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# Impact of the substrate thermal inertia on the thermal behaviour of an extensive vegetative roof in a semiarid climate

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## ABSTRACT
The aim of this paper is to evaluate the impact of thermal inertia of the substrate of a vegetative roof on its thermal behaviour. Thermal inertia of the substrate was incorporated in two existing thermal models of vegetative (green) roof systems, the Sailor (2008) and Tabares and Srebric (2012) models. The predicted temperatures across the substrate, with and without inertia, were compared with experimental data obtained on a real vegetated roof located in a semiarid climate. The study shows the absolute need to consider the thermal inertia of the substrate to accurately predict the temperatures within the substrate and thus the heat flux through the roof. When taking into consideration the thermal mass, substrate temperatures predicted by both models agree well with experimental data, with a Root-Mean-Square Deviation of about 1°C at a depth of 10 cm. For the analysed period and investigated vegetative roof, the Tabares and Srebric model outperforms the Sailor model.

## KEYWORDS
Vegetative roof substrate, thermal inertia, thermal models, substrate temperature.

## INTRODUCTION
At global level, buildings are responsible for one third of greenhouse gases and around 32% of energy consumption. Consequently, the energy efficiency of buildings represents a key factor in limiting global warming and mitigating the impacts of climate change. Therefore, improving the energy performance of the building envelope is one of the main objectives to achieve. In this context, vegetative roofs (VRs), usually called green roofs, offer a technological solution that contributes, through an appropriate design, to the reduction of the energy consumption of buildings (Berardi et al. 2014; Castleton et al. 2010; Fioretti et al. 2010; Tabares-Velasco, 2009; Vera et al. 2017).

The impacts of VRs on the energy performance of buildings have been widely studied. Table 1 summarizes the main heat and mass transfer mechanisms occurring in the VRs that might contribute to the reduction of the building energy consumption. Several heat and mass transfer models of VRs have been developed since 1982. Currently, Sailor model (2008) is the only one incorporated in the building simulation tool *EnergyPlus*, whereas Tabares and Srebric model (2012) is currently being included in the same tool. However, none of these two VR models incorporates thermal inertia of the substrate, which can influence the heat transfer through the roof and the energy consumption of buildings.

The objective of this study is to incorporate thermal inertia of the substrate in the vegetative roofs models developed by Sailor (2008) and Tabares and Srebric (2012) in order to evaluate its impact on the predictions of both models. These two thermal models were first programmed in Matlab without any substrate thermal inertia and then thermal inertia was incorporated by finite differences method. The predicted temperatures across the substrate with and without thermal inertia were compared with experimental data of a real vegetated roof located in Santiago of Chile at the Laboratory of Vegetated Infrastructure of Buildings at Pontificia Universidad Católica de Chile, location that is characterized by a semiarid climate.

Table 1. Heat and mass transfer mechanisms in VRs (Vera et al. 2015).

| Heat and mass transfer mechanisms | Description |
|---|---|
| Substrate evaporation and vegetation transpiration | This is known as evapotranspiration or latent heat transfer. It is a combined effect of water evaporation from the substrate and transpiration of plants. Evapotranspiration is the main contributor to counterbalance the incident solar radiation on the roof. |
| Shading provided by the canopy | The foliage reduces the amount of solar radiation that reaches the outer roof surface. This reduces the roof surface temperature in comparison with a traditional roof. Thus, heat flux into the roof also decreases. |
| Thermal inertia provided by substrate | The growing media contributes with thermal mass that helps to stabilize indoor temperature. |
| Additional insulation provided by substrate | The substrate adds thermal resistance to the roof, which helps to reduce heat losses through the roof and heat gains into the roof. |

## METHODS

### Brief description of the Sailor (2008) and Tabares and Srebric (2012) vegetative roof models

The VR model developed by Sailor (2008) is based on the Fast All-season Soil STrenght (Frankenstein and Koenig, 2004a, 2004b), the Biosphere Atmosphere Transfer Scheme (Dickinson et al. 1993) and the Simple Biosphere (Sellers et al. 1986) models. This model is currently the only model implemented in the building energy simulation tool *EnergyPlus* (Crawley et al. 2001, 2004). The VR model developed by Tabares and Srebric (2012) can consider partially-covered VRs. This model has been validated using laboratory and field data (Tabares-Velasco et al. 2012).

Both VR models are similar in the way they present the energy balance and the components they consider and neglect. In fact, both models assume one-dimensional heat transfer, a single vegetation layer located above the surface of the substrate layer. The differences that exist are only evidenced in the way both models calculate each of the components of the energy balance. For both the substrate and foliage layers, the energy balances equations consider the absorbed short-wave solar radiation ($R_{\mathrm{sh,abs}}$), the absorbed infrared radiation from the sky ($Q_{ir}$), the radiation heat transfer between the foliage and substrate surface layers ($Q_{ir,s-f}$), the latent (L) and sensible (H) heat transfer and the conduction heat transfer from the substrate surface going downwards ($Q_{cond}$) (only for the substrate layer). The net heat fluxes to the foliage $F_f$ and to the substrate $F_s$ are given by Equations 1 and 2, respectively:

$$F_{\mathrm{f}} = R_{sh,abs,f} + Q_{\mathrm{ir,f}} + Q_{\mathrm{ir,s-f}} + H_f + L_f \quad (1)$$

$$F_{\mathrm{s}} = R_{sh,abs,s} + Q_{\mathrm{ir,s}} - Q_{\mathrm{ir,s-f}} + H_s + L_s - Q_{cond} \quad (2)$$

**Implementation of the thermal inertia in the models**

Both VR models were implemented in Matlab, including the thermal inertia of the substrate. While some simulation tools use conduction transfer functions to propagate the heat fluxes to the interior of the building, the VR models in Matlab use the finite difference approach. The original assumption that says that the canopy has a neglectable thermal mass was maintained. Assuming a vertical direction for the heat flux through the roof, the thermal behaviour of the VR can be approximated using the finite difference method with a discretization of the layers as shown in Figure 1, and can be represented by Equation 3.

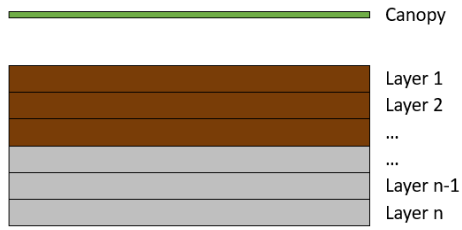


Figure 1. Discretization of the different layers of the VR (Brown and grey layers correspond to the substrate and concrete slab structure, respectively)

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = k_{i+1} \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\Delta x} + k_{i-1} \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\Delta x} \tag{3}$$

where $k_i = k\left(T_i^{j+1}, VWC_i^{j+1}\right)$ is the thermal conductivity that depends on the temperature T and volumetric water content VWC; $T_i^j$ the temperature of node *i* at time *j*; $\Delta t$ the time step; $\Delta x$ the finite-difference layer thickness; and $C_p$ and $\rho$ the specific heat and the density of the material.

In this study, 16 layers were defined (8 for substrate and 8 for concrete slab). To model the substrate without thermal inertia, parameters $C_p$ and $\rho$ were set to very negligible values, leading to a steady state solution to the energy balance.

**Experimental dataset**

The experimental data was collected in the city of Santiago, Chile (33°26'S, 70°39'W) and corresponds to measurements performed on a real vegetated roof system installed in a test facility called 'Laboratory of Vegetative Infrastructure of Buildings' (LIVE, for its acronym in Spanish). The experimental data considered in this study was measured during 10 days in September 2017 (end of the winter period). Santiago is characterized by a typical dry Mediterranean climate (semiarid) and has a warm temperate climate with dry summers (Peel et al. 2007). The average annual temperature is 14.6°C and the mean annual precipitation is 313 mm, with 25-30 rainy days per year (DGAC, 2015). The LIVE consists of 4 testing modules of 2 m height, with high level of thermal insulation in their walls and floors. Three of the modules are 25 m² each while one is 35 m². This facility allows testing up to 18 different specimens of VRs, each of one has an area of about 1.8m x 1.8m (see Figure 2) (Reyes et al. 2016).

This paper presents the results obtained on only one vegetated roof installed on one of the four testing modules. It is composed by the following layers (from top to bottom): (1) a vegetation layer (grass); (2) a 15 cm thick substrate composed by 1/3 part of humus, 1/3 part of garden soil and 1/3 part of perlite (measures in volume); (3) a filter layer; (4) a root barrier; (5) a drainage layer; (6) a waterproofing layer and (6) a support structure (a 15 cm thick concrete slab).

Measured data included the weather data conditions, the temperatures at different depths in the substrate (at the surface and at a depth of 5 cm and 10 cm), the heat flux across the substrate, the vegetation and substrate properties and the volumetric water content of the substrate.

Figure 2. Photo of the four specimens of the investigated vegetated roof in the LIVE.

**Analysis method**

In order to assess the level of agreement between the model results and the measured data, the metric 'Root-mean-square deviation' (RMSD) was used. It is a measure of the average value of the absolute deviation between the simulation results and the experimental data, and it is calculated according to Equation 4.

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n}\left(x_{1,t}-x_{2,t}\right)^2}{n}} \tag{4}$$

where $x_{1,t}$ is the simulated substrate temperature (°C) at time step $t$, $x_{2,t}$ is the measured substrate temperature (°C) at time step $t$ and $n$ is the quantity of data compared.

## RESULTS AND DISCUSSIONS

Figures 3 and 4 shows the comparison of the simulated and measured values of the surface temperature and at 10 cm depth of the VR substrate for the Sailor and Tabares models, with and without thermal mass. All data points that were measured and simulated during the considered period (10 days in September 2017), with a time step of 5 minutes, are plotted in the graphs. Table 2 shows the RMSD-values between the simulated and measured temperatures at different.

Table 2. RMSD for the different models investigated

| | With Thermal Inertia | | Without thermal inertia | |
|---|---|---|---|---|
| | Tabares | Sailor | Tabares | Sailor |
| Surface | 1.12 | 2.18 | 1.41 | 4.38 |
| 5 cm depth | 1.13 | 1.74 | 1.88 | 4.19 |
| 10 cm depth | 0.76 | 1.25 | 1.80 | 3.39 |

These results evidence vegetative roof models that consider thermal inertia perform significantly better than the same models without thermal inertia. These results show a good agreement between the measured temperatures at different depths in the substrate and the ones predicted with both models – the Tabares model and the Sailor model – when thermal mass is taken into account. For the considered period and investigated vegetative roof, the Tabares and Srebric model is performing slightly better, showing lower RMSD-values around 1°C when thermal inertia is considered.

On the other hand, models that do not consider thermal inertia significantly overpredict the temperatures within the substrate. They present RMSD-values of 1.3 to 2.7 times higher than those that do consider thermal inertia. In particular the Sailor model without thermal inertia shows very high RMSD-values around 4°C, which is not acceptable for a correct estimation of the heat flow through the roof.

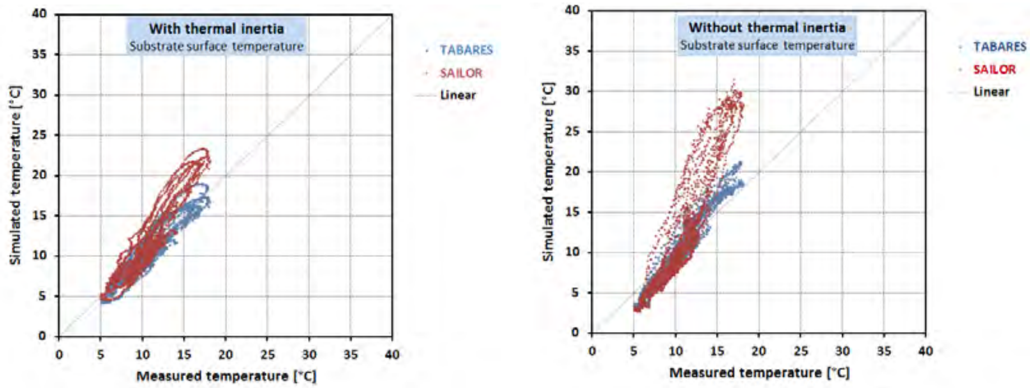


Figure 3. Simulated vs Measured surface temperatures of the substrate for models with and without thermal mass.

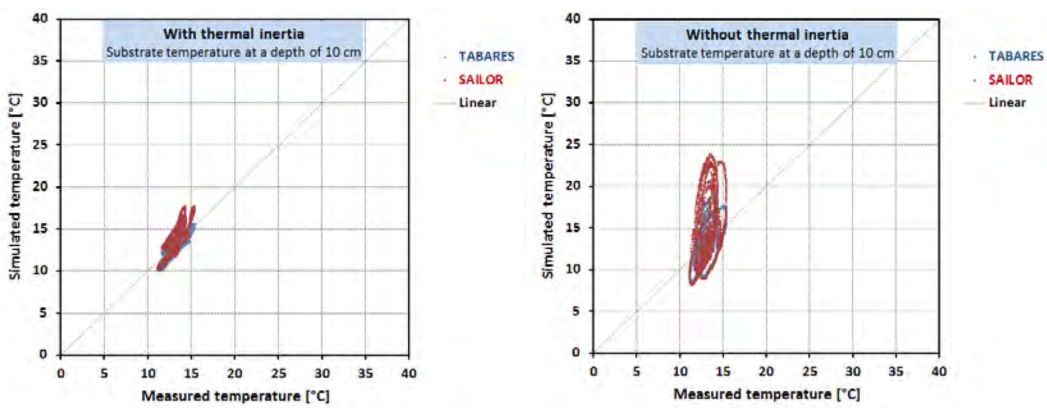


Figure 4. Simulated vs Measured substrate temperatures at a depth of 10 cm for models with and without thermal mass.

## CONCLUSIONS

This paper discusses the impact of the thermal inertia of the substrate on the thermal behaviour of a vegetative (green) roof system. Two thermal models – the Sailor (2008) and the Tabares and Srebric (2012) models - were implemented in Matlab and the thermal inertia was implemented in them by using the finite difference approach. Substrate temperatures simulated by the two models were then compared with experimental data during 10 days at the end of the winter period, first without considering the thermal inertia of the substrate and secondly by taking it into account. The results clearly evidence the importance of considering thermal inertia of the substrate to accurately predict the temperatures within the substrate. When thermal mass of the substrate is taken into consideration, both investigated VR models are capable of accurately predicting the substrate temperature, with a RMSD about 1°C at 10 cm of depth. For the analysed period and investigated vegetative roof, the Tabares model outperforms the Sailor model. The future work of this study should include other periods of evaluation such as summer and mid-seasons and different climates and vegetation species.

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