DESIGN OF NEARLY ZERO ENERGY BUILDINGS COUPLED WITH AN EARTH TO AIR HEAT EXCHANGER IN MEDITERRANEAN CLIMATE: DEVELOPMENT OF AN ANALYTIC MODEL AND VALIDATION AGAINST A MONITORED CASE STUDY

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ABSTRACT

At the Passivhaus of Cherasco, located in Pianura Padana (Italy), an earth to air heat exchanger (EAHE) and natural night ventilation (in summer) are used to deliver comfort conditions with very low energy consumption. One year and a half of continuous measurements have been carried out in order to evaluate the energy and comfort performances of this building, which combines the Passivhaus concept with local architectural solutions. We present an analysis of the system constituted by building envelope and EAHE. Monitored data (with a particular focus on cooling potential) were evaluated with the use of established indicators and compared with simulations performed by coupling dynamic simulation software (EnergyPlus) and an analytic model for the EAHE. Based on this analysis a simplified steady-periodic model is developed to provide an estimate of the behaviour of the coupled system building envelope (including night ventilation) and EAHE from the point of view of energy and comfort, over a period of few weeks. The model is validated towards monitored data and shows a good agreement in terms of temperature profile, with a slight phase discrepancy, as expected based on the simplifying assumptions about thermal capacity effects.

The analytic model is proposed as a tool for (i) evaluating the integration of EAHEs during the early design phase and (ii) optimise their operation under variable weather and occupation conditions, via incorporation in the control software of the building.

INTRODUCTION

As the minimum energy requirements for new building construction have been made more stringent during the last few years and the target Nearly Zero Energy is the challenging horizon for the construction industry in the near future (e.g. the recast of the EU Directive on energy performance of buildings (EPBD-r) requires all new buildings to be nearly zero starting by 2021), there is a rising interest for low-energy heating and cooling strategies both in research and application.

As for the heating and cooling systems that use the ground as source/sink of energy, many valuable experiences (Mihalakakou 1994, Zimmermann 2001, Hollmuller 2002, Pfafferott 2003) described direct and indirect coupling systems using air as the thermo-vector fluid and streamlined their design, some including their hydraulic optimization (De Paepe 2003) and their life cycle costs (Chel 2009). In these cases, the Earth-to-Air Heat Exchangers (EAHEs) are generally underground horizontal ducts (under the building or the surrounding area) to moderate depths (generally not exceeding 5 m), where outside fresh air or re-circulation air is channelled.

Interesting application examples have been documented in various building typologies: from shopping centres to greenhouses (Santamouris 1996), from large office buildings (Zimmermann 1997) to traditional residential building and passive houses (Wagner 2000, Carlucci et al. 2013). As their application has initially taken place in the central and northern Europe, whose climatic characteristics (low average yearly temperature and sometimes high annual and daily temperature swing) may enhance their effectiveness for cooling, in recent years some more research and test of their potential in other climatic regions – e.g. in the Mediterranean and hot climates (Al-Ajmi 2006) – has been performed.

Regarding the cooling phase, the EAHEs are used either as stand alone systems or as additional auxiliary systems. E.g. in summer the pre-cooling effect can be used to increase the performance of reversible air-to-air heat pumps (GSHP), but it is also possible to combine it with other passive or low-energy strategies, such as night natural or mechanical ventilation and radiant systems (slab cooling and cooled ceiling).

According to Zimmermann (2001), for the design of EAHEs for the warm season it is possible to refer to the following major categories of application:

- "comfort cooling" designed to increase indoor comfort (and indoor air quality) and generally characterized by a mechanical ventilation system set on relatively low and constants flow rates (ach in the range 0,5 to 1,0 h^{-1}).

- "room cooling systems", where the operating flow rates are increased (between 2,0 to 4,0 h^{-1}) to remove the high internal loads; if with constant loads such strategy is often limited by the exhaustion of the storage capacity of the soil, in presence of a good daily range of the outside temperature, that capacity can be regenerated during the night (by correctly adopting bypass logics).
- as "auxiliary cooling system" coupled with systems able to meet the peaks of temperature, their use can be very effective in dissipating the base load and ensure adequate levels of ventilation.

While the past experiences discuss a rather large range of realizations, providing consolidated design information and showing the potential of these systems, critical issues are recognized about modelling their integration with the building (Kalz 2006, Hollmuller 2005) in ways appropriate to various design stages.

Regarding the modelling of EAHEs, a number of studies have been proposed for the calculation of the main design variable: the air temperature at the outlet of the heat exchanger. The physical problem, which covers the intermediate calculation of unknowns such as the undisturbed soil temperature and wall temperature of the buried pipe, has been treated through a variety of geometric configurations, simplifying assumptions and mathematical treatment.

The main phenomena characterizing the problem are:

- the heat flow by convection and radiation at the free surface of the ground, mainly under the action of the air temperature and the solar radiation, and the energy transfer by re-radiation and evapotranspiration from the soil surface to the sky and the atmosphere;
- the penetration of the thermal wave (by conduction) into the ground;
- the thermal interaction between the EAHE system and the volume of surrounding soil;
- the reciprocal influence of underground pipes when more than one is present;
- the thermal influence of the building;
- the influence of thermal aquifers;
- the condensation of water vapour inside the heat exchanger;
- the flow of geothermal energy from the earth's core.

With the development of computational tools, two families of approaches have consolidated: the analytical and the numerical models. While to the latter is generally recognized the ability to derive quantitative results with more detail, the analytical approach is being rediscovered for its simplicity and because it allows a more direct understanding of the influence of the different driving forces.

THE CASE STUDY

Description

The case study, located in Cherasco (CN), was built in 2005 and it represents an interesting example of combination of a Passivhaus concept and the Italian building tradition. The residential building has two floors with a net heated surface of 200 m^2 and an underground floor (used as a garage and tavern), unheated and located outside the insulated continuous envelope. Its S/V ratio is equal to 0,54 and the whole building envelope is characterized by very low values of thermal transmittance.

The adoption of traditional structures has led to medium-high levels of effective heat capacity and the Blower Door Test (conducted in accordance with EN 13829), which was performed at the end of the construction, found a value of 0,6 h-1 for the parameter n_{50} (hourly air change by infiltration with a pressure difference of 50 Pa).

The building, besides for housing, is used as the seat of a small architectural study. Such use results in internal heat gains larger than those normally recorded in similar Passivhaus buildings (in PHPP calculation it is assumed a reference value of 2,1 W/m^2 per day).

As for the thermal plant, following a common Passivhaus approach, the building has a compact heating unit, comprising a cross-flow heat exchanger with nominal efficiency of 85%, an air-to-air heat pump with low thermal power (1695 W), two fans with power of 50 W each for supply and return air, a microfiber synthetic pocket filter and a storage tank for domestic hot water of 200 litres. Upstream of these components is an Earth-to-Air heat exchanger in polypropylene (diameter of 200 mm), 32 meters long and with an average depth of 2,4 meters.

The air distribution system consists of two main supplies and 40 m of secondary pipes. The inflow of fresh air (nominally of 205 m^3/h) is distributed in the rooms (not in the kitchen and in the bathrooms) through 9 nozzles and the extraction is carried out through 11 hygro-adjustable nozzles.

During the summer season, in addition to low-energy cooling due to the EAHE, a natural night ventilation strategy is implemented (through manual opening of some windows in the ground floor) and different shielding elements are used: adjustable blinds in aluminium and roller shades on the South and West expositions, traditional venetians on the East orientation.

Analysing the building

We installed various sensors in the building in summer 2007. Monitoring was performed from August to October 2007 and for the entire period August 2008 - October 2009. The monitored variables were the power consumption of the thermal plant (heat pump and fans), equipment and lighting systems, heat transfer rates at various points in the thermal plant and interior micro-climatic parameters.

To measure electric power consumption disaggregated in final end uses we used a non-intrusive system, which consists of a central data storage, a set of sensors at individual equipment and the main meter, communicating with the logger via power line and then via a modem to the central server.

The long term measurement of temperature, relative humidity and lighting sources on-off status was carried out using stand-alone data loggers. Short-term measurements of micro-climatic parameters were conducted, in October 2007 and July 2009, using a mobile system with 3 sets of probes (with high accuracy) at different heights, according with ISO 7726 and the Class I measurement protocol of the ASHRAE RP 884. Consistent with available access, we evaluated the performance of the EAHE placing the sensors at the end of the vertical input pipe (about 50 cm deep) and in the duct connecting with the heating unit. Point measurements of air velocity inside the EAHE were made with a propeller anemometer.

In order to characterize the behaviour of the EAHE, the collected data were processed (Table 1) according to established methodologies proposed by the reference literature (Pfafferott, J. 2003). While the convection coefficient inside the tube – function of and the NTU number describes the regimen of heat exchange between air and pipe wall, the parameter J (specific pressure drop) – proposed by De Paepe et al. (2003) – introduces information about its hydraulic behaviour. These indicators are functions only of the geometric characteristics (diameter, length and number of curves) and air flow rate (fixed if, as in our case study, the air change rate in the building is set to be constant). Then we can define a coefficient of the EAHE performance (Coefficient of performance - COP or Energy Efficiency Ratio - EER) as the ratio between the sensible heating/cooling energy supplied to the air flow and the mechanical energy spent, during the reference season. Unlike previous indexes, the COP or EER also depends on the regimen of heat exchange between soil and EAHE and then mainly on the depth of the tube and thermo-physical characteristics of the adjacent ground.

Table 1
Main characteristics and performance indicators of the monitored EAHE.

CHARACTERISTIC	VALUE
Number of ducts =	1
Length of duct =	32 m
Diameter of duct =	200 mm
Mean depth of duct =	2,4 m
Specific surface area =	0.082 $m^2/(m^3/h)$
Air Velocity =	2,2 m/s
Reynolds number =	28810
Convection coefficient (h_c) =	8,5 W/m^2K
NTU =	2,1
Total pressure drop =	18 Pa
Specific pressure drop: J =	5,3 Pa
COP heating =	262 kWh_{th}/kWh_{mec}
EER cooling =	252 kWh_{th}/kWh_{mec}

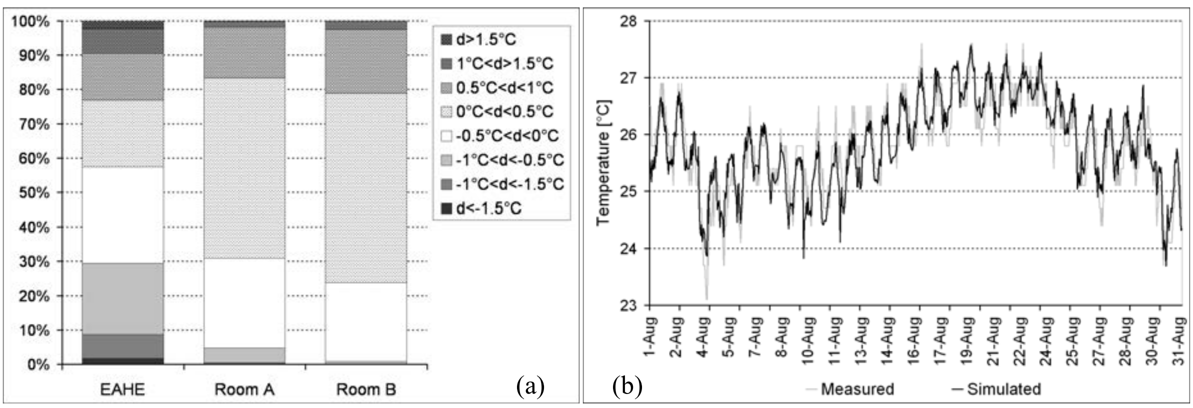

Figure 1 Simulation results: a) Temperature difference (d) between simulation results and measured data at the exit of the EAHE and in two rooms (period: 1 May – 30 September 2009); b) comparison on air temperature in the living room (A).

We used the monitored data for the calibration of a building model developed in the EnergyPlus environment. On one hand this dynamic simulation software is able to model reliably the building envelope (including geometrical features that influence radiation exchange) and natural ventilation strategies (with the implemented AirFlowNetwork), on the other hand there are some limitations in modelling the ground heat exchangers . To overcome these limitations, the simulation of this component has been conducted outside the main simulation environment through the analytic model of Heidt (Benkert, S., Heidt, F.D. 2000).

ANALYTIC MODEL

Theory and validation

Based on physical analysis we developed a parametric model providing an approximate evaluation of the system formed by the building envelope and plant under study (Passivhaus and EAHE), both in terms of energy and comfort performances. In particular, we have considered the previous models of Keller (1997, 1998) and Pfafferott (2005) which we have extended to consider, in addition to natural ventilation, the geothermal pre-cooling due to the EAHE and the requirements proposed by the Standard EN 15251.

Following the approach of Keller, to characterize the behaviour of a building in free-floating mode, it is possible to obtain an approximate solution of the energy balance on the air contained in the building, under the assumption of steady-periodic condition. The daily profile of the internal air temperature [°C] (assumed equal to the operative temperature) is approximated as:

$$T_i(t) = T_{i,m} - \Delta T_i \sin\left(\frac{2\pi}{t_0} t\right) \tag{1}$$

where t_0 is the time period (24 h) and $T_{i,m}$ [°C] the daily mean indoor temperature, calculated as:

$$T_{i,m} = \frac{H_a \cdot T_{a,m} + H_g \cdot T_{g,m}}{H_a + H_g} + \frac{G_m}{H_a + H_g} \tag{2}$$

ΔT_i [°C] is the daily variation of indoor temperature, calculated as:

$$\Delta T_i = \frac{t_0 (H_a + H_g)}{2\pi \cdot C} \left(\frac{H_a \Delta T_a + H_g \Delta T_g}{(H_a + H_g)} + \frac{\Delta G}{(H_a + H_g)} \right) \tag{3}$$

where $T_{a,m}$ is the daily mean of outdoor air temperature [°C], $T_{g,m}$ is the daily mean of air temperature at outlet of EAHE [°C], ΔT_a is the daily variation of outdoor temperature [°C] and ΔT_g the daily variation of EAHE outlet temperature [°C].

In this formulation, the coefficients H [W/m^{2}K], G [W/m^2] and C [kJ/m^{2}K] represent respectively the heat losses, the heat gains[1] and the storage capacity of the building. In comparison with the original approach, we have introduced a new dispersion coefficient (H_g) – function of the outlet temperature of the EAHE and the ventilation rate – defined similarly to factor H (renamed here H_a) of Pfafferott, which is able to consider daily variations of air flow rate:

$$H_g = \frac{1}{A_{ext.surf}} \left[ACH_{eff,g} V \frac{c_{air}\rho_{air}}{3600} \right] \tag{4}$$

where $ACH_{eff,g}$ [h^{-1}] is the effective air change from EAHE, equal to:

$$ACH_{eff,g} = \frac{\sum_{t=1}^{24} \left[ACH_{g,t} \left(\hat{T}_{i,t} - T_{g,t}\right)\right]}{\sum_{t=1}^{24} \left(\hat{T}_{i,t} - T_{g,t}\right)} \tag{5}$$

where $A_{ext.surf}$ is the total external wall area of the building [m^2], c_{air} is the specific heat of air [J/kgK], ρ_{air} the density of air [kg/m^3], V is the volume of the building [m^3], $\hat{T}_{i,t}$[2] the indoor temperature at time t [°C] and $T_{g,t}$[3] is the outlet EAHE temperature at time t [°C].

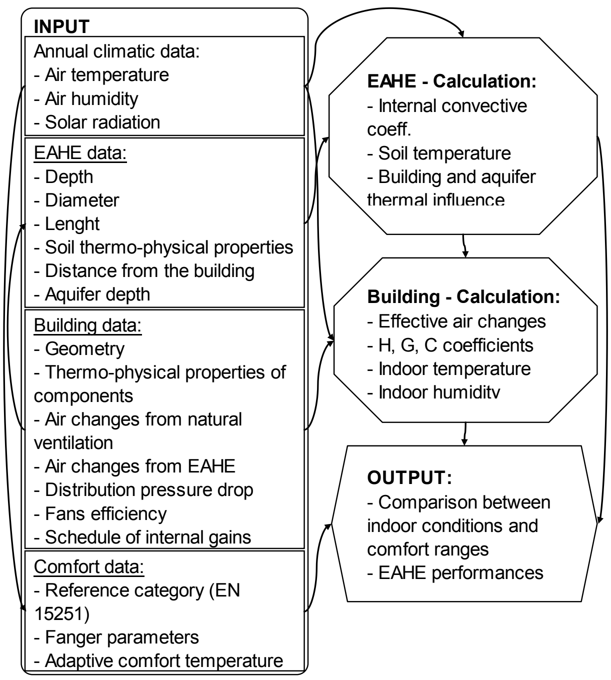

Figure 2 Calculation scheme of the analytic model developed.

The resulting model was calibrated and an initial validation was performed using the results of the monitoring campaign carried out in the case study: in particular, the monitoring data of summer 2007 were used to calibrate the model and those of summer

[1] Described by the mean value (G_m) and its variation on the calculation period (ΔG).

[2] Because both effective natural air change ($ACH_{eff,a}$) and mechanical ($ACH_{eff,g}$) depend on the indoor temperature, the final result of the model, it is necessary to initialize this value and re-iterate the calculation.

[3] Calculated with the analytic model of Heidt.

2009 to validate it.. In Fig. 3 we present a comparison between measurement data, dynamic simulations and output of the analytic model.

In accordance with the Keller's remarks and given the medium-low values of the time constant (τ) of the building – between 30 and 50 h – we have chosen as reference interval the period of a week (168 h) . The analytical model developed is aimed at evaluating in a simplified way the thermal behaviour of a system EAHE-building during summer for time intervals of about a week (given as input the expected average values of outside temperature, solar radiation and levels of internal loads). The objective is to have an algorithm which can be run by local controls and support an optimal use of the EAHE taking into account expected future conditions over short periods of time (few days). The model will be further tested and validated in a new zero energy house recently constructed in Sicily (progetto Botticelli), which has been equipped with sensors for a detailed monitoring activity and is one of the facilities included in IEA annex 58 activities.

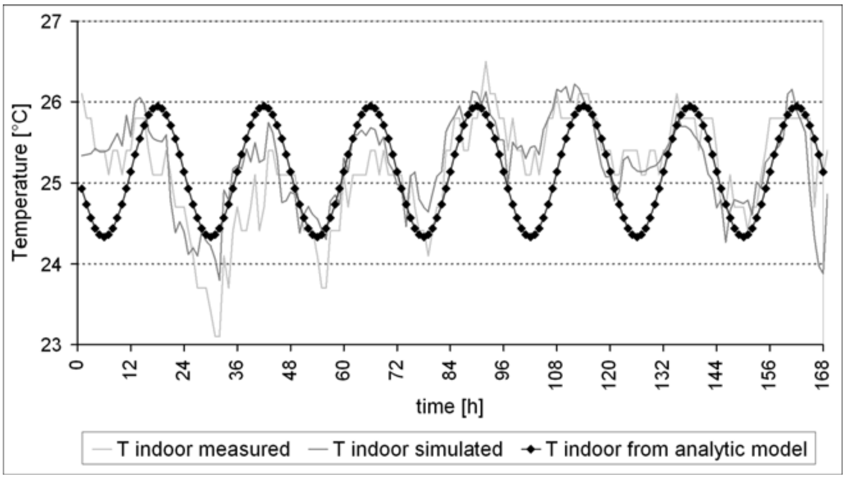

Figure 3 Comparison between the temperature profile estimated with the parametric model and those obtained from measurement and dynamic simulation. Period: 3-10 August 2009.

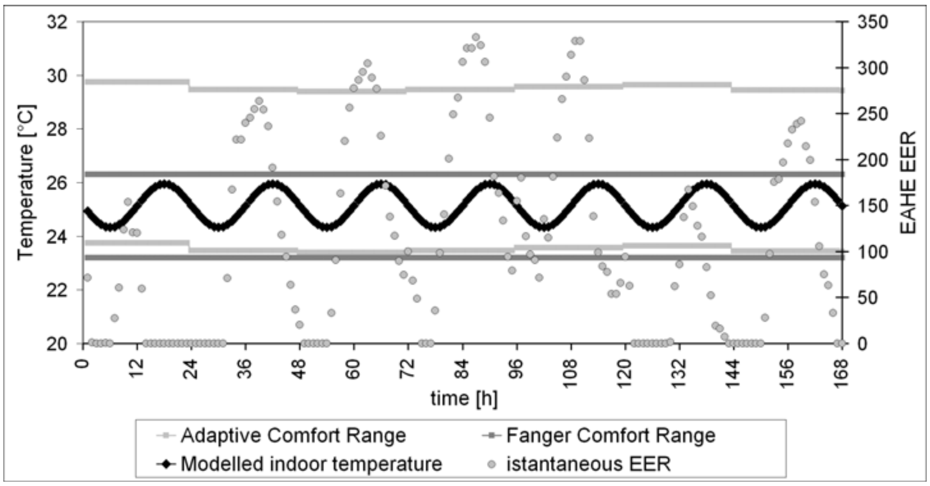

Figure 4 Example of output of the analytic model: the estimated indoor temperature is compared with the Fanger and Adaptive comfort ranges and the hourly values of EAHE EER (ratio of thermal energy extracted from air and mechanical energy necessary to overcome losses in the tube).

CONCLUSION

In order to adapt the Passivhaus concept to the South of Europe and to identify design references in view of the objective Nearly Zero Energy, an Italian case study is presented. We have monitored for 18 months a Passivhaus located in the Po Valley and its Earth-to-Air Heat Exchanger (EAHE); based on the measured data we have performed dynamic simulations of calibrated building models with the aim to identify optimized strategies for maximum indoor summer comfort in accordance with the standard EN 15251.

Based on the measurement campaign and analysis performed – which also contributed to European and International research projects (IEE Commoncense, IEA Task 40 Annex 52) – we developed and tested a steady-stationary analytical model aimed at estimating the behaviour of the system building-

EAHE in term of both energy performances and indoor thermal comfort.

The model will be further tested and validated in a new zero energy house recently constructed in Sicily (progetto Botticelli), which has been equipped with sensors for a detailed monitoring activity and is one of the facilities included in IEA annex 58 activities.

Regarding a future possible use as a predesign tool for EAHEs, the model introduces an interesting feature (Fig. 4): unlike previous experiences the behaviour of the earth-to-air exchanger is not modelled here as a problem separate from the building and the performance of the coupled system building and plant can now be expressed directly in terms of achieved thermal comfort levels, in addition to the energy indicators cited and used in this study (NTU, J, COP or EER).

NOMENCLATURE

t = time [h]
t_0 = time period [h]
$T_i(t)$ = indoor air temperature at time t [°C]
$T_{i,m}$ = daily mean indoor air temperature [°C]
ΔT_i = daily variation of indoor air temperature [°C]
$T_{a,m}$ = daily mean of outdoor air temperature [°C]
ΔT_a = daily variation of outdoor temperature [°C]
$T_{g,m}$ = daily mean of air temperature at outlet of EAHE [°C]
ΔT_g = daily variation of EAHE outlet temperature [°C]
G_m = mean value of the internal gains [W/m^2]
ΔG = variation of the internal gains [W/m^2]
C = storage capacity coefficient [kJ/m^{2}K]
H = dispersion coefficient [W/m^{2}K]
H_a = dispersion coefficient related to air infiltration and natural ventilation [W/m^{2}K]
H_g = dispersion coefficient related to the EAHE system [W/m^{2}K]
$ACH_{eff,g}$ = the effective air change from EAHE [h^{-1}]
$T_{g,t}$ = outlet EAHE temperature at time t [°C].
$A_{ext.surf}$ = total external wall area of the building [m^2]
V = volume of the building [m^3]
c_{air} = specific heat of air [J/kgK]
ρ_{air} = density of air [kg/m^3]

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