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HEATING AND COOLING POTENTIAL OF BURIED PIPES IN SOUTH BRAZIL

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Abstract. *The present numerical study aims to evaluate the heating and cooling potential of buried pipes in three cities of South Brazil i.e. Curitiba, Florianópolis and Porto-Alegre. In a first part, ground temperatures at the buried pipe location (between 1 and 3 m depth) are calculated by both a simplified model and a three-dimensional volume-finite code (SOLUM). Then, a prototypical house and its buried pipe are modeled with a building energy simulation tool (TRNSYS) to evaluate the positive and negative effects of such system on thermal comfort and heating and cooling energy. Results show that this passive system is particularly efficient in Curitiba, can reduce energy consumption in Porto Alegre and is not well-adapted to Florianópolis.*

Keywords*. Ground, Buried Pipes, Building, Energy, Simulation*

1. Introduction

Minimizing energy consumption and providing good indoor thermal comfort are the main goals of the building physics area. In Europe and North America, a growing interest in heating and cooling systems based on renewable energy sources arises from the energy demand reduction of new office buildings. In particular, earth heat exchanger that consists of forcing air from outside through buried pipes system before using it for air ventilation has been the object of recent several studies: Bojic *et al.* (1999), Wagner *et al.* (2000), Hollmuller and Lachal (2001), Pfafferott (2003) and Al-Ajmia *et al.* (2006).

In South America, Larsen *et al.* (2003) presented results about a buried pipe located in La Pampa (Argentina) that indicate a poor performance of the system, but as suggested by the authors, it can originate from the location of the pipe which was buried at only 0.4 m depth. Hollmuller *et al.* (2005) in their study of passive cooling for buildings located in São Paulo and Florianópolis concluded that buried pipes system alone is not efficient and has to be used in combination with nocturnal ventilation to improve its potential.

Figure (1) illustrates how a buried pipes system can reduce heating and cooling loads and improve thermal comfort in the case of a building located in Curitiba. For clarity, all data have been sort according to the outdoor temperature and averaged over 24 data period. The temperature of a building zone without buried pipes or heating/cooling systems (2a) is a function of the building itself, outdoor temperature (1), solar (6) and internal gains and infiltration/ventilation rates. In the present example, a sanitary air change rate of 1.0 ACH has been set except during summer where it has been increased to 3.0 ACH. As a result, the zone temperature lies between the outdoor temperature and the comfort temperature (18 - 28 °C) during winter and is close to the outdoor temperature that is higher than the comfort temperature during summer. The principle of buried pipes system is to (pre-) heat or (pre-) cool the ventilation air by flowing it through the ground. The ventilation air temperature can then reach the ground temperature at a specified depth (3 - 5) that will increase the zone temperature (2b) during winter and cool the zone during summer.

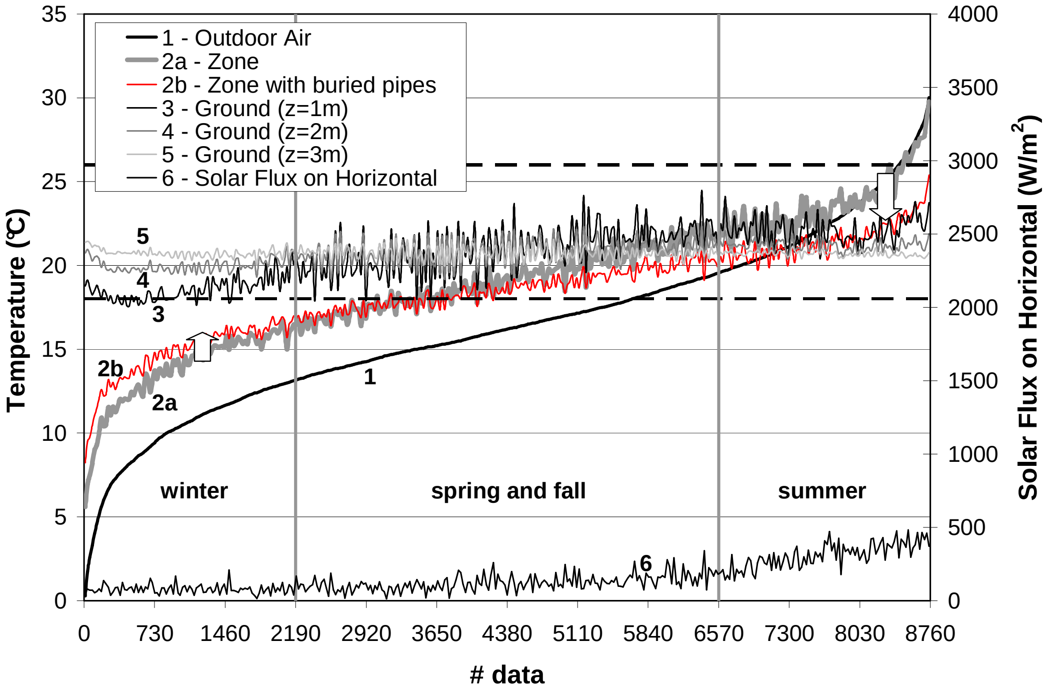

Figure 1. Position of the problem.

The present study aims to evaluate the potential of buried pipes in three cities of south Brazil (Curitiba, Florianópolis and Porto Alegre). These three locations have been chosen because the buried pipes system is expected to be more efficient in those regions as the heating energy demand is not high enough to require heating systems so that discomfort occurs in buildings during winter and cooling loads are less important than in other Brazilian cities. In a first part, the modeling procedure and the description of the studied case are provided. Then results concerning both the ground temperature evaluation and the effects of a buried pipes system on the heating and cooling loads and comfort are presented and commented.

2. Modeling procedure

2.1. Ground temperature model 1

The equation obtained by Kusuda and Archenbach (1965) is usually used to evaluate the ground temperature in building physics. It is based on the heat conduction analytical solution of a semi-infinite homogenous solid under sinusoidal solicitation at its boundary. The solution can be found in Carslaw and Jaeger (1959):

$$T_{ground}(z,t) = \overline{T}_{surf} + a_{surf} \times exp\left(-z \times \left(\frac{\pi}{365\alpha}\right)^{0.5}\right) \times cos\left(\frac{2\pi}{365}\left((t - t_{max}) - \frac{z}{2} \times \left(\frac{365}{\pi\alpha}\right)^{0.5}\right)\right) \quad (1)$$

where $T_{ground}(z,t)$ is the ground temperature (°C), $\overline{T}_{surf}$ is the mean surface temperature over the year (°C), a_{surf} is the surface temperature variation amplitude (°C), z is the considered depth (m), α is the ground thermal diffusivity (m^2/day), t is the time (day) and t_{max} is the day of the year when the surface temperature is maximal (day).

The accuracy of the undisturbed ground temperature is very sensitive to the values of the input parameters of Eq. (1). According to Labs (1989), when the variables are determined from field measurements, the model generally yields errors of no more than ± 1.1 °C. The main difficulty lies in the evaluation of the ground surface temperature because it is not yet included in the weather data. Tools such as the EnergyPlus Weather Utility that is part of the EnergyPlus (Crawler et al., 2004) package, reads and translates common weather files and creates statistical file where the monthly ground temperature values at 0.5, 2 and 4 m depth can be found. Unfortunately, the 0.5 m depth data that can be considered as the ground surface undisturbed temperature is the same than the outside air temperature monthly averaged. Same approximation is used in TRNSYS Type 77 - Simple ground temperature profile model (TRNSYS, 2006).

This assumption can be justified in cases where no solar radiation reaches the ground surface (ground covered by deep vegetation for example) but, as soon as short-wave solar and long-wave sky radiation exchanges take place, this simplification does not stand any longer and the complete problem has to be numerically solved.

2.2. Ground temperature model 2

The governing equations utilized in the code SOLUM, based on the theory of Philip and De Vries (1957) to model heat and mass transfer through porous media, are given by Eqs. (2) and (3). The energy conservation equation is written in the form:

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \nabla.(\lambda\ (T,\theta)\nabla T) - L(T)(\nabla.\boldsymbol{j}_v) \tag{2}$$

and the mass conservation equation as:

$$\frac{\partial \theta}{\partial t} = -\nabla.\left(\frac{\boldsymbol{j}}{\rho_l}\right) \tag{3}$$

where ρ_0 is the solid matrix density (m³/kg), c_m is the mean specific heat (J/kg.K), T is the temperature (K), λ is the thermal conductivity (W/m.K), L is the latent heat of vaporization (J/kg), θ is the volumetric moisture content (m³/m³), j_v is the vapor flow (kg/m².K), j is the total flow (kg/m².K) and ρ_l the water density (kg/m³).

The total three-dimension vapor flow (j) given by summing the vapor flow (j_v) and the liquid flow (j_l) can be described as:

$$\begin{aligned}\frac{\boldsymbol{j}}{\rho_l} = &-\left(D_T(T,\theta)\frac{\partial T}{\partial x} + D_\theta(T,\theta)\frac{\partial \theta}{\partial x}\right)\mathbf{i} - \left(D_T(T,\theta)\frac{\partial T}{\partial y} + D_\theta(T,\theta)\frac{\partial \theta}{\partial y}\right)\mathbf{j} \\ &-\left(D_T(T,\theta)\frac{\partial T}{\partial z} + D_\theta(T,\theta)\frac{\partial \theta}{\partial z} + \frac{\partial K_g}{\partial z}\right)\mathbf{k}\end{aligned} \tag{4}$$

with $D_T = D_{Tl} + D_{Tv}$ and $D_\theta = D_{\theta l} + D_{\theta v}$, where D_{Tl} is the liquid phase transport coefficient associated to a temperature gradient (m²/s.K), D_{Tv} is the vapor phase transport coefficient associated to a temperature gradient (m²/s.K), $D_{\theta l}$ is the liquid phase transport coefficient associated to a moisture content gradient (m²/s), $D_{\theta v}$ is the vapor phase transport coefficient associated to a moisture content gradient (m²/s), D_T is the mass transport coefficient associated to a temperature gradient (m²/s.K) and D_θ is the mass transport coefficient associated to a moisture content gradient (m²/s).

The boundary conditions at the ground surface can be expressed as:

$$\left(\lambda(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} + (L(T)\,j_v)_{y=H} = h(T_{ext} - T_{y=H}) + \alpha q_r + L(T)h_{ms}(\rho_{v,ext} - \rho_{v,y=H}) - \varepsilon\, R_{lw} \tag{5}$$

where λ is the thermal conductivity (W/m.K), $h(T_{ext} - T_{y=H})$ represents the heat exchanged by convection with the external air, αq_r is the absorbed short-wave radiation and $L(T)h_{ms}(\rho_{v,ext} - \rho_{v,y=H})$ is the phase-change energy term. The long-wave radiation loss is defined as R_{lw} (W/m²) and ε is the surface emissivity. The solar absorptivity is represented by α and the mass convection coefficient by h_m, which is related to h by the Lewis' relation.

Similarly, the mass balance at the ground surface is written as:

$$\left(D_\theta(T,\theta)\frac{\partial \theta}{\partial y} + D_T(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} = \frac{h_{ms}}{\rho_l}(\rho_{v,ext} - \rho_{v,y=H}) \tag{6}$$

where ρ_l is the water density (kg/m³), $\rho_{v,ext}$ is the vapor density in the external air (kg/m³) and $\rho_{v,y=H}$ is the vapor density at the upper surface of the soil domain (kg/m³).

The other soil domain surfaces were all considered adiabatic and impermeable. Equations (5) and (6) show a vapor concentration difference $\Delta\rho_v$ on their right-hand sides. This difference is between the porous surface and air and is normally determined by using the values of previous iterations for temperature and moisture content, generating additional numerical instability. Due to the instability created by this source term, the solution of the linear set of discretized equations normally requires the use of very small time steps, which can be exceedingly time consuming especially in long-term soil simulations; in some research cases, a time period of several decades has to be simulated, taking into account the three-dimensional heat and moisture transfer through a very refined grid.

In order to raise the simulation time step, Mendes *et al.* (2002) presented a procedure to calculate the vapor flow, independently of previous values of temperature and moisture content. In this way, the term $\Delta\rho_v$ was rewritten as a linear combination of temperature and moisture content:

$$\left(\rho_{v,ext}-\rho_v(s)\right)=M_1(T_{ext}-T(s))+M_2(\theta_{ext}-\theta(s))+M_3 \tag{8}$$

where

$$M_1=A\frac{M}{\Re}\phi\,,\quad M_2=\frac{M}{\Re}\left(\frac{P_s(s)}{T(s)}\right)^{prev}\left(\frac{\partial\phi}{\partial\theta(s)}\right)^{prev},\quad M_3=\frac{M}{\Re}\begin{bmatrix}\left(\frac{P_s(s)}{T(s)}\right)^{prev}R(\theta^{prev}(s))+\\ \phi_{ext}(R(T_{ext})-R(T^{prev}(s)))\end{bmatrix}.$$

In the equations above, the index (s) represents the surface in contact with external air (ext) far from that surface, R is a residual function of $\left(\frac{P_s}{T}\right)$, P_s is the saturated pressure (Pa), $\Re$ is the universal gas constant (J/kmol.K), M is the molecular mass (kg/kmol), ϕ is the relative humidity, $prev$ means previous iteration and A is the straight-line coefficient from the approximation $\left(\frac{P_s}{T}\right)=AT+B$.

The governing partial differential equations (Eq. (2) and (3)) are discretized using the control-volume formulation method (Patankar, 1980). The spatial interpolation method used is the control-difference scheme (CDS) and the time derivatives are integrated using a fully-implicit approach.

2.3. Building and earth heat exchanger simulation

Heat and moisture transfer within the building has been modeled within the TRNSYS environment. This program has been chosen because the thermal behavior of buildings (Type 56) is quickly and accurately predicted (Judkoff and Neymark, 1995) as it involves the transfer function methodology (Stephenson and Mitalas, 1971) to treat heat transfer through the building's envelope. Moreover, TRNSYS environment allows the user to model and couple to the building simulation other physical phenomena in a simple manner by adding equations, reading external files or linking external programs. Those possibilities would allow direct modeling of the whole earth heat exchanger and its coupling to the building simulation but, as the study's main goal is the evaluation of the heating/cooling potential, it would unnecessary complicated the analysis by increasing the number of variables affecting the system efficiency (pipes diameter and length, number of pipes, pipes material, perturbation of the ground temperature in the pipes surroundings…). The ground temperatures is then directly read using an external file considering the earth heat exchanger well-dimensioned such that the air that exits the buried pipes is at the same temperature than the ground at the considered depth. This simplification also induces that the soil temperature is not perturbed by the building and the buried pipes presences.

2.4. Studied Case

Three south Brazil locations have been investigated in the present study: Curitiba, Florianópolis and Porto-Alegre. The sandy silt soil has been used for those three regions. According to Santos and Mendes (2005), 5 m depth domain is enough to study the evolution of heat and moisture in the ground surface region. Grid of 3×3×50 cells has been used to discretize the 1×1×5 m^3 domain. Initial conditions are 15 °C and 50 % RH. All ground boundaries are considered adiabatic and impermeable except the ground surface where weather's solicitations are imposed. Convective heat transfer convection coefficient has been set to 10 $W/m^2.K$, long-wave radiation emission and short-wave radiation absorption coefficients to 0.5. Convective moisture transfer convection has been evaluated considering Lewis number equals to 1. Simulations have been carried out during ten years to reach the periodic ground temperature responses.

The prototypical Brazilian house has the following dimensions: 8×8×2.8 m^3. Vertical walls are made of brick (15 cm) covered on each surface by plaster (2 cm). The roof consists of a 10 cm-concrete slab covered by plaster (2 cm). The floor is linoleum covered 10 cm-concrete slab. Thermal properties of the materials are presented in Tab. (1).

Table 1: Thermal properties of the building materials.

Material	λ (W/m.K)	ρ (kg/m^3)	c_m (J/kg.K)
brick	0.749	1900	920
plaster	0.72	2050	932
concrete slab	1.113	849	921.1

Single glazing windows (6 m^2) are located on the north and west walls. There is solar protection for the north wall to limit solar loads during summer. Short-wave radiation absorption coefficients are set to 0.4 at external wall surfaces and to 0.6 at internal ones. The external surface of the floor is considered adiabatic in order to avoid the modeling of the complex coupling with the ground which would add additional complexity to the present study. No moisture transfers through the walls have been modeled in the present study. Constant convective heat transfer coefficients of 3.2 $W/m^2.K$ and 24.7 $W/m^2.K$ are imposed at the internal and external wall surfaces, respectively. Two seated people and an internal load of 500 W are imposed during whole day. For the reference case, a total external airflow rate of 180 m^3/h (1.0 ACH) from June, 1st to September, 1st and 3.0 ACH for the rest of the year have been considered to take into account the cumulated effect of infiltration and ventilation. For the case with earth heat exchanger, no more external air enters the house and the same amount of air is heated/cooled through the buried pipes.

3. Results

3.1. Ground temperature

Figure (2) presents the ground temperature obtained with SOLUM at the end of each year of simulation for Curitiba. Convergence is reached after only five years. Increasing the cell number from 50 to 100 gives the same results showing that the grid is thin enough to correctly evaluate the temperature evolution.

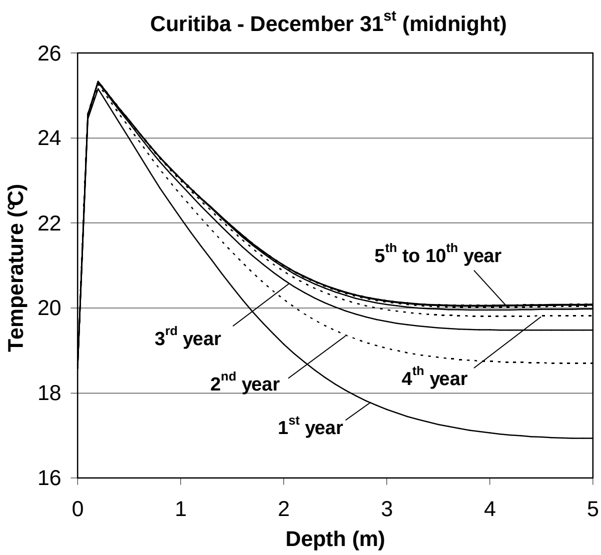

Figure 2. Ground temperature calculated with SOLUM at the end of each year of simulation.

Figure (3) – left graph shows the ground temperature evolution at 1, 2 and 3 m depths for Curitiba. The analytical solution referred as Kusuda and Archenbach (1965) in the graph has been added in order to check the validity of the results obtained with SOLUM. The ground surface temperature obtained with SOLUM has been used to evaluate the mean surface temperature ($\overline{T}_{surf}$), the surface temperature variation amplitude (a_{surf}) and the day of the year when the surface temperature is maximal (t_{max}) (see Eq. (1)). Even if the ground surface temperature is not perfectly sinusoidal (regression coefficient close to 0.9), the absolute difference between the SOLUM and the analytical predictions stays lower than 1 °C and decreases with the depth (Fig. (3) – right graph).

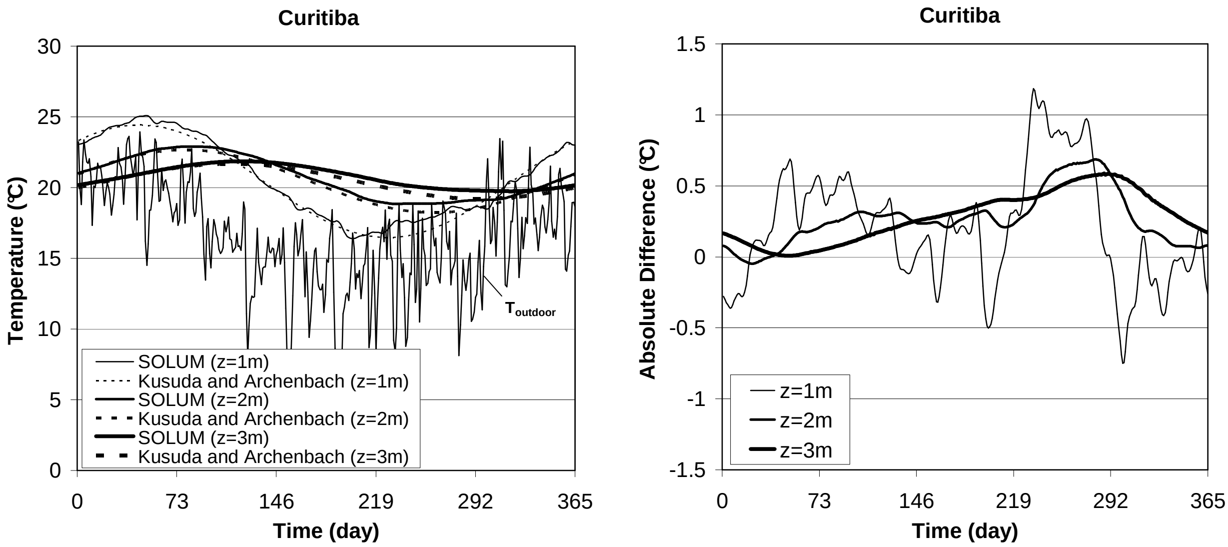

Figure 3. Ground temperature (left) and absolute difference between SOLUM and Kusuda and Archenbach (1965) predictions (right) – Curitiba.

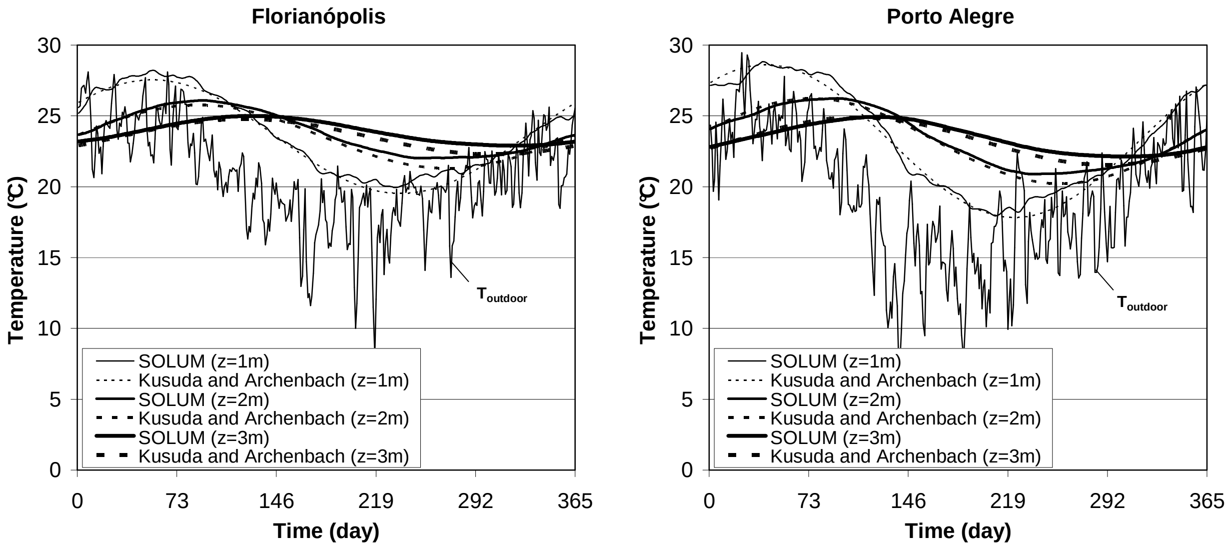

Figure 4. Ground temperature for Florianópolis (left) and Porto Alegre (right).

Table 2: Parameters of Eq. (1) for the present test case.

	$\overline{T}_{surf}$ (°C)	a_{surf} (°C)	t_{max}(day)
Curitiba	20.45	7.13	11
Florianópolis	23.54	7.18	21
Porto Alegre	23.22	9.65	8

Figure (4) presents the ground temperature evolution for the two other locations. From those three graphs, it is clear that the pipes have to be buried at a depth higher than 3 m to obtain ground temperatures lower than outdoor air ones in summer and to increase the difference between them in winter.

Table (2) gives the parameters of Eq. (1) obtained for the three locations considering sandy silt soil whose thermal diffusivity is about 2.5×10^{-2} m^2/day. This equation that can be applied to evaluate the ground temperature at any depth is used in the next sections at a depth of 3 m to evaluate the buried pipes system potential.

3.2. Effects on energy loads

In this section, set temperatures of 18 °C in winter and 28 °C in summer have been imposed. Figures (5) to (7) present the heating and cooling energy for the three locations in the case of the studied building with and without buried pipes system.

Concerning the building without buried pipes system, referred as “reference” in the graphs, the location of the building implies three different requirements: heating needs in Curitiba, low heating and cooling needs in Florianópolis and moderate heating and cooling needs in Porto Alegre.

The buried pipes system can induce a 52, 62 and 63 % reduction of the heating energy loads for Curitiba, Florianópolis and Porto Alegre respectively and a 95, 41 and 48 % diminution of the cooling ones. In terms of energy economy, the system is more efficient in Curitiba permitting an economy of 54 kWh/m^2.year and in Porto Alegre (49 kWh/m^2.year) than in Florianópolis (17 kWh/m^2.year).

3.3. Effects on thermal comfort

In this section, the effect of buried pipes on people comfort is studied considering that there are no heating/cooling systems. As the buried pipes system presence modifies both the temperature and the relative humidity of the zone, the results are presented in Figs. (8) to (10) in terms of Predicted Percentage of Dissatisfied for the three cities. The graphs presents PPD values for the building with buried pipes system versus one for the reference case so all points located below the dotted line show the positive effect of the buried pipes system on the comfort (PPD diminution).

The same trend appears for the three cities during the winter. PDD values tend to be lowered by the presence of the buried pipes system improving the thermal comfort of about 8 %PPD. Note that the maximum PPD values still remains with the buried pipes system showing that this system is inadequate to avoid high discomfort period but improve comfort below PPD value of 90 %.

During the summer period, the system is very efficient in Curitiba as it decreases the discomfort of about 4 %PPD on average with a peak of 33 %PPD during the highest periods of discomfort. In Florianópolis and Porto Alegre, the system is less efficient to reduce the discomfort.

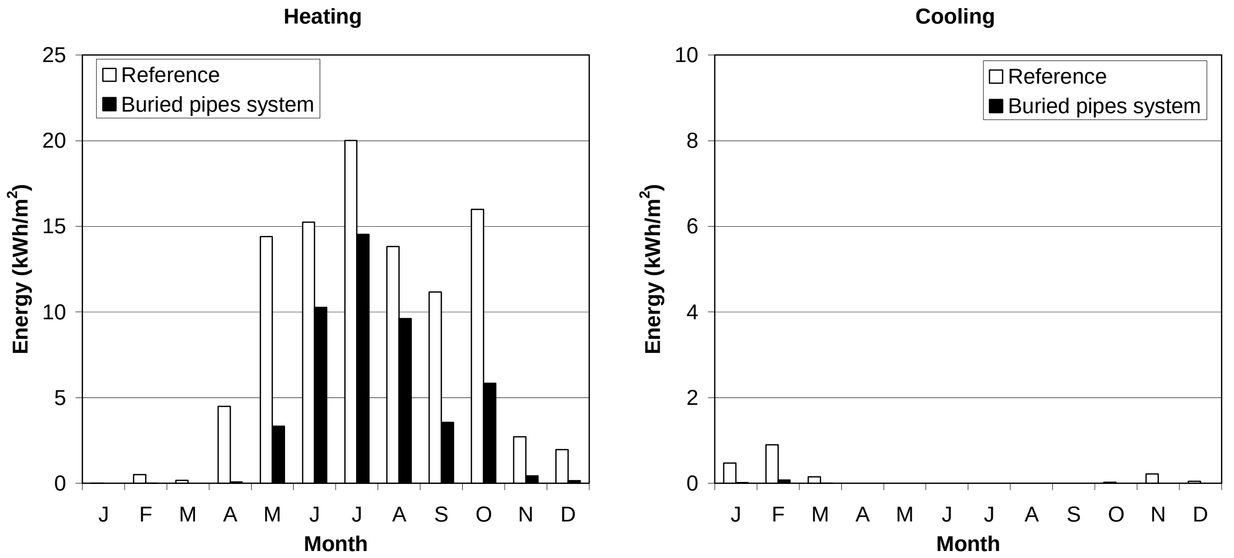

Figure 5. Heating and cooling energy – Curitiba.

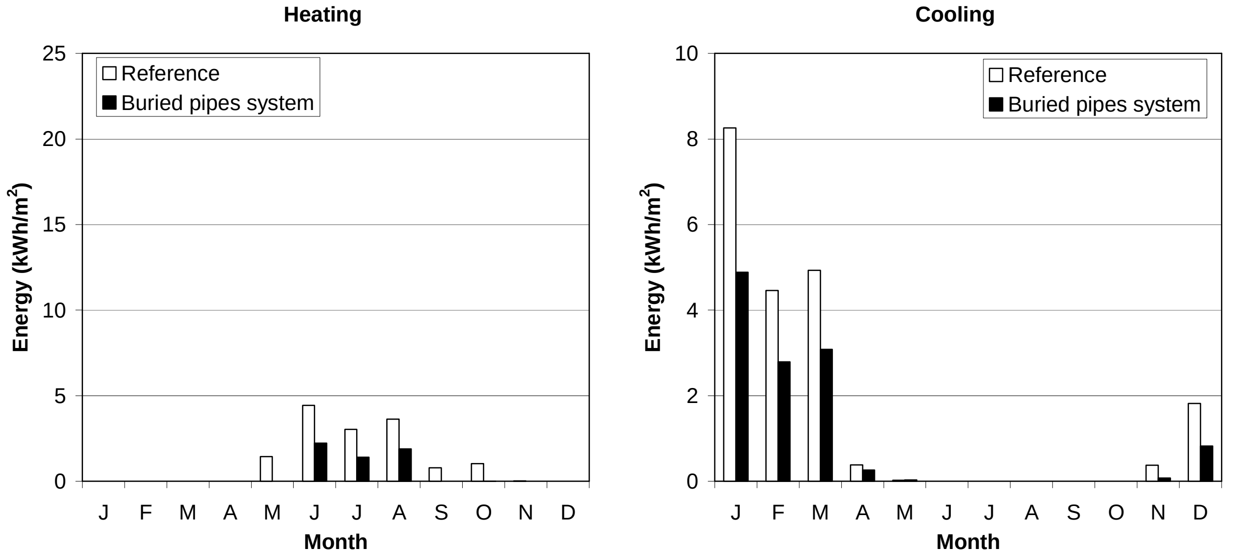

Figure 6. Heating and cooling energy – Florianópolis.

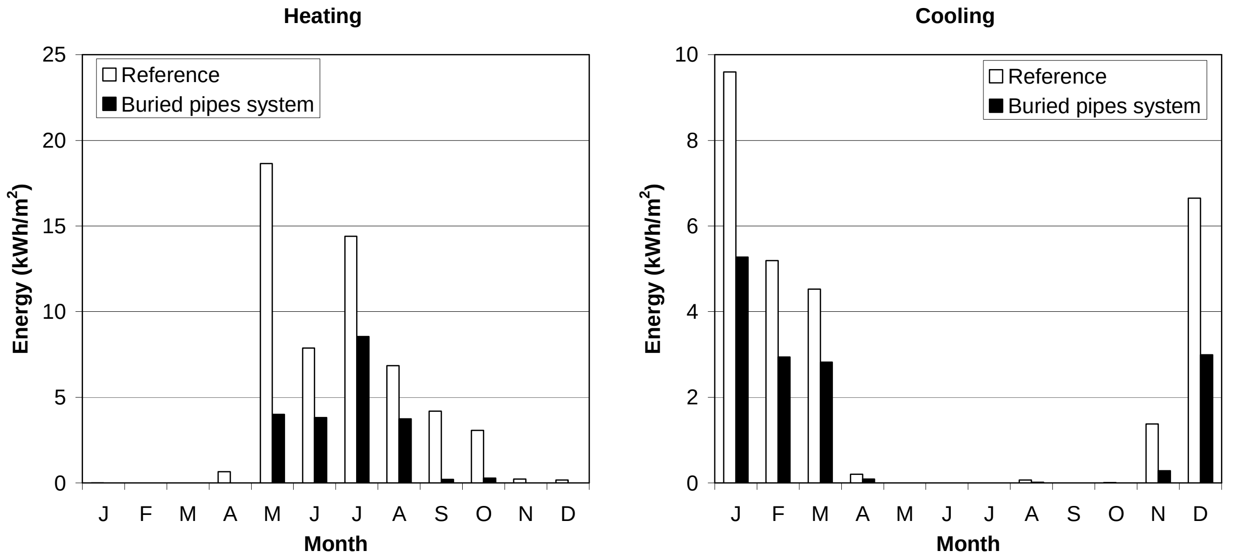

Figure 7. Heating and cooling energy – Porto Alegre.

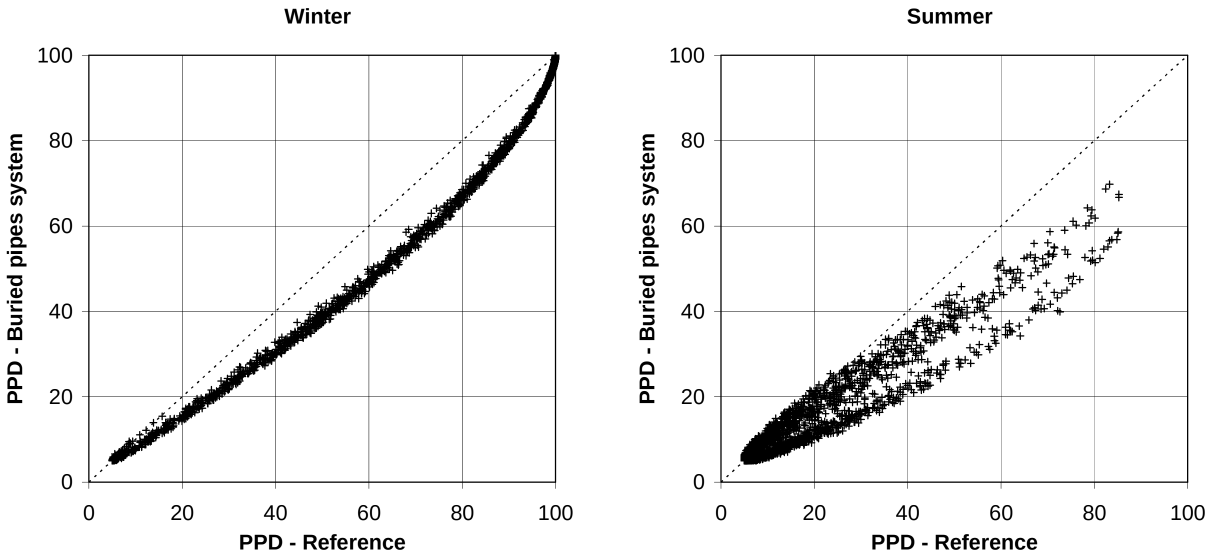

Figure 8. Predicted Percentage of Dissatisfied (PPD) people – Curitiba.

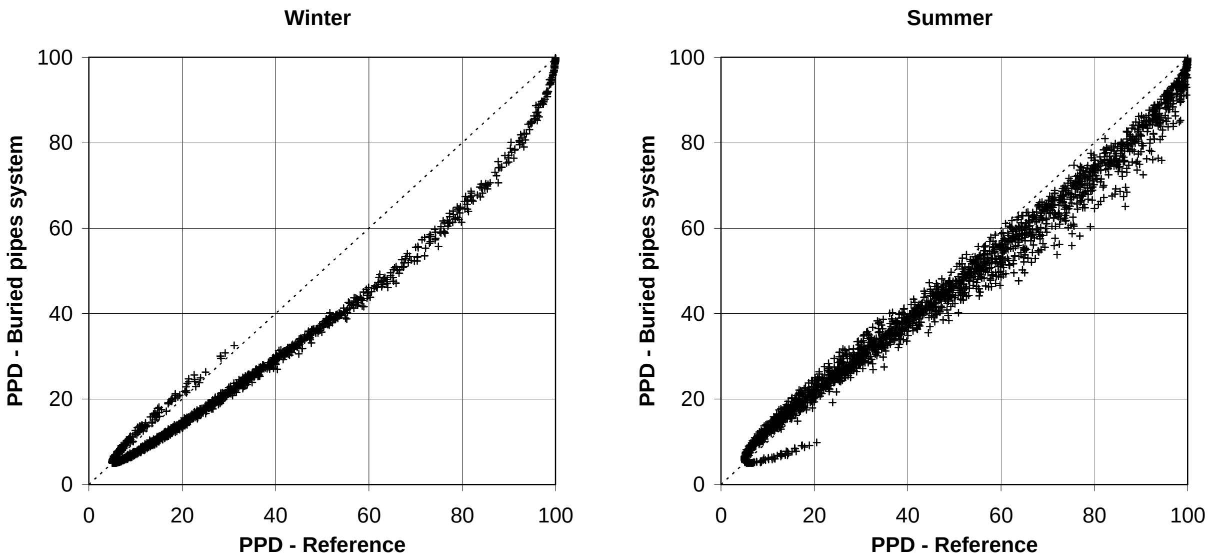

Figure 9. Predicted Percentage of Dissatisfied (PPD) people – Florianópolis.

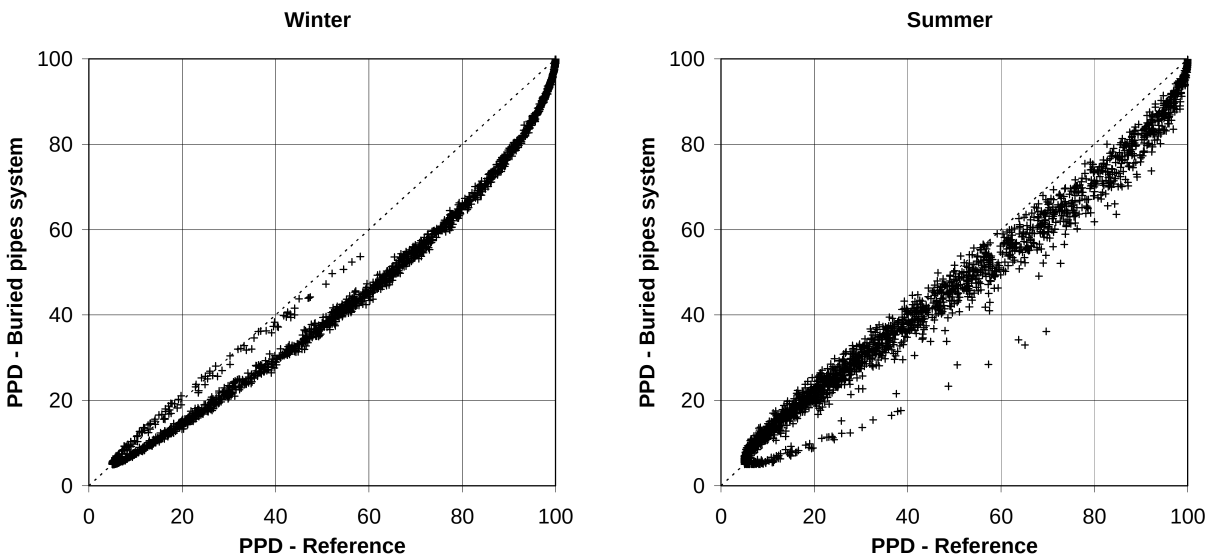

Figure 10. Predicted Percentage of Dissatisfied (PPD) people – Porto Alegre.

3. Conclusion

The potential of using buried pipes system to (pre-)heat and (pre-)cool the air of ventilation has been studied in three cities of south Brazil (Curitiba, Florianópolis and Porto Alegre). The first part of the study has put in evidence the need to take into account the solar radiation in the evaluation of the ground surface temperature and thus in the calculation of the temperature within the ground. Simulation results reveal that buried pipes system has a good potential in south Brazil, particularly in Curitiba where it shows positive effects for reducing the energy loads in the case of conditioned spaces and improving the comfort in the case of unconditioned buildings. A direct perspective of the present work concerns the modeling of the complete buried pipes system and its surrounding ground.

4. Acknowledgement

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