Methodological development of seasonal cooling energy needs by introducing ground-cooling systems

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ABSTRACT: In past years, building professionals increased their interest on passive systems as sustainable solutions to reduce energy needs. This has been driven by the building certification program and new Portuguese building thermal code enacted in 2006. For residential and small office buildings, the methodology adopted is a seasonal quasi-stationary approach for calculating cooling energy following EN ISO 13790:2007. However, this method lacks specific recommendations for accounting passive cooling systems, namely ground-cooling systems. In this paper, the ground-heat exchanger contribution is included in the energy needs method. This development is sustained by measurements obtained in the ground-heat exchanger running on Solar XXI office building at LNEG campus, complemented by simplified and Fourier theoretical formulations. The horizontal ground-heat exchanger at Solar XXI is constituted by 32 concrete ducts, with a 30 cm diameter and buried 4.6 m deep. The air entrance is made from a feeding well about 15 m away from the building and its functioning during summer warm days supplies cool air for room offices.

Keywords: energy needs, ground-cooling, ground-heat exchanger, ventilation, passive building

1. INTRODUCTION

In European Union, building sector is the largest energy user and carbon dioxide (CO_2) emitter, where 40% of the energy and CO_2 emissions derive from energy use in residential and commercial buildings [1]. To overcome this situation, in 2000, the European Commission identified the need to introduce specific measures in the building sector, namely with the Energy Performance of Building Directive (EPBD) published on December, 16th 2002 [2] and followed by its recast on June 18th 2010 [1]. This Directive proposes, among other issues, the adoption of common methodologies for calculating energy consumption and opens the way to net zero energy buildings in 2020 [1].

According to the EPBD, Portugal prepares the evaluation of national requirements for energy performance of new buildings until 2011, which is an excellent opportunity to devise a national strategy making way to very low energy buildings.

Summer Mediterranean climate causes a great thermal stress in buildings, nevertheless, traditional and passive architecture shows reduced cooling energy demanding examples, so that HVAC systems are not required [3].

In the latest years, architects and building professionals increased their interest on passive systems as sustainable solutions to reduce energy needs. However, the method for calculating cooling energy needs incorporated into Portuguese thermal building code [4], RCCTE, which is based on the method developed by Dijk and Spiekman [5] and gave rise to EN ISO 13790 [6], lacks specific recommendations for accounting passive cooling strategies, namely ground-cooling.

This fact penalizes passive buildings, especially residential and small services, because when compared with standard buildings similar cooling energy needs are estimated.

This paper studies a simplified method to account for the additional heat transfer by ventilation with supply of air from a ground-heat exchanger (GHE), therefore cooler than external air for the most part of the day during summer. Calculation of cooling energy needs follows EN ISO 13790 and the ground-to-air heat exchanger approach in EN 15241 [7], which proposes a methodology to account for preheating air supply for commercial buildings, instead of cooling air supply.

2. EN ISO 13790: SUMMER

2.1. Cooling energy needs

The method developed by Dijk et al. [8] is also described in detail in EN ISO 13790 and consists of a numerical estimative of the physical quantities of heat transfer ($Q_{C,ht}$) and heat sources ($Q_{C,gn}$), different from a merely comparison between gains and losses. The heat transferred by ventilation (including infiltration) and transmission (conduction, convection and longwave radiation) directly depends on the inside-to-outside air temperature difference and is part of the first term. The exchange of energy which does not fit in the first term constitutes the heat sources, e.g. shortwave radiative gains, additional sky longwave radiative exchange and internal gains.

There are two formulations of the same numerical method to calculate cooling energy needs ($Q_{C,nd}$), one uses the loss utilization factor ($\eta_{C,ls}$) and the other uses the gain utilization factor ($\eta_{C,gn}$). In the gain utilization factor formulation, the one adopted in RCCTE, cooling energy needs are given by

$$Q_{C,nd} = (1 - \eta_{C,gn}) Q_{C,gn}$$

where $\eta_{C,gn}$ is a function of the ratio between heat sources and heat transfer, $\gamma_C=Q_{C,gn}/Q_{C,ht}$, according to the expression valid for $\gamma_C>0$, which covers most of the cases for Portuguese climate conditions

$$\eta_{C,gn} = \frac{1-\gamma^{a_C}}{1-\gamma^{a_C+1}}$$

with a_C a constant depending on building time constant and, therefore, on its inertia.

It is noteworthy that the formulation with loss utilization factor has some advantages over the remaining, because it can be used in climates with monthly or seasonal average temperatures above set-point temperature and, therefore, the heat transfer term contributes to the increase of cooling energy demand; and the passive cooling concept is better understood because the heat transfer term is explicitly a reduction for cooling energy demands.

2.2. Ventilation heat transfer

The heat transfer term, besides heat transmission, accounts for the overall ventilation heat transfer coefficient (H_{ve}) expressed by the time-averaged airflow rate air flow element k, $q_{ve,k}$, given by

$$H_{ve} = \rho_a c_a \sum_k b_{ve,k} q_{ve,k}$$

where $\rho_a c_a$ is the heat capacity of air per volume, and $b_{ve,k}$ is a temperature adjustment factor for air flow element k, when the supply air temperature (θ_{sup}) is not equal to the temperature of the external environment (θ_{ext}).

This adjustment factor is exactly the parameter accounting for the benefits, during summer, of using the air from a GHE (θ_{ghe}) as supply for room ventilation.

The GHE functioning will be analysed for periods when:

- Fans are on and air is supplied by a ground-heat exchanger;
- Fans are on and air is supplied from outside;
- Fans are off, infiltrations only.

Each one of the above ventilation strategies is characterized by an air flow rate, which is $q_{ve,mech}$ for the first two and $q_{ve,inf}$ for the last one. The $b_{ve,k}$ adjustment factor is different from one (desirably above one) when air is supplied from the GHE and calculated according to

$$b_{ve} = \frac{\theta_{int,set} - \theta_{ghe}}{\theta_{int,set} - \theta_{ext}}$$

with $\theta_{int,set}$ the set-point room air temperature.

The following variables are here introduced:

- $\vartheta_{x\text{-}y}$ for an x-y average temperature difference during 24 hours of the day;
- $\vartheta'_{x\text{-}y}$ for an x-y average temperature difference during a limited period of the day.

For periods where external ventilation increases during specific hours of the day, such as for night-time cooling, the adjustment factor can also theoretically be applied, considering as numerator the average internal-to-external temperature difference for the period of ventilation use with

$$b_{ve} = \frac{\vartheta'_{int-ext}}{\vartheta_{int-ext}}$$

3. GROUND-HEAT EXCHANGER

3.1. Amplitude-dampening

The GHE consists of one or more buried ducts along which the air travels and cools down. A theoretical formulation of the problem [7] shows that the amplitude-dampening of the external air is a function of the physical GHE characteristics by

$$\theta_{ext} - \theta_{ghe} = \left(1 - e^{-\zeta}\right)\left(\theta_{ext} - \theta_{grd}\right)$$

where θ_{grd} is the ground temperature (assumed as invariable) and ζ is dimensionless ratio between the air-duct heat transferred (H_{tr}) and the convective inflow (H_{cv}), thus

$$\zeta = \frac{H_{tr}}{H_{cv}}$$

The numerator depends on the duct thermal resistance and the inner duct surface area and the denominator is calculated by the air flow rate and its heat capacity per volume.

The duct characteristic constant - A_ζ - given mathematical by $1-e^{-\zeta}$, expresses the efficiency of the ground-heat exchanger which is highest (close to one) when air-duct heat transferred is large compared with convective inflow.

3.2. Ground temperature

The ground temperature has small variations throughout the year and can be approximated by a sine function [7] by

$$\theta_{grd} = g_m \left[\bar{\theta}_{ext} - a_m \overline{\Delta\theta}_{ext} \sin\left(2\pi \frac{J_H - \phi_m}{8760}\right)\right]$$

with the dimensionless coefficients g_m and a_m, respectively, a ground material characteristic and the amplitude correction factor, and ϕ_m and J_H the curve shift and the Julian date expressed in hours, i.e. 24 x (Julian day-1).

The climate conditions are evaluated by the annual average of the external air temperature ($\bar{\theta}_{ext}$) and its annual average amplitude swing ($\overline{\Delta\theta}_{ext}$).

3.3. Ground-heat exchanger adjustment factor

Taking into account the previous formulation for GHE amplitude-dampening, the adjustment factor could be rearranged in

$$b_{ve} = 1 + A_\zeta \frac{\vartheta'_{ext-grd}}{\vartheta_{int-ext}}$$

Note, however, that temperature difference between interior and exterior is always calculated as the average for the entire period (monthly or seasonal). On the other hand, the external-to-ground average temperature difference - ϑ' - refers to the hours of the day where ground-cooling system is used (fans are on). Therefore, the adjustment factor for a ground-cooling system linearly depends from the period of its use.

4. CASE-STUDY

4.1. Solar XXI building

Solar XXI office building [9], at LNEG campus (Fig. 1), has a GHE constituted by 32 concrete ducts (Fig. 2), 30 cm in diameter and buried 4.6 m deep. The air entrance is made from a feeding well about 15 m away from the building (Fig. 3) and the system is projected to function during summer warm days supplying cool air to the room offices facing south. Each office room in the south part of the building has two ducts supplying an air flow rate that corresponds to 8.7 ACH.

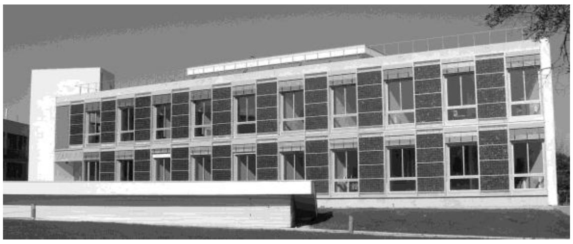

Figure 1: South façade of Solar XXI building. Architects: Pedro Cabrito and Isabel Diniz.

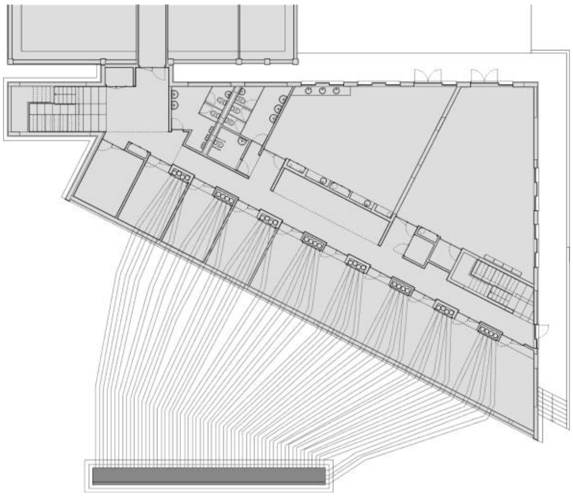

Figure 2: Semi-buried floor plan: ground-heat exchanger ducts.

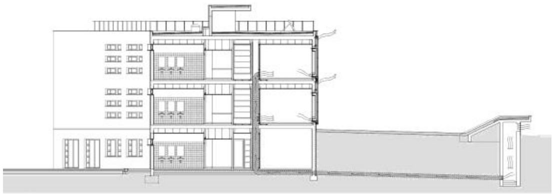

Figure 3: Building cross-section: ground-heat exchanger.

4.2. Ground temperature

The amplitude correction factor at 4.6 m deep (d) is obtained from the empirical correlation [7]:

$$a_m = -c_1 d^3 + c_2 d^2 - c_3 d + 1$$

with c_1=3.35x10^{-4}, c_2=1.382x10^{-2} and c_3=1.993x10^{-1}. The other parameters were set according to the annual measurements for ground temperature at the corresponding depth (Table 1).

Annual average and amplitude swing are taken from a typical reference year of Lisbon climate and are, respectively, 16.3 and 8.5ºC.

Table 1: Ground characteristics.

Ground-cooling system	
Amplitude correction factor, a_m	0.34
Ground material factor, g_m	1
Curve shift, ϕ_m (h)	0

4.3. Ducts characteristic constant

For one duct of the GHE of Solar XXI building (see characteristics in Table 2), the estimated air-duct heat transferred is 64.9 W/K and the convective inflow is 65.7 W/K, which results on ζ=0.987 and a GHE efficiency of A_ζ=0.63.

Table 2: Duct physical characteristics and air flow rate.

Ground-cooling system	
Inside surface coefficient	4.7 W/(m^{2}K)
Concrete conductivity	2.0 W/(m^{2}K)
U-value	4.6 W/(m^{2}K)
Total surface area	14.1 m^2
Air-flow rate	200 m^3/h

The complete analytical solution for the heat diffusion of a cylindrical air/soil heat-exchanger proposed by Hollmuller [10], was used to compute, on an hourly basis, the room supply air from the GHE - θ_{ghe} - for the summer period of Lisbon's climate. The theoretical dashed line (Fig. 4) of that model can be approximated by

$$\theta_{ext} - \theta_{ghe} = 0.53(\theta_{ext} - 15.7)$$

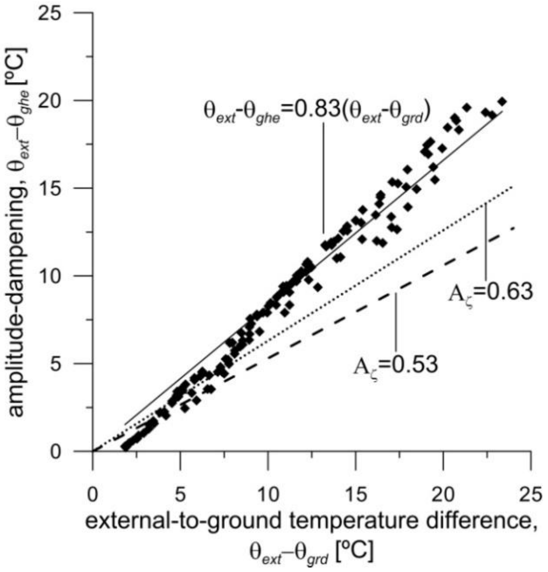

Figure 4: Ground-cooling efficiency from a theoretical approach (dotted line), Fourier analysis (dashed line) and fitted to measurements (solid line).

It is noteworthy, that the duct constant physically estimated for this system - the ground-heat exchanger efficiency, A_ζ=0.63 - is above the calculated by a detailed hourly method based on Fourier analysis of the external air temperature (A_ζ=0.53), which takes also into account the soil-duct-air heat transferred.

Furthermore, the ground-cooling system was monitored during a summer week keeping the fan continuously on. During that period the office room was unoccupied and the external shading devices were kept semi-opened.

The empirical correlation found for the experimental data (Fig. 4) establishes a duct characteristic constant of 0.83.

It is noteworthy, that an efficiency of 0.83 requires that ratio between H_{tr} and H_{cv} be ζ=1.7, therefore the air-duct heat transmission should be higher than the estimated or the convective inflow be lower. For example, ducts tightness could cause differences between fan and duct flow rate.

Future measurements will take into account the above discussed issues to infer about the GHE efficiency.

5. COOLING ENERGY NEEDS

The test case for cooling energy needs calculations is a double office room, located in the first floor of Solar XXI building, with the characteristics of Table 3.

Table 3 Thermal descriptive parameters for office room.

Office room	
Floor area (m^2)	30.6
Volume (m^3)	91.8
Overall transmission heat transfer coefficient (W/K)	53.8
South effective collecting area (m^2)	1.66
Horizontal effective collecting area (m^2)	0.13
Thermal inertia, a_C	2.6
Fans total air-flow rate (ACH)	8.7

Calculations are performed for Lisbon climate, 38.8ºN, 9.1ºW, for a four-month period (June to September), with an average external air temperature of 21.6ºC and an integrated global horizontal solar radiation of 792 kWh/m^2. The set-point temperature is set to 25ºC.

The cooling energy needs are estimated for the following ventilation strategies:

- No mechanical ventilation, infiltrations of 1 ACH ($q_{ve,inf}$ = 91.8 m^3/h);
- Continuous mechanical ventilation ($q_{ve,mech}$ = 800 m^3/h) supplying air from exterior (EXT);
- Continuous mechanical ventilation ($q_{ve,mech}$ = 800 m^3/h) supplying air from GHE;
- Mechanical ventilation supplying air from exterior for limited hours of use, infiltrations of 1 ACH for the remaining period;
- Mechanical ventilation supplying air from GHE for limited hours of use, infiltrations of 1 ACH for the remaining period.

In this analysis, cooling energy needs are only influenced by the overall ventilation heat transfer coefficient, H_{ve}, calculated from the air flow rate and the adjustment factor, b_{ve}, for each type of ventilation type according to the hours of use.

Table 4 shows the average values for external-to-ground and internal-to-external temperature differences, which are the parameters used to obtain b_{ve}. Those adjustment factors (Table 5) are calculated assuming that $\vartheta_{int\text{-}set}$ (different from $\vartheta'_{int\text{-}set}$) is 3.44, the average temperature difference for 24h, and a GHE efficiency equal to 0.63.

Table 4: Average external-to-ground and internal-to-external temperature differences, calculated for Lisbon climate, from June to September, for different periods.

hours of use	$\vartheta'_{ext\text{-}grd}$ (ºC)	$\vartheta'_{int\text{-}ext}$ (ºC)
0-24 h	4.06	3.44
9-18 h	8.50	-1.00
22-7 h	-0.14	7.63
9-13 h	5.75	1.75
14-18 h	10.81	-3.32
9-11 h	3.69	3.80
11-13 h	7.80	-0.31
13-15h	10.71	-3.22
15-17 h	11.13	-3.64
17-19 h	8.97	-1.48

Table 5: Ventilation thermal parameters for different hours of use of mechanical ventilation with supply air from exterior (EXT) and ground-heat exchanger (GHE).

Hours of use	b_{ve}		H_{ve} [W/K]	
	EXT	GHE	EXT	GHE
Infiltrations	1	-	30.6	-
0-24h	1	1.74	266.7	464.9
9-18 h	-0.29	2.56	-9.9	274.8
22-7 h	2.22	0.97	240.9	116.6
9-13 h	0.51	2.05	48.1	116.7
14-18 h	-0.97	2.98	-17.4	157.9
9-11 h	1.10	1.68	52.6	65.3
11-13 h	-0.09	2.43	26.0	82.0
13-15 h	-0.94	2.96	7.2	93.9
15-17 h	-1.06	3.04	4.5	95.6
17-19 h	-0.43	2.64	18.5	86.8

From the above overall ventilation heat transfer coefficients for each solution, it can be concluded that air supplied by GHE is always the best solution, with the exception of night-time ventilation (22-7 h) where b_{ve} and, therefore H_{ve}, are higher compared with GHE use. This study underlines, therefore, that daytime ventilation is not recommended for warm summer periods because it increases thermal loads.

On the other hand, GHE use is a good solution to ventilate during daytime hours.

It is also relevant that the two-hours period where for most efficient GHE use is 15-17 h characterized by an exterior-to-ground temperature difference of 11.13ºC, which results in the maximum value for be of 3.04.

In respect to the selection of preferential period to use GHE, morning or afternoon, the results show that b_{ve} and H_{ve} are higher for 14-18h in respect to 9-13h.

The results obtained for cooling energy needs of the tested office room (Fig. 4) show that mechanical ventilation with external air supply reduces office cooling energy needs if it occurs during nocturnal and morning periods. When the air is supplied by GHE, however, mechanical ventilation can also be promoted during afternoon hours, characterized by air temperatures above the set-point temperature, so that the average external-to-internal air temperature difference is above 3ºC (Table 4, 13-15h, 15-17h).

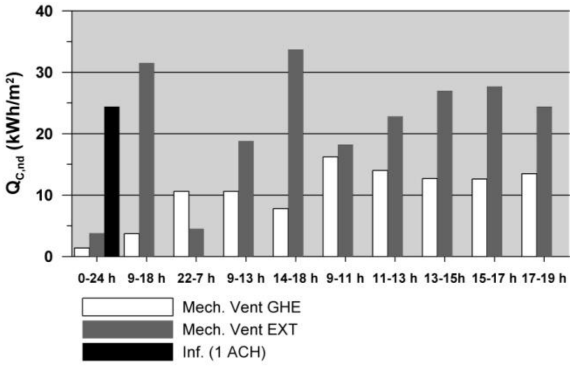

Figure 5: Cooling energy needs for mechanical ventilation with external air (EXT) and GHE (ground-heat exchanger) for different periods.

Table 5 shows also that the b_{ve} factor is generally above one whenever GHE is used, and it is largest when GHE use is restricted to the warmest day hours. For example, for a two-hours period, 15-17h, the exterior-to-ground average difference is 11.1ºC (Table 4). It is noteworthy that, compared with no mechanical ventilation use (21.9 kWh/m^2), cooling energy needs decrease by 43%, when air supplied by GHE is fanned for the aforementioned two hours (Table 4).

For the most part of the ventilation strategies with air supplied by GHE, cooling energy needs are reduced to values below 15 kWh/m^2.

The possibility of GHE use during 9-daytime hours leads to cooling energy needs below 5 kWh/m^2. This fact leads to conclude that the ground-cooling system is an effective passive strategy toward very low energy buildings during summer season. In fact, Solar XXI does not have any active air conditioning system and 73% among users manifested that thermal environment is acceptable during summer [11].

6. CONCLUSION

This paper proposes a simplified formulation to include ground-cooling systems, i.e. mechanical ventilation where air is supplied comes by a ground-heat exchanger (GHE).

For the ground-cooling system of Solar XXI building, the measured GHE efficiency was compared with two theoretical formulations – physically simplified [7] and Fourier method [10] – having been obtained lower estimatives compared with measurements.

The adjustment factor, b_{ve}, already established in EN 15241 for air preheating with GHE is here adapted for cooling ventilation. This factor depends on ducts characteristic constant, A_{ζ}, or GHE efficiency and average external-to-ground temperature difference for mechanical ventilation hours of use.

The method proposed can be easily implemented in both seasonal and monthly methods, as well as in the Portuguese thermal code (RCCTE).

Future studies should address the ground-heat exchanger efficiency, as well as climate characterization in terms of period's average air temperature, in order to enable extrapolating the method for multiple cases.

7. ACKNOWLEDGEMENTS

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