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EAHX – Earth-to-air heat exchanger: Simplified method and KPI for early building design phases

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ABSTRACT

Earth-to-air heat exchangers (EAHX) are a recognised technology which are able to naturally pre-cool and preheat an airflow. In this paper a method is presented to analyse the potentiality of this technique in specific locations in order to optimise and check their ability to cover the expected building energy demand as early as possible. The proposed method is conceived for early-design phases and includes a model to estimate outlet air temperature after EAHX treatment including an average local meteorological year, soil typology and early-design choices. The model is further validated on long-term experimental data and used to develop 3 Key Performance Indicators (KPI) to better define the early design conception of an EAHX in the site context. These KPI include the analysis of activation hours based on a psychrometric chart, the calculation of the expected sensible heat exchange of the system (winter and summer), and the "virtual" COP in consideration of the theoretical calculation of pressure drops. Finally, main limitations of this simplified approach are discussed.

1. Introduction

The building sector is responsible for a large amount of energy consumption (about 40% of primary energy consumption in industrialised countries [1–3]) and consequent GHG emissions in the atmosphere [4]. Some advancements have been made in the form of regulations and agreements to reduce this consumption and relative impact but further efforts are required. With reference to building, most consumption is related to space heating, cooling and ventilation [5] suggesting, on the one hand, the need to increase the efficiency of the systems and, on the other hand, to incentivize and spread the use of alternative solutions based on natural and renewable sources. In this sense, passive cooling and heating technologies are welcome and may be used to substantially reduce energy needs. Nevertheless, especially for cooling, potential technologies for heat-gain dissipation need to be carefully analysed from early-design phases due to their local potentiality, which is not as simple as in the majority of passive heating solutions which are linked with solar gains [6,7]. For this reason, specific early-design tools and methods are important to ensure an early local-climate evaluation of these technologies, based on heat sinks – i.e. air, water, ground, night sky – [see also [8] [9] [10]], in order to increase their potential integration into building design and their diffusion. Of these technologies, the ones related to ground cooling can be classified according to the flow used (e.g. water, air), the typology of system (vertical, horizontal), and their integration with building mechanical systems (e.g. Air Handling Units – AHU, heat pumps). For a description of Borehole Heat Exchangers (vertical water systems) it is possible to refer to [11,12], while a literature review about water-based systems and calculation models is included in Ref. [13]. This paper, however, focuses on Earth-to-Air Heat Exchangers – EAHX – which are horizontal ventilative ground cooling/heating systems based on the use of air as a heat flow. EAHXs are characterised by low installation and maintenance costs, due to limited laying depth and the simple materials used (e.g. polyethylene tubes), and high integration potentials both directly in free-running buildings, and coupled with HVAC systems. Even if the number of monitored databases related to EAHX systems is limited [10], some examples are reported in literature [see Refs. [12] [14], [15] [16], [17] [18]]. Furthermore, methodologies for designing EAHX systems are reported in Refs. [10,19,20]. A simplified tool to design an EAHX system is represented by GAEA, developed by the Software Laboratory for Low Energy and Solar Energy at the Department of Physics in the University of Siegen [21–23], while specific modules to dynamically simulate the behaviour of EAHXs were developed for TRNSYS – i.e. TRNSYS Type 31 or TESS libraries GHP components –, see models and analyses in Refs. [24–27] and further validation in Ref. [28], and EnergyPlus, as described in Refs. [29,30] and further validated in Ref. [31]. Furthermore, CFD applications are, for example, reported in Ref. [32] by using AirPak v2.1 and in Ref. [31] for Fluent. Different approaches are also reported in Ref. [33] using THERM and in Ref. [34] using Sim Space. Even if several models are presented in literature,

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most of them are devoted to advanced design stages which involve high costs and long simulation times. However, a simplified approach to designing EAHX can be found in the above-mentioned GAEA software, which has a simple interface but needs attentive processes to be used for climates not included in the internal database, and is focused on expected heat gain and loss. Furthermore, another simplified approach to designing EAHX systems is described in Ref. [70] which suggests calculating the treated airflow by using the NTU (net transfer unit) approach. However, this approach, as mentioned by the author, can be used only when the NTU parameter doesn't exceed 2.5. Furthermore, the calculation of NTU, which does not include the transitional nature of EAHX, thus risking the overestimation of the effectiveness of the system, can be a difficult point for architects and environmental designers to deal with. Moreover, other approaches, such as the one described in Ref. [71], allow us to define the potential effectiveness of an EAHX system by using a series of polynomial expressions that normalise the effect of single design choices to further correlate all modifiers. In this paper a methodology is introduced and validated by using long term monitoring results in order to define an early-design approach – see Ref. [65] – to EAHX, including energy and technological issues and relating to a performance-driven approach – see for example [68] - which is conceived to be used by architects and constituted by different indicators – see the following §1.1. Furthermore, this approach allows us to generate maps of applicability easily for large sets of locations and can be used in energy policy approaches.

1.1. Paper's structure and main objective

In this paper, a methodology to evaluate EAHX potential in preheating and pre-cooling an airflow together with the main technological requirements connected with the design of EAHX systems are presented. This method is principally devoted to early design stages to facilitate a first definition of the possible contribution of EAHX systems in covering the heating and cooling demands of a building by also taking into consideration a "virtual" potential coefficient of performance (COP [$\mathrm{kWh_{th}/kWh_{mech}}$]). Furthermore, the method is also adapted to be used to calculate the number of comfort/discomfort hours, which is a recognised indicator for free-running buildings [e.g. Ref. [67]], and also to analyse potential EAHX effect on comfort hours on a Givoni-Milne bioclimatic chart, which is widely used by environmental and bioclimatic architects [69].

The proposed method is illustrated in §2. In particular, in §2.1. A model to estimate the treated air conditions due to EAHX including the definition of principal connected parameters is discussed. In §2.1., a validation of this simplified model is also presented by using a long-term monitoring database. Furthermore, in §2.2., three Key Performance Indicators – KPI – to define EAHX potential in early-design phases while considering comfort analysis on an hourly basis along with a virtual approach to estimate winter and summer heat exchange due to EAHX and a method to calculate virtual COP to optimise early-design decisions are introduced. Moreover, in §3. The limits of the presented simplified method are analysed and discussed. The proposed method can be used both by energy consultants and designers including architects and engineers. The approach is principally devoted to early design phases such as building programming and further preliminary design. For a definition of building programming with regard to environmental and low-energy issues see Refs. [65,66].

2. Climate-based method to pre-define EAHX potential in early design stages

2.1. Simplified EAHX outlet-air estimation model

An EAHX system allows for sensible heat exchange between an airflow and the soil. A simple parameter to define the effectiveness of such types of system is reported in the following expression, also known as the Scott, Parson and Koehler' formula [10,14,15]:

$$\varepsilon_{EAHX} = \frac{(\vartheta_{in} - \vartheta_{out})}{(\vartheta_{in} - \vartheta_{soil,h})} \quad [-] \tag{1}$$

Where, ϑ is the dry bulb temperature of the inlet airflow ($_{\mathrm{in}}$), the outlet treated airflow ($_{\mathrm{out}}$), and the ground at the EAHX depth ($_{\mathrm{soil,h}}$).

It is possible to estimate the outlet airflow temperature at a given hour as a function of the inlet air condition, the soil temperature at a given depth and the average effectiveness of system [20,35]. Hence, the expression will be:

$$\vartheta_{out} = \vartheta_{in} - \varepsilon_{EAHX} \cdot (\vartheta_{in} - \vartheta_{soil,h}) \quad [°C] \tag{2}$$

Here below each of these three parameters is analysed in detail.

2.1.1. Definition of principal parameters to estimate the EAHX outlet temperature

2.1.1.1. Environmental-inlet air temperature. The inlet-airflow temperature can be assumed to be that of the environmental air. It is possible to assume this value from several sources such as typical hourly-defined meteorological years (TMY), meteorological databases (e.g. Meteonorm 7. x or EnergyPlus and TRNSYS databases), or monitored data. Furthermore, it is also possible to consider data with a different temporal definition, for example, the average monthly temperatures included in devoted national regulations such as, for Italy, the UNI 10349, which was recently updated (2016) to take into account climate changes based on new database elaborations (CTI). The choice of the meteorological database can significantly influence the results of energy simulations, as was demonstrated in several studies [36–39]. Furthermore, other local parameters may affect the environmental air temperature such as the presence of obstacles (shading etc.), the average heat absorption of outdoor materials, or the local urban heat island, which can be estimated in order to generate a modified TMY as described in Refs. [40,41].

2.1.1.2. Ground temperature at a given depth. The ground temperature is influenced by several factors. These factors can be classified into two main categories: the approximate constant yearly temperature of the soil at a sufficient depth (e.g. 100 m [10]), and the soil surface temperature over a year [35]. The first boundary condition class can be estimated by measuring the temperature of water in a sink in the considered location. Nevertheless, it is also possible to assume this value by using as a rule of thumb the average yearly outlet temperature increased by 1–1.5 °C [42]. The second condition is a function of several variables, for example, local meteorological conditions, the presence of obstructions, the ground surface materials and colours, or soil thermal properties. Nevertheless, daily variations, e.g. due to direct solar radiation and air humidity, principally influence the first centimetres of ground depth and have a low impact on the average behaviour of deeper soil. For this reason, they can be almost ignored for EAHX estimation [10]. Hence, in early design, it is possible to approximate the ground temperature at a given depth by assuming a fluctuation around the yearly average outdoortemperature [12] – see also Ref. [43].

As regards the EAHX, the required parameter is the ground temperature at a given depth. This value can be estimated by using Hadvig's expression reported here below [7,35]:

$$\vartheta_{soil,h} = \vartheta_{av.\,soil_{surf.}} + \Delta\vartheta_{s.yr}\ \exp\left(-h\sqrt{\frac{\pi}{\alpha t_0}}\right)\cos\left(\frac{2\pi}{t_0}(t - t_\varphi) - h\sqrt{\frac{\pi}{\alpha t_0}}\right) \quad [°C] \tag{3}$$

Where $\vartheta_{av.\,soil_{surf.}}$ is the annual mean dry bulb temperature of the soil surface [°C], $\Delta\vartheta_{s.yr}$ is the annual semi-amplitude of the variation of the soil surface temperature [°C], α is the diffusivity of the ground [m^2/s] – calculated using the following expression: $\alpha = \frac{\lambda}{\rho c}$, where λ is the