction in Belgium, using a more advanced earth-air heat exchanger. These were designed using the CAPSOL software [5] and a 1 dimensional model developed at the Ghent University [6]. In the near future measurement results of the performance of these buildings will be published.

Up till now no thorough analysis was made of the possibilities of the earth-air exchanger in the Belgian climate. In this paper a three-dimensional model is developed to study the performance of the earth-air heat exchanger. The conduction through the ground and the heat transfer at the ground-air surface are taken into account. This model is coupled to weather data for Uccle (Belgium) [7]. The model allows analysing the performance of the earth-air heat exchangers in the Belgian climate.

## 2 LITERATURE REVIEW

In the literature several calculation models for earth-air heat exchangers are found. Tzaferis et al. [8] studied eight models. The authors classified the algorithms in two groups:

- The algorithms that first calculate the convective heat transfer from the circulating air to the pipe and then calculate the conductive heat transfer from the pipe to the ground inside the ground mass. The necessary input data are :
  - the geometrical characteristics of the system
  - the thermal characteristics of the ground
  - the thermal characteristics of the pipe
  - the undisturbed ground temperature during the operation of the system

- Those algorithms that only calculate the convective heat transfer form the circulating air to the pipe. In this case the necessary input data are :
  - the geometrical characteristics of the system
  - the thermal characteristics of the ground
  - the temperature of the pipe surface

Six of the models use a one-dimensional description of the pipe. A relation between inlet and outlet temperature of the tube is derived. For al these models no influence of thermal capacity of the earth can be taken into account. Secondly the influence of different pipes on each other cannot be studied. They cannot predict the temperature profiles in the ground.

In one algorithm the ground is divided into coaxial cylindrical elements. The thermal resistance of the ground is considered to be time-dependent. The pipe is divided in segments. In each segment the exit temperature is determined. In another algorithm the steady-state heat balance is solved between a point in the ground and the tube.

Mihalakakou et al. [9] present a model in which the ground surrounding the pipe and the pipe itself are described in polar co-ordinates. In this model temperature and moisture profiles are included in the equations. The influence of the ground surface temperature is modelled by the superposition of the algebraic solution of the undisturbed temperature field caused by the surface air temperature and the temperature field caused by the pipe. The authors claim the importance of including the moisture content in the soil. They show good comparison of calculations and measurements. The model is solved in the TRANSYS environment. In this model it is not possible to study the influence of several pipes on each other.

Bojic et al. [10] developed a model in which the soil is divided into horizontal layers. It is assumed that the temperature of each layer is uniform. All the pipes are placed in one layer. The heat transported from the air to the soil is modelled by solving the heat balance between entrance and exit of the pipe and taking the temperature difference between the temperature at the pipe wall and the average air temperature between entrance and exit of the pipe. This model is a 2 dimensional model and the temperature variation through the pipe cannot be studied with this model. No validation is given.

None of the aforementioned models is capable of directly predicting the fully transient three-dimensional heat transfer in a multiple pipe earth-air heat exchanger. Gauthier et al. [11], describe a fully three-dimensional model. A Cartesian co-ordinate system is used. To be able to do this, the round pipes are replaced with square pipes with of equivalent areas. In this model the influence of different layers in the soil, concrete foundations and insulation can be added. Validation of the model is discussed

In this paper the last approach is further refined. In order to be able to calculate any type of geometry a unstructured grid is used. This enables the use of round tubes, without any further constraints. Furthermore the size of the grid can be varied to give more detail around the pipes and reduce calculation time where the precision is not needed.

## 3 PHYSICAL MODEL AND NUMERICAL PROCEDURE

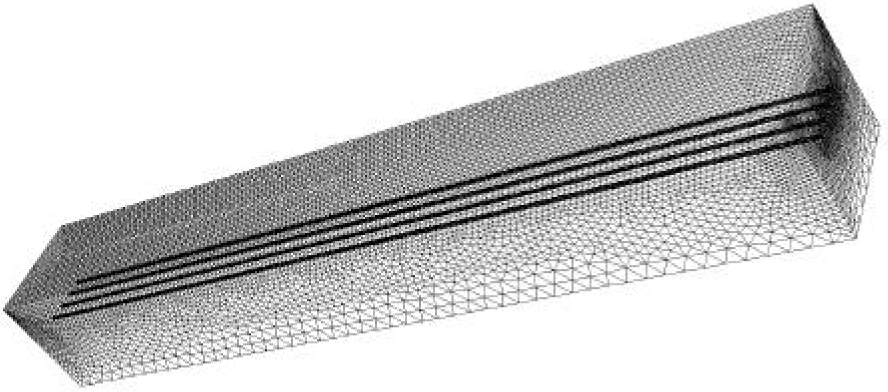

Figure 2 : A typical calculation grid

The calculation grid is considered to be a rectangular block in which cylindrical holes are drilled representing the buried pipes (Figure 2). The upper side of the rectangular block is the outside air surface. The lower side is considered to be at great distance (infinity) from the tubes. The left-hand and right-hand side of the calculation domain are considered to be adiabatic and at a sufficient distance from the tubes. The front and rear sides contain beginning and ending of the tubes.

The calculation domain is divided in finite tetrahedral volumes. For each volume the temperature is constant. For each volume the conduction equation is solved. The mesh spacing near the surface and the tubes is more refined than at the boundaries of the grid.
The airflow inside the tubes is coupled with the calculation grid through he boundary conditions at the tube wall. The tubes are divided in equal segments. The number of segments can be varied to obtain more accuracy, but is always taken big enough to have a good resolution. Figure 3 illustrates the principle. In each segment the temperature is taken to be constant. The temperature of the previous segment and the heat flux through the wall are used to calculate the temperature in a given segment.
The heat transfer model is based on the following assumptions :

1. Conduction heat transfer is transient and fully three dimensional in the soil
2. The thermophysical properties of the soil and other materials are constant.
3. Heat transfer by moisture gradients in the soil is neglected.
4. Heat transfer in the pipe is dominated by convection. It is coupled with the temperature field of the surrounding soil by the boundary conditions at the pipe surface.

Assumption 3. is justified by the fact that heat transfer processes take place over periods of 24 h and involve temperature differences of less than 10 K. Gauthier [12] showed that the maximal influence of the moisture gradients on heat transfer is below 0.1% of the total heat transfer in the soil. Puri [13] also reached the conclusion that moisture movement has little effect on heat transfer. The thermal conductivity of the soil increases with water content, but so does in a similar proportion the heat capacity.

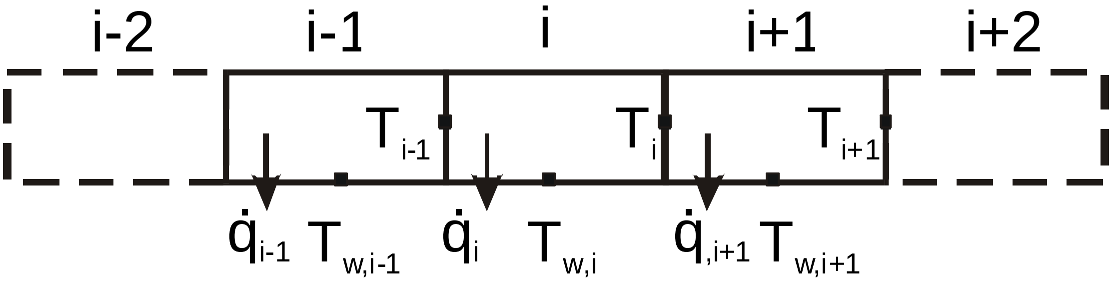

Figure 3 : Calculation of the convection inside the tube

The governing equations for the conduction in the soil may be stated as :

$$r\, c_p \frac{\partial T}{\partial t} = l\ .\nabla T \qquad (1)$$

The boundary conditions for the underground lateral external surfaces of the computational domain are assumed to be adiabatic, i.e. :

$$\frac{\partial T}{\partial n} = 0 \qquad (2)$$

where *n* is the unit vector normal to the surface.

A constant and uniform temperature for the horizontal plane deep underground is imposed.
At the ground surface the heat flux from the outside air to the surface is calculated by :

$$l\,\frac{\partial T}{\partial z} = h_{surr}\left(T_{soil} - T_{surr}\right) + \dot{q}_{sol} \qquad (3)$$

where $T_{surr}$ is the temperature of the surrounding air and $\dot{q}_{sol}$ the solar radiation at the surface. This can be a constant value or a time dependent function. $h_{surr}$ is the convection coefficient determined by an empirical correlation [14]:

$$h_{surr} = 0.5 + 1.2.u^{0.5} \qquad (4)$$

where $u$ is the wind speed above the ground surface. The temperature of the surrounding air, the solar radiation and wind speed are taken from experimental data or the Test Reference Year [7].

For the air flow inside the tubes the following equations are solved (see Figure 3) :

$$\dot{q}_n = h_{tube}\left(T_{i,m} - T_w\right) \qquad (5)$$

$$\dot{q}_n A_{segment} = \dot{m}_{air} c_{p,air}\left(T_i - T_{i-1}\right) \qquad (6)$$

where $A_{segment}$ is the inside surface area of the tube segment, $\dot{q}_n$ the heat flux over it. Equation (6) is the energy balance for the air flow. The convection coefficient $h_{tube}$ is determined by the Gnielinski correlation for turbulent flow [15]:

$$Nu = \frac{\frac{x}{8}\left(Re - 1000\right)Pr}{1 + 12.7\sqrt{\frac{x}{8}}\left(Pr^{\frac{2}{3}} - 1\right)} \qquad (7)$$

$$x = \left(1.82\log(Re) - 1.64\right)^{-2}$$

and for laminar flow [15] :

$$Nu = \left[3.66^3 + 0.7^3 + \left(1.615\frac{Re\,Pr\,d}{L} - 0.7\right)^3\right]^{\frac{1}{3}} \qquad (8)$$

Finally the heat flux is calculated by equation (5). Here the driving force is the temperature difference between the wall temperature $T_w$ and the average temperature of the air in the segment :

$$T_{i,m} = \frac{\left(T_i + T_{i-1}\right)}{2} \qquad (9)$$

The wall temperature is calculated by taking the weighted average over the surface of the segment's faces :

$$T_w = \frac{1}{A_{segment}}\sum_{faces} A_{face} T_{face} \qquad (10)$$

The entrance temperature of the tube is taken to be the air temperature at the surface and can be varied with time.

The boundary condition at the tube surface is thus :

$$\lambda\frac{\partial T}{\partial z} = \dot{q}_n \qquad (11)$$

The calculation is generated with the GAMBIT grid generation software [16]. The conduction equations are solved with FLUENT 3D [16]. The routines for the boundary conditions of the tubes have been added by user defined subroutines to the Fluent environment.

## 4 VALIDATION OF THE MODEL

### 4.1 One-dimensional conduction

In a first test case the solution of the conduction equations is validated. The problem of a semi-infinite solid onto which at one side a temperature is imposed is calculated. As there is no heat flux in x and y directions (sideways) this problem can be analytically solved as a one-dimensional conduction problem. Following boundary conditions can be applied :

The surface temperature is :

$$T(t,0) = T_s \qquad (9)$$

And the initial value of the ground temperature is

$$T(0,z) = T_\infty \qquad (10)$$

The analytical solution is given by :

$$T(t,z) = T_s + (T_\infty - T_s)\, erf\left(\frac{z}{2\sqrt{at}}\right) \qquad (11)$$

where $\alpha = \frac{\lambda}{\rho c_p}$.

Calculations were done with $\rho$ = 1800 kg/m³, $\lambda$ = 0.5 W/m.K, and $c_p$ = 2000 J/kg.K.

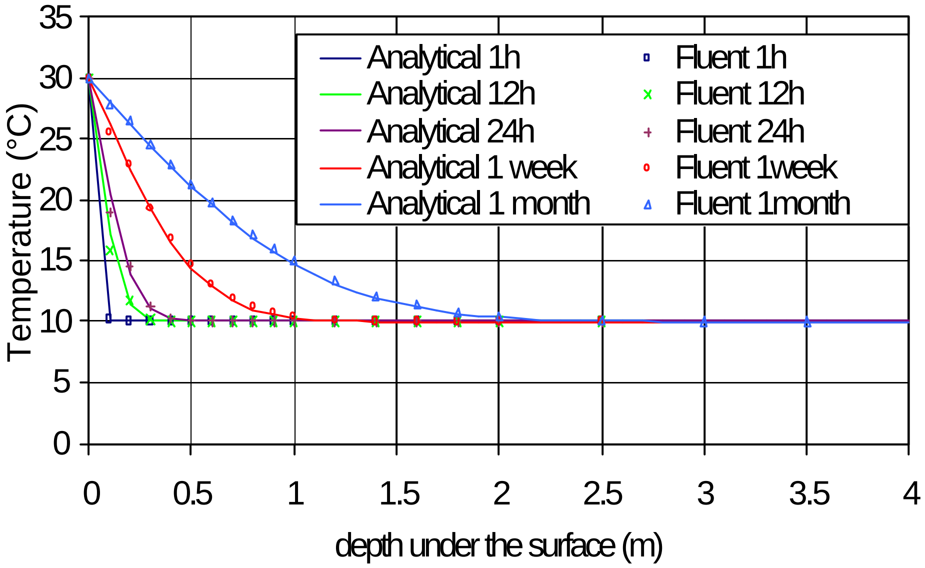

Figure 4 : Validation of the conduction model with an analytical solution

In Figure 4 the analytical solution is shown for time steps of 1h, 12h, 24 h, 1 week and 30 days, with initial value of $T_\infty = 10$ °C and $T_s = 30$ °C. The abscissa shows a variation of depth from z = 0 m to 4 m. In the same figure the numerical results are shown for the simulation with the same values. A good correspondence is found. It is also shown that temperature influence at a depth of more than 3 m is not important.

### 4.2 Earth-air heat exchanger

Secondly measurement data provided by Tzaferis et al. [8] were used to validate a real simulation of a ground tube. In Figure 5 the input data are shown. These were realised by placing a heater in front of the tube to control the inlet air temperature. The ground temperature at 1.1 m depth is nearly constant and is 23 °C.

The tube has a diameter of 0.15 m and a length of 14.8 m and is placed at a depth of 1.1 m. A constant air mass flow rate of 4.5 m/s is circulated continuously through the pipe during 9 days. Calculations were made with the same values for the soil characteristics as in the previous section.

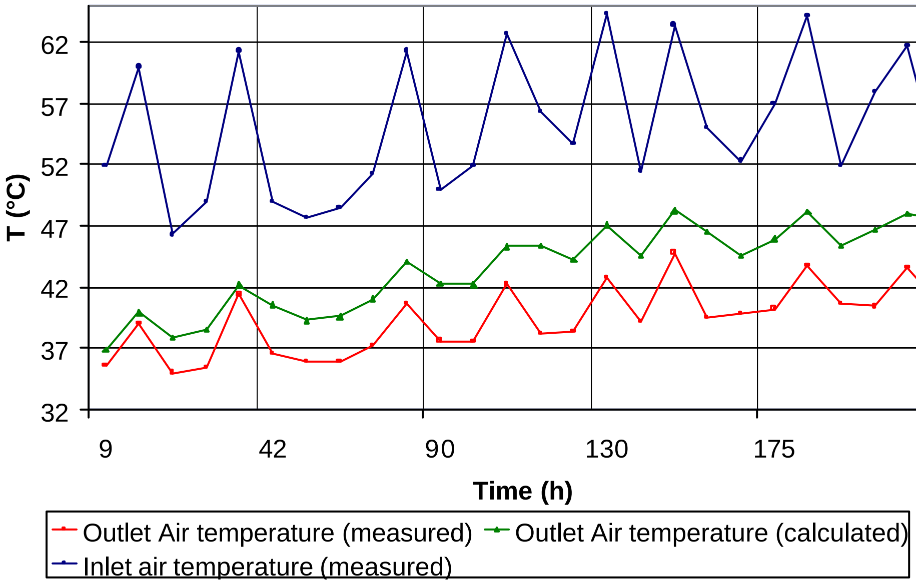

Figure 5 : Validation of the model with measurements

In Figure 5 the measured outlet temperatures and the calculated outlet temperatures are shown. The calculations follow the same trend as the measurements. The model underpredicts the cooling by approximately 2 °C to 5 °C on average. This is caused by the fact the exact composition of the soil and thus the characteristic values for heat capacity and thermal conductivity are not known. The results show that the calculation model gives a good representation of the behaviour of the earth-air heat exchanger.

## 5 PERFORMANCE IN THE BELGIAN CLIMATE

### 5.1 Scope

The described model was use to study the behaviour of an earth-air heat exchanger in the Belgian climate situation. Therefore the weather data of the Test Reference Year of Uccle (Belgium) were added to the simulation [7]. With these data the whole year was simulated twice tot damp out the transient phenomena. The obtained solution was used as basis for the simulation of a real year.

The problem of four tubes with a diameter of 0.2 m and a length of 50 m was solved as a reference case. A total air flow rate through the tubes of 3000 $m^3$/h is assumed, resulting in and air velocity of 7.8 m/s inside the tubes. The tubes are placed at a depth of three meter under the ground surface. The distance between the tubes is 1 m. These data were chosen in accordance with the rules of thumb for the design of earth-air heat exchangers given by Santamouris et al. [17].

With the aforementioned assumptions the heat exchangers were calculated for the whole year. First some general aspects will be discussed. Secondly a typical summer week in the Belgian climate is studied. Finally a typical winter week is analysed.

## 5.2 General aspects

Figure 6 shows two planes cutting through the calculation domain,one along the length of a tube, and one perpendicular to it. The data presented are for the winter situation. We can see that the top layer of the soil is frozen (below 0 °C). At a depth of about 1 m the temperature starts to rise to about 15 °C at 2.5 m. This high temperature zone is strongly influencing the top side of the tubes.

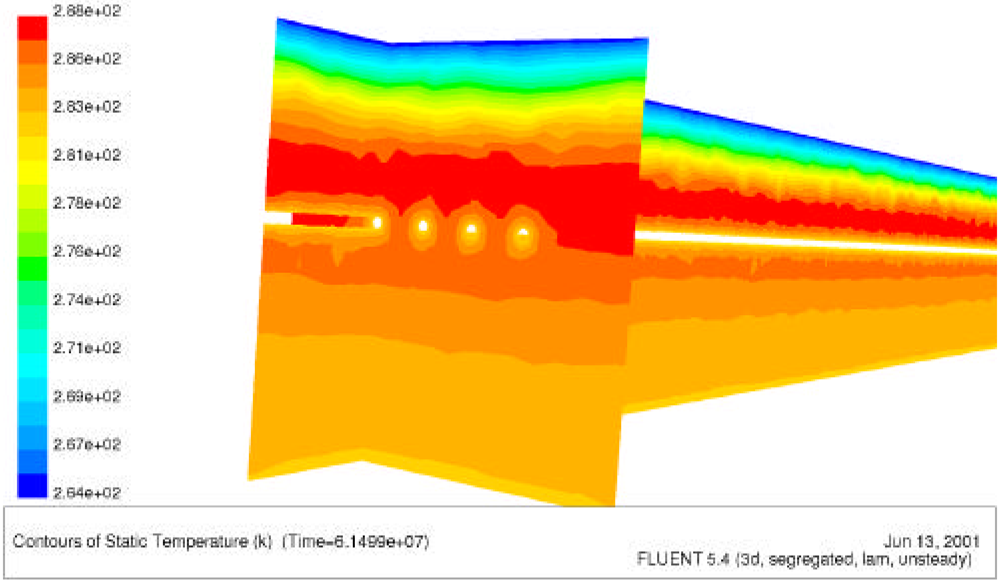

Figure 6 : A cut through the calculation domain

In the surroundings of tubes a clear temperature drop in the soil can be detected up to two diameters from the tubes. This zone is seen along the whole length of the tubes. Due to the use of the 3-dimensional model, this can be clearly calculated. The tube spacing of 1 m is not sufficient to damp out the influence of the tubes on each other.

## 5.3 A typical summer week

To address the summer performance of the earth-air heat exchanger the week from July 21 to July 28 was calculated. Figure 7 shows the inlet air temperature (i.e. the outside air temperature) as defined by the TRY and the calculation results. At a maximum air temperature of 27.6 °C cooling to 18.2 °C is possible, which is a temperature difference of 9.4 °C. In general the calculations show that the earth-air tubes used here, damp out the variations in air temperature. This is mainly caused by putting them at a depth of 3 m and by the length as shown in the previous paragraph.

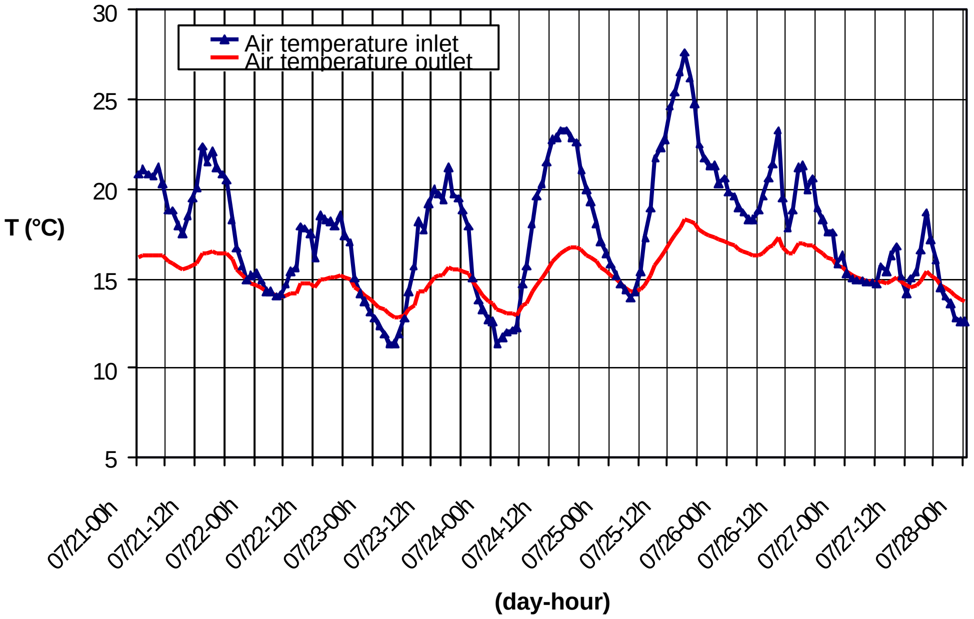

Figure 7 : Calculations for week from 21/7 to 28/7

Secondly a phase shift between the tube exit temperature and the inlet temperature can be detected. The response of the tubes is about 1 hour slower than the temperature at the exit.
Figure 7 also shows that during the night the air temperature is lower than the temperature leaving the earth-air heat exchanger. This clearly shows that a good control strategy is needed when an earth-air heat exchanger is connected to a building. By-passing of the tubes, and thus taking air directly from the surroundings of the building, has to be allowed. As the summers

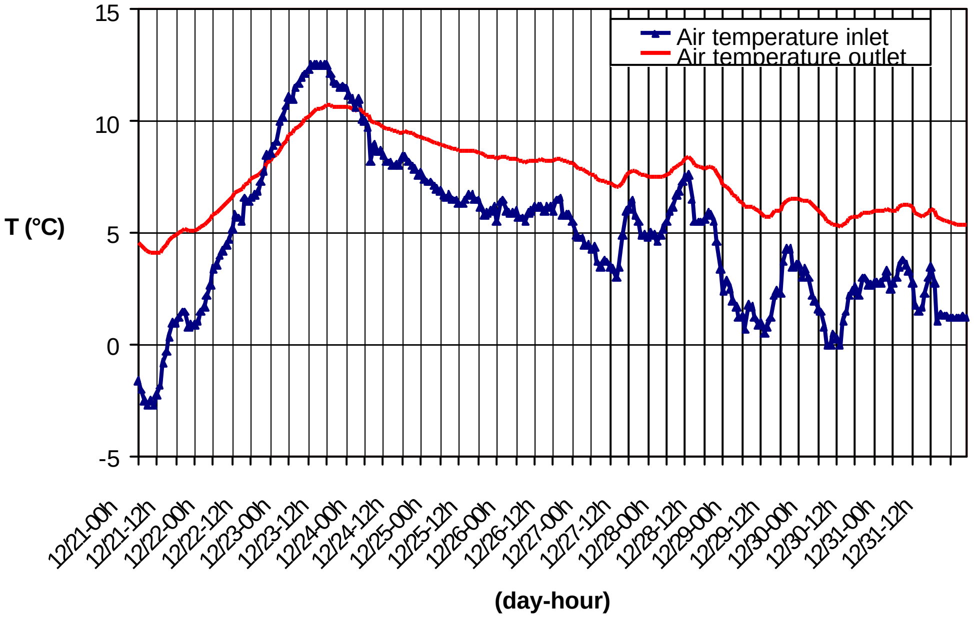

Figure 8 : Calculations for week from 21/12 to 28/12

in the Belgian climate are moderate, the earth-air heat exchanger has potential to supply a building with low temperature air. By doing this, cooling installations can be reduced in capacity or even omitted.

### 5.4 A typical winter week

In figure 8 the results are shown for the week from December 21 to December 28. During cold days the air is heated from -2.7 °C to 4.3 °C, being a temperature difference of 7.0 °C.

The same phase shift can be detected as in summer. During warmer winter days the air is not heated but cooled by the ground tubes. This is a situation that is not allowable. This again confirms the fact that at all times it is necessary to monitor the outside air temperature and the exit temperature of the earth-air heat exchanger. For the Belgian winters the earth-air heat exchanger can reduce the power needed for heating, but heating cannot be avoided.

## 6 CONCLUSION

In this paper a fully three-dimensional unstructured conduction model is presented, which is coupled to the convection problem of air flowing through tubes buried in the soil. This model can be used for studying earth-air heat exchangers. The model is validated with two different test cases. The model is used to study the use of earth-air heat exchangers in the Belgian climate situation.

It is shown that the influence of the pipe on the temperature of the surrounding soil is detected to a distance of twice the diameter of the tube. To make optimal use of the thermal capacity of the soil and to eliminate the influence of the outside air, the tubes have to be buried below 2.5 m. Finally typical summer and winter weeks have been simulated. It is shown that the earth-air heat exchangers have great potential. Cooling with 9 °C or heating with 7 °C is possible.

Due to the moderate winters and summers in Belgium, it is important to apply a good control strategy when an earth-air heat exchanger is used. Bypassing of the heat exchanger has to be allowed.

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