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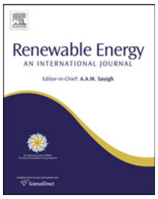

Earth-to-air heat exchangers for Italian climates

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ABSTRACT

The European Energy Efficiency Building Directive 2002/91/CE, as well as other acts and funding programs, strongly promotes the adoption of passive strategies for buildings, in order to achieve indoor thermal comfort conditions above all in summer, so reducing or avoiding the use of air conditioning systems.

In this paper, the energy performances achievable using an earth-to-air heat exchanger for an air-conditioned building have been evaluated for both winter and summer. By means of dynamic building energy performance simulation codes, the energy requirements of the systems have been analysed for different Italian climates, as a function of the main boundary conditions (such as the typology of soil, tube material, tube length and depth, velocity of the air crossing the tube, ventilation airflow rates, control modes). The earth-to-air heat exchanger has shown the highest efficiency for cold climates both in winter and summer.

The possible coupling of this technology with other passive strategies has been also examined. Then, a technical-economic analysis has been carried out: this technology is economically acceptable (simple payback of 5–9 years) only in the cases of easy and cheap moving earth works; moreover, metallic tubes are not suitable.

Finally, considering in summer a not fully air-conditioned building, only provided with diurnal ventilation coupled to an earth-to-air heat exchanger plus night-time ventilation, the possible indoor thermal comfort conditions have been evaluated.

1. Introduction

An earth-to-air heat exchanger (EAHX) consists in one or more tubes lied under ground in order to cool (in summer) or pre-heat (in winter) air to be supplied in a building. This air is often outdoor air necessary for ventilation, but also useful to partially or totally handle the building thermal loads. The physical phenomenon is simple: the ground temperature is commonly higher than the outdoor air temperature in winter and lower in summer, so it makes the use of the earth convenient as warm or cold sink, respectively. Normally, the soil temperature, at a depth of 5–8 m under the ground level, remains almost constant throughout the year; its temperature profile as a function of the depth depends on several factors, such as the physical properties of the soil, the sky covering and the climate conditions [1].

Givoni [2] identified two macro-groups of earth tubes, those with open and closed loop; in this paper, the first typology has been considered. Typical buried tube lengths are 30–60 m, usually posed at 2–4 m under ground level. The tubes are located in almost horizontal position, with a slight inclination to remove possible condensed water.

A physical model to simulate the EAHX was developed and validated by Mihalakakou et al. [3,4]. Benkert et al. [5] underlined the lack of optimisation criteria; moreover, they developed the computer tool GAEA, based on a physical model and then experimentally validated with good results.

The EAHXs are characterised by high energy saving potential and require low maintenance. Moreover, Pfafferot [6] underlined that in winter the re-heating of the air downstream of the EAHX is however necessary before supplying air in the building, while in summer indoor comfort conditions are sometimes achievable also without an active re-cooling.

However, few research investigations [7,8] have been carried out to evaluate the energy performances of the EAHX as a function of the main boundary conditions, above all for Italian climates.

Thus, in this paper an extended parametric analysis on EAHXs is presented, starting from a validated physical-mathematical model. This investigation has been carried out by using appropriate dynamic simulation codes, especially Energy Plus [9] and Calculation Soil Temperature [10]; some modelling conditions adopted in

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these codes have been calculated also by means of the above mentioned GAEA code.

Three different Italian climates (cities of Naples, Rome, Milan) and an air-conditioned building have been analysed for both winter and summer. The energy requirements of these systems have been evaluated as a function of the main boundary conditions (such as the typology of soil, tube material, tube length and depth, velocity of the air crossing the tube, ventilation airflow rates, control modes). Then, the possible coupling of this technology with other passive strategies has been examined, and a technical-economic analysis has been performed.

Finally, considering in summer a not fully air-conditioned building, only provided with diurnal ventilation coupled to an earth-to-air heat exchanger plus night-time traditional ventilation, the possible indoor thermal comfort conditions have been evaluated.

2. Case study and results

2.1. The complex building-system and the used physical model

In Fig. 1, the modelled office building is shown: it is well thermally insulated, with efficient heating and cooling systems. The main characteristics of the building and systems are reported in Table 1.

Several authors studied the physical model governing the earth-to-air heat exchange: the Krarti's model [11] is here used. A full description of the model, as well as the model validation, is reported in Reference [7], while in the following only the main characteristics of the model are shown.

The heat transfer mechanisms around the earth tube are quite complex, so some assumptions have been made:

- the pipe has a uniform internal/external diameter in the axial direction;
- the soil around the pipe is homogeneous and its thermal conductivity has a constant value;
- the soil temperature near the pipe is not influenced by the pipe, so the surface temperature of the pipe is uniform in the axial direction;
- the convective flow inside the pipe is thermally and hydrodynamically developed.

The annual $T_{MEAN\ SURF}$ of the soil is calculated by means of the Equation (1):

$$T_{MEAN\ SURF} = (1/h_e)\cdot[h_r\cdot T_{MEAN\ AIR} - \varepsilon\cdot\Delta R + \beta_s\cdot S_m - 0.0168\cdot h_s\cdot f\cdot b(1-RH)] \quad (1)$$

As regards h_e and h_r, both are related to the convective heat transfer coefficient at the soil surface, h_s, as described in the Equations (2) and (3), with $a = 103$ Pa/°C.

$$h_e = h_s\cdot(1+0.0168\cdot a\cdot f) \quad (2)$$

$$h_r = h_s\cdot(1+0.0168\ \cdot a\ \cdot RH\cdot f) \quad (3)$$

So, h_e and h_r represent the convective heat transfer coefficient at the soil surface, increased taking into account, respectively, the fraction of evaporation rate (h_e) and the fraction of evaporation rate plus the relative humidity of the ambient air (h_r).

The phase angle difference between the air and the soil surface temperature trends, the amplitude of the soil surface temperature variation (A_s), and the related phase constant (t_0) are then determined. Considering a soil characterised by uniform thermal diffusivity α_s, the Equation (4) provides the ground temperature as a function of depth and time.

$$T_{GROUND}(z,t) = T_{MEAN\,SURF} - A_s\exp\left[-z(\pi/365\cdot\alpha_s)^{1/2}\right] \cdot\cos\left\{(2\pi/365)\cdot\left[t-t_0-(z/2)(365/\pi\cdot\alpha_s)^{1/2}\right]\right\} \quad (4)$$

The main equations describing the heat exchange between soil, buried tubes and crossing air are:

$$R_{conv} = 1/(2\pi\cdot r_1\cdot L\cdot h_c) \quad (5)$$

$$R_{cond-tube} = \left[1/(2\pi\cdot L\cdot k_p)\right]\cdot\ln\left[(r_1+r_2)/r_1\right] \quad (6)$$

$$R_{cond-tube/soil} = [1/(2\pi\cdot L\cdot k_s)]\cdot\ln[(r_1+r_2+r_3)/(r_1+r_2)] \quad (7)$$

The distance between the tube external surface and the undisturbed soil (r_3) is assumed equal to the radius of the tube.

$$h_c = Nu\cdot k_{air}/2\cdot r_1 \quad (8)$$

$$U_t = 1/R_{tot} \quad (9)$$

$$R_{tot} = R_{conv} + R_{cond-tube} + R_{cond-tube/soil} \quad (10)$$

The heat transfer between the air inside the tube and the soil is characterised by the following equation:

$$U_t dy[T_a(y) - T_{GROUND}(z,t)] = -\dot{m}_a c_a[dT_a(y)] \quad (11)$$

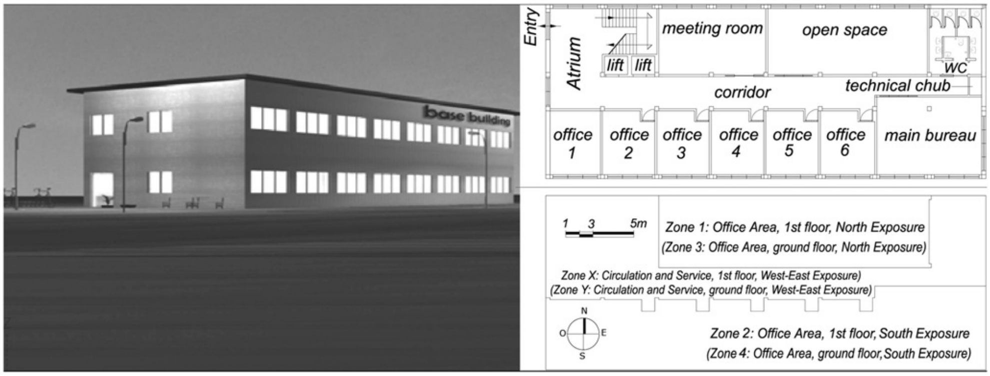

Fig. 1. The modelled building: volumetric scheme, plan of the ground floor and thermal zones.