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Analysis of thermal effects of vegetated envelopes: Integration of a validated model in a building energy simulation program

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ABSTRACT

In this paper, a newly developed heat and moisture transfer model for green envelopes is integrated in a transient building simulation program (TRNSYS) in order to investigate its dynamic performances coupled with a multizone building code. On the one hand we focus on the understanding of the coupled heat and mass transfers between green envelopes and the building; and on the other hand we study the model accuracy to assess the vegetation impacts together with building design. At first, the model reliability is verified through experimental comparisons during a summer period. Then, the developed simulation tool is used to assess the impacts of green walls on building energy performance. Since this model involves different hygrothermal transfer phenomena, the detailed numerical model results are analyzed to determine the weight of each phenomenon: evapotranspiration, shading effect and additional thermal resistance of green roof or wall. The results highlight the thermal benefits in summer and winter, especially for the west walls. The analysis of the different transfer mechanisms show that the foliage shading reduces the surface temperature variation whereas the evapotranspiration ensures the passive cooling when the water availability is sufficient.

1. Introduction

To reduce buildings energy consumption various innovative construction techniques can be employed. Among these techniques, green roof and green walls are increasingly used in new construction projects. Green roofs effectively contribute to urban reconciliation ecology [1] and provide solutions for several environmental problems stemming from buildings. In addition, green roof strategy is not only a solution for new built projects but also for retrofitting [2–4]. Pulselli et al. [5] have evaluated, in emergy terms the direct and indirect environmental resource appropriation by green walls and found that living walls and grass walls systems can achieve a condition of comprehensive sustainability in 25 years lifetime.

Green roofs, living walls and green façades can be valuable for building energy performance and for urban microclimate mitigation [6–8]. They reduce the temperature peaks of external surfaces of buildings envelope in summer [9–13]. Green envelope modules affect the heat transfer through the building envelope layers. Several experimental studies seek out quantifying the heat gains and losses from green envelopes, especially green roofs [10,14–17]. Several studies estimate that green roofs reduce significantly the building's cooling load during summer [18–20]. Santamouris et al. [21] found that a green roof reduce the energy demand up to 6–49% for the whole building when the major impact is observed for the last floor. Regarding the heating loads, the effects of green roof were not significant in this study. Other studies highlight similar trends but with different energy impacts due to various building configurations and different climates. When green walls are studied, a lot of parameters need to be considered such as the walls orientation [22] and the water content distribution within the green wall, from top to bottom [12,23].

However, the heat and moisture transfer through the vegetated building envelope depends on its thermal insulation, on the radiative properties of external surfaces and on thermohydric properties of the vegetation species and growing medium of green roofs and green walls. According to a study of Wong et al. [14] on a five-story commercial building located in Singapore, the variation of the green envelope parameters (vegetation and growing media) has a non-negligible impact on the annual energy consumption which

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can range between 0.6 and 14.5%. Hence, it is necessary to develop models able to assess the complex hygrothermal behavior of vegetated envelopes in different climates under various configurations. Several green roof models have been published over the last fifteen years [24–28]. Besides, there are fewer simulation works on the green walls impact on energy performance. Green walls were often modeled only through their shading effects [29,30]. Building simulations (with TAS) of Wong et al. [31] were performed to determine the vertical greening systems effects on thermal comfort and energy consumption. However, the influence of greening systems on buildings was modeled only through shadings coefficient linked to the leaf area index. Recently, Scarpa et al. [32] develop a living wall mathematical model that accounts for different features of living walls. Validation against field measurements for two different kinds of living walls have been carried out.

Olivieri et al. [33] have study the thermal behavior of an extensive green roof during the summer. Subsequently, a simplified numerical model based on experimental data was established in order to calculate the thermal resistance of the roofing during summer. The model aims to assess the energy performance of green roofs on the basis of three variables: the leaf area index, the height of the plants and the thermal conductivity of the substrate. However, this approach is valid for a given roof in summer with a given climate and the results cannot be generalized to other seasons according to Moody and Sailor [34].

In order to assess the thermal incidence of vegetated envelopes on building energy performance, reliable models of green envelope modules should be coupled to the detailed building model. D.J. Sailor has developed and integrated a green roof model [25], based on the Army Corps of Engineers' FASST vegetation models [35] into the EnergyPlus building energy simulation program. The model was compared with a monitored green roof in Florida. Although the diurnal temperature variations were only about 10 °C, the average bias of the simulation was 2.9 °C with an RMSE of 4.1 °C. It is true that such numerical deviation may be due to incorrect inputs for the model parameters, but the reason may be also due to the simplifying assumptions of the green roof model. A more recent work [36], accomplished at the University of La Rochelle has yield to the integration, into TRNSYS, of a green roof model [37] based on Sailor's model and enhanced with a water balance. A comparative study of temperature and heat flux evolution through green roofs and conventional roofs allowed the assessment of the green roofs thermal impact and some parametric studies.

In this paper, an improved model of green envelope, previously developed and compared to experimental studies at the university of la Rochelle [28], is adapted to the building simulation software TRNSYS. The developed model takes into account the major thermal, aeraulic and hydric phenomena and overcomes certain limitations and assumptions of previous modeling approaches that assume quasi-steady state heat transfer and neglect the effect of water transfer on heat transfer. This new TRNSYS type can be applied in both green roofs and green walls modeling by introducing the proper meteorological inputs and adjusting the model to each technique and their specific implementation.

2. Model development

Following a review [28] of green roof models, a new model has been developed to improve the thermo-hydric modeling of the green modules by considering the coupling mechanisms of heat and mass transfer. Modified resistances to heat and vapor transfers have been proposed; taking into account the radiative characteristics, the physiological and the thermophysical properties of the green modules constituents and their change according to the water availability. The developed model was compared under various weather conditions with experiments (July 2011) in La Rochelle (France). Predicted surface temperature and water content evolutions were in good agreement with experimental data. The parametric studies highlighted the effect of the saturation ratio on the temperature peaks and clarified the role of evapotranspiration in passive cooling.

This green envelope model requires the climatic data at the external side, and, at the internal side, the bottom substrate temperature or the conducted heat flux to the building structure. The actual impact on the building energy performance has to be computed by coupling the model to the thermal building model on this internal side. In the following sections the model equations are summarized and its coupling with the multizone building model is detailed.

2.1. Green envelope model

The model [28] considers coupled heat and mass transfer phenomena through the green module. The leaf canopy is characterized by the coverage ratio (σ_f), the leaf area index (F) and semitransparent radiative properties. The substrate is a porous medium characterized by its water content and thermophysical properties depending on this later [38]. The model equations establish the heat balances on the leaf canopy and on the substrate surface (see Fig. 1). The energy balances include the main heat fluxes; namely the shortwave radiations (solar irradiance I_S [W m^{-2}]) and longwave radiations (temperatures [K] of sky T_{sky}, of foliage T_f and substrate T_g), sensible heat fluxes (H_f and H_g [W m^{-2}]) and latent heat fluxes (L_f and L_g [W m^{-2}]). These latent and sensible fluxes (H and L) are evaluated using a resistance scheme (r_a, r_s, r_c and r_{sub} [s m^{-1}] given in reference [28]) that opposes heat and vapor transfer and that incorporates the aerodynamic resistance, the stomatal resistance, and the resistance to the diffusion of heat and vapor from the soil surface throughout the leaf canopy.

The heat balance of the foliage can be expressed by unit area:

$$\left(\rho c_p\right)_f d_f F \frac{\mathrm{d}T_f}{\mathrm{d}t} = \sigma_f \left[\left(1-\tau_s-\rho_s\right)\left(1+\tau_s\rho_g\right) I_s + F_{sky,f}\,\varepsilon_f\sigma\left(T_{sky}^4 - T_f^4\right) + \varepsilon_{fg}\sigma\left(T_g^4 - T_f^4\right)\right] - H_f - L_f \tag{1}$$

where T_a is the ambient temperature, $(\rho c_p)_f$ and d_f are, respectively, the specific thermal capacity and the average leaf thickness. The radiative coefficients τ_s, ρ_s, ε_f, ρ_g, $F_{\text{sky},f}$ and σ are, respectively, the foliage shortwave transmittance, the foliage shortwave reflectance, the foliage emissivity, the soil reflectance, the sky view factor and the Stefan–Boltzmann constant.

The sensible heat flux H_f and the latent heat flux L_f through the foliage are given by the following equations:

$$H_f = F\frac{\left(\rho c_p\right)_a}{r_a}\left(T_f - T_a\right) \tag{2}$$

$$L_f = F\frac{\left(\rho c_p\right)_a}{\gamma\left(r_a + r_s\right)}\left(p_{v_{f,sat}} - p_{v_a}\right) \tag{3}$$

similarly, the energy balance on the substrate surface is given as follows by unit area:

$$-\lambda\omega_g \left.\frac{\partial T}{\partial z}\right|_{z=0} = \sigma_f\left[\left(1-\rho_g\right)\tau_s I_s\right] + \left(1-\sigma_f\right)\left[\left(1-\rho_g\right)I_s\right] + \sigma_f\varepsilon_{fg}\sigma\left(T_f^4 - T_g^4\right) + \left(1-\sigma_f\right)F_{\text{sky},g}\,\varepsilon_g\sigma\left(T_{\text{sky}}^4 - T_g^4\right) - H_g - L_g \tag{4}$$