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INTEGRATION OF A GREEN ENVELOPE MODEL IN A TRANSIENT BUILDING SIMULATION PROGRAM AND EXPERIMENTAL COMPARISON

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ABSTRACT

Green roofs and green walls have several benefits on buildings and cities. They are most often used for water management and for the aesthetical value they provide to the urban environment. These green coatings have a positive impact on the sustainability of building materials. They can improve building energy performance and reduce the amplitude of diurnal variations of the surfaces temperature in summer. The energy saving or comfort improvement is more obvious for hot climates. This paper presents a green envelope model integrated in a transient building simulation program (TRNSYS). This software integration allows dynamic thermal simulations of multizone buildings with green roofs or green walls. The reliability of the model is tested through comparisons to measurements performed on a reduced scale model of buildings during summer period. The impact of the vegetated envelope on cooling energy demand is modeled for various climates.

INTRODUCTION

Green roofs, living walls and green façades can be valuable for building energy performance. They reduce the temperature peaks of external surfaces of buildings envelope in summer (Teemusk and Mander, 2009; Wong et al., 2003). In parallel, the green envelope modules affect the heat conduction through the building envelope layers. Several studies seek out quantifying the heat gain or loss by conduction, Liu & Minor (Liu and Minor, 2005) reported that a green roof improves the building thermal insulation, thereby reducing solar heat gain by approximately 70–90 % in the summer and reducing heat loss by 10–30% in the winter. However, the heat conduction transfer is not necessarily affected up to this point because the heat conduction magnitude, even for the same green envelope modules with the same properties, depends strongly on the envelope insulation. Besides, there is a little simulation works on the green walls impact on energy performance. Building simulations (with TAS) of Wong et al. (Wong et al., 2010) 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 relied on the leaf area index.

In order to assess the thermal incidence of vegetated envelopes on energy building performance, reliable models of green envelope modules should be coupled to detailed building models. D.J. Sailor has developed and integrated a green roof model (Sailor, 2008), based on the Army Corps of Engineers' FASST vegetation models (Frankenstein and Koenig, 2004) 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 (Jaffal et al., 2012), accomplished at the University of La Rochelle has yield to the integration, into TRNSYS , of a green roof model (Ouldboukhitine et al., 2011) 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.

The present work is dealing with the integration into TRNSYS of a recently developed and experimentally validated green envelope model (Djedjig et al., 2012b). 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. The 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.

VEGETATED ENVELOPE MODEL

The developed green envelope model (Djedjig et al., 2012a, 2012b) evaluate the coupled heat and mass transfer through the green module. The vegetation is characterized by the coverage ratio (σ_f) and the leaf area index (F). The substrate is a porous medium characterized by its water content and thermophysical properties depending on this later (Ouldboukhitine et al., 2012). The model equations establish the heat balance on the leaf canopy and on the substrate surface (see *Figure 1*). The energy balances include the main heat fluxes namely the short- and longwave radiations, sensible heat fluxes and latent heat fluxes. The direction of heat and mass flux is perpendicular to the building vegetated envelope. These fluxes are evaluated on the foliage using a resistance scheme 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.

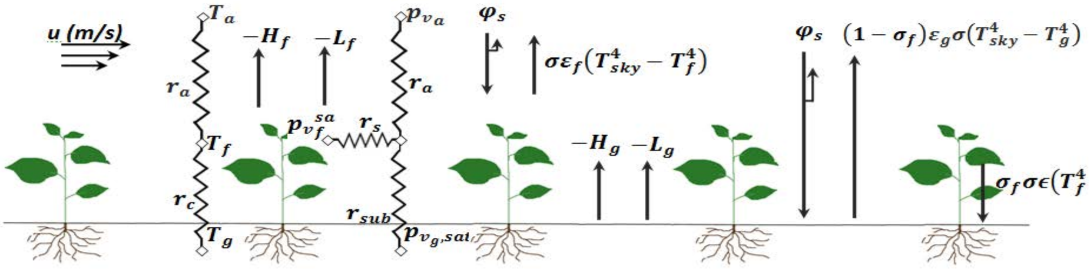

Figure 1 Main modeled heat fluxes on a vegetated envelope module and corresponding heat and vapor transfer resistances

The heat balances on the foliage and the substrate surfaces are expressed as following for a uniform unit area:

$$(\rho c_p)_f d_f F \frac{dT_f}{dt} = Rn_f + H_f + L_f \tag{1}$$

$$-k_{\omega_g} \frac{\partial T}{\partial z}\bigg|_{z=0} = Rn_g + H_g + L_g \tag{2}$$

Where T is the temperature; $k_{\omega g}$ is the substrate conductivity at the water content ω_g; $(\rho c_p)_f$, d_f and F are respectively the specific thermal capacity, the average leaf thickness and the leaf area index. Rn, H and L (W.m^{-2}) are respectively the net radiation exchange, the sensible heat transfer and the latent heat transfer through the foliage (f) and the substrate surface (g).

The sensible and the latent heat fluxes are formulated by equations (3, 4, 5 and 6). See reference (Djedjig et al., 2012b) for more detail about the calculation of the thermal resistances (r_a, r_s, r_c and r_{sub} [s.m^{-1}]), and net radiation exchanges Rn_f and Rn_g (W.m^{-2}).

$$H_f = F\frac{(\rho c_p)_a}{r_a}(T_a - T_f) \tag{3}$$

$$L_f = -F\frac{(\rho c_p)_a}{\gamma(r_a + r_s)}(p_{v_{f,sat}} - p_{v_a}) \tag{4}$$

$$H_g = \frac{(\rho c_p)_a}{(r_c + r_a)}(T_a - T_g) \tag{5}$$

$$L_g = -\frac{(\rho c_p)_a}{\gamma(r_{sub} + r_a)}(p_{v_{g,sat}} - p_{v_a}) \tag{6}$$

The heat conduction through the substrate layer is modeled by the one-dimentional heat equation (7) in which the thermophysical properties are calculated by accounting for the change in the water content ω_g.

$$(\rho c_p)_{g,\omega_g} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_{\omega_g}\frac{\partial T}{\partial z}\right) \tag{7}$$

Determining the change over time in the water content of the substrate is essential for estimating the intensities of the different heat fluxes. The water balance of the green roof is written as following:

$$\rho_w \Delta z \frac{\partial \omega_g}{\partial t} = P + A - D - E \tag{8}$$

Where P, A, D and E are respectively the rainfall, the watering, the drainage and the evapotranspiration rates (kg.m^{-2}.s^{-1}).

The heat flux exchange at the contact surface between the building and the green module is given as follows:

$$-k_{\omega_g} \frac{\partial T}{\partial z}\bigg|_{z=-d_g} = \dot{Q}_{ext} \tag{9}$$

Where $\dot{Q}_{ext}$ (W.m^{-2}.K) is calculated by other TRNSYS components taking into account the multi-layers of the building envelope.

The simulation results were compared to experimental data carried out at the University of La Rochelle. The good agreement between predicted and measured surface temperature and water content evolutions allowed us to verify the model reliability and to validate it (Djedjig et al., 2012b) . The parametric studies highlighted the effect of the saturation ratio on the temperature peaks and clarified the role of evapotranspiration in passive cooling.

In order to assess the thermal effect of green envelopes on building energy demand, the model described here briefly has been integrated into TRNSYS system simulation tool. This tool allow detailed multizone building modeling.

TRNSYS INTEGRATION OF THE GREEN ENVELOPE COMPONENT AND VERIFICATION

TRNSYS software has a graphical user interface (TRNSYS Simulation Studio) that allows intuitive creation of simulations by dragging and dropping available TRNSYS library components. Each component have defined number of inputs, outputs and parameters. Thereafter, the outputs of each component are connected to the inputs of other ones in order to make up a physical system. In this work, the developed model, written in python programming language, was coupled to the multizone building model component (*Type 56*) by creating a new TRNSYS component (see *Figure 2*).

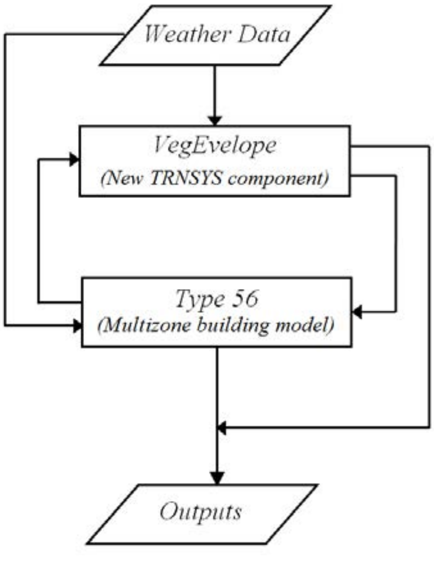

Figure 2 Coupling Type 56 multizone building model to the new green envelope TRNSYS component

The inputs of the new TRNSYS component are mainly the meteorological data: the air temperature and relative humidity, the wind velocity, fictive sky temperature total shortwave radiation on the vegetated surface. The outputs are the heat flux through the green building envelope; the sensible heat flux, the latent heat flux and the radiative flux on the foliage and on the substrate surfaces. The green envelope component computes also the substrate water content which may be fixed or variable according to watering and rainfall rates.

We have mentioned that the green envelope model have been already validated through comparison to measurements carried out on experimental green roofs. To verify also the accuracy of the model coupling in TRNSYS, the thermal effects prediction of the vegetated module on building should be compared to experimental data. The outdoors experimental platform (reduced scale 1:10) which allowed to validate (Djedjig et al., 2012b) the green module model, is formed by five rows of concrete buildings. Two of these buildings have green roofs and one has a green wall system on the west façade. The successive buildings rows form a set of urban canyons. The temperature evolution at several measurement points inside the green roofs and the green wall layers is monitored using a set of sensors connected to a datalogger. This latter records also continuously the air temperature evolution, the humidity variations and radiative fluxes in all specific spots of the experimental platform.

In the following, we compare the predicted green wall impact on the west façade temperature to measurements. It is obvious that the façade temperature, which is originally exposed to solar radiation during the evening, would be decreased by the green wall module. To make a good comparison, all inputs parameters of the building model and the green wall system properties have to be well identified, as well as the microclimate conditions. The street microclimate reproduced on the experimental bench is not precisely modeled. So, we propose a comparison of the overall trends of this specific surface temperature in order to verify the relevance of the numerical simulations. It should be noted that the effects of the substrate inertia, the higher wall solar absorptivity and the evapotranspiration's intensity over time, which depend on wall orientation, have all a significant impact on the façade surface temperature evolution.

The evolution of the west façade temperatures is compared for Buildings 2 and 3 (concrete surfaces), see *Figure 3*. The left plots concern the experimental data namely: the air temperature (T_a), the air relative humidity (HR), the shortwave irradiance on horizontal (ϕ_s) and the measured temperatures of the white façade and the green wall covered façade. The right plots show the main standard weather data for La Rochelle city used for the numerical simulation and compares the west façade temperature evolution for the white painted wall and the green wall.

Although there are significant differences in meteorological conditions and there is some lack of precise input parameters for building model, the two graphs present the same overall trends. When the façade is covered with a green wall, its temperature is less variable. Hence, the pic of façade temperature is more decreased when reference white façade reaches high temperatures (up to 15 °C difference). The façade with the green wall have more important thermal inertia. The numerical results show substantially the same effects. At night, the vegetated façade remain hotter than the white façade, because there is less infrared loss.

This comparative analysis of the façade temperature evolution allowed verifying the coupled models by checking the consistency of the numerical results.

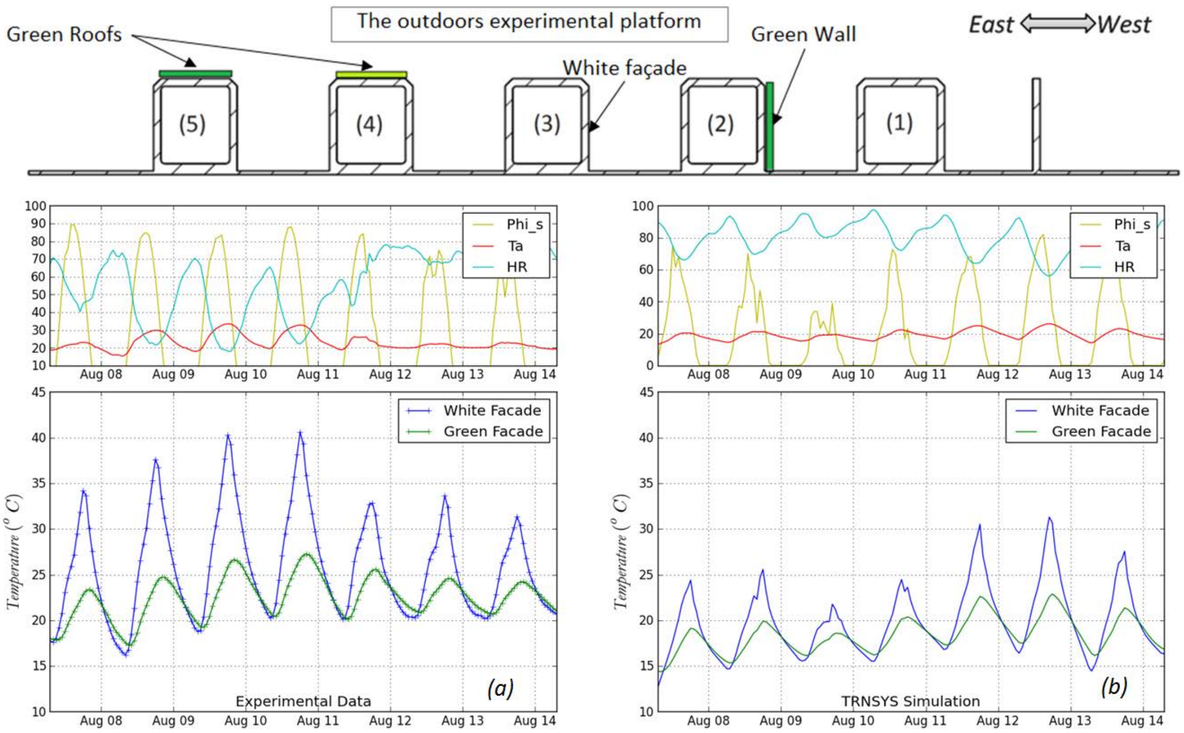

Figure 3 West façade temperature evolution on a reference white façade and a green wall at given weather conditions: (a) experimental results and (b) TRNSYS simulation

THERMAL IMPACT OF GREEN WALLS ON A REAL BUILDING

To evaluate the thermal impact of green roofs and green walls on buildings, the developed TRNSYS component has been used. In this paper, we chose to study the green walls impact on buildings energy demand as there are no similar simulation studies in the literature. The case study is a three story building that have allowed us previously verifying the thermal similarities of the experimental platform with full scale buildings (Doya et al., 2012). The building includes glazing surfaces on the north/south façades (see *Figure 4*). The walls are made of 20 cm cinder block and the roof and ceilings made of 12 cm concrete. The south facade and the north facade have glazing surfaces that represents 20 % of the floor area. The infiltration rate is set at 0.6 Vol/hour. The building is supposed unoccupied, so no internal gains are considered. The solar absorptivity of the roof and the reference façades is 0.5.

TRNSYS allow internal calculation of the direct and diffuse short wave radiation components for tilted surfaces. Hence, the east façade receive more radiation in the morning and the west façade receive more radiation in the evening.

To assess the thermal incidence of green walls on this building, two green walls are added on the east and the west façades. The green walls substrate depth is 12 cm and its saturation ratio is fixed at 60 %. The vegetation coverage (σ_f) ratio is set at 1.0 and the leaf area index is set at 4.

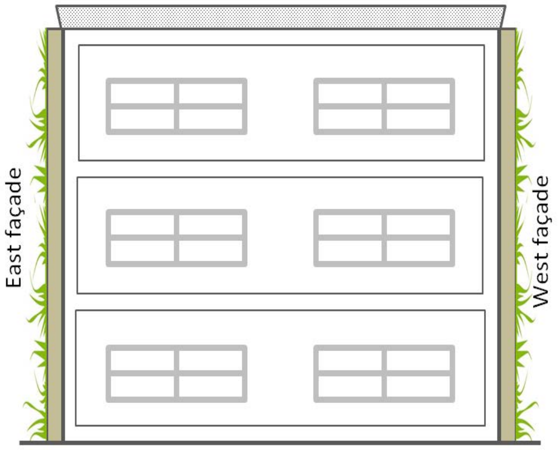

Figure 4 Three story building studied for green walls incidence evaluation on energy demand

The expected green walls thermal effects will depend on the climate. So, the simulations are presented for two cities with two different climates. Selected cities are La Rochelle, where the climate is oceanic and Athens which enjoys a Mediterranean climate.

The façade temperature decrease has advantage on the building cooling performance and on the urban microclimate mitigation in summer. The temperature decrease depends mainly on the green wall characteristics as the coverage ratio, the leave area index and the water content. *Figure 5* shows a comparison of the external surface temperature for the studied buildings. The blue lines represent the evolution of the East and the West façade temperature for the reference building when the green lines show the evolution of the substrate surface temperature for the green walls of the vegetated building. We can see that the temperature difference reach up 10 °C for the east side as well as for west side.

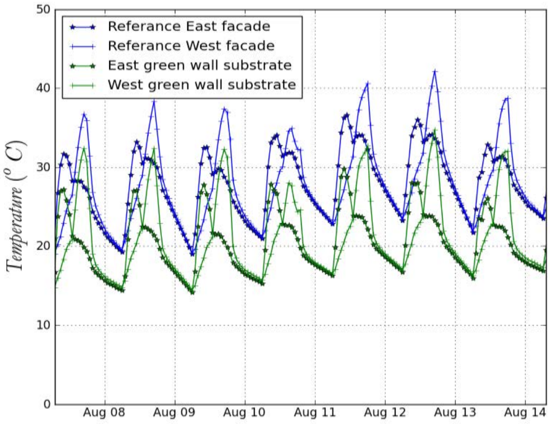

Figure 5 Comparison of the East and the West façade temperature evolution of the reference building to the substrate surface temperature of the green walls

Dynamic thermal simulations were performed for the period from May to September. The setpoint temperature above which cooling is needed is set at 26 °C. *Figure 6* compares the cooling load for the reference building and for the same building covered with two green walls on the East and on the West façades. The cooling energy demand of the air conditioning system is not computed here; indeed it depends on this cooling thermal load, but also on the latent loads and the COP of the system. This figure shows that the green walls reduce the cooling load for the two climates. For La Rochelle city there is no very high cooling load; only less than 0.3 kWh.m^{-2} for July and August. By cons, the relative reduction in this energy demand is considerable. The vegetated building has less than one half of the cooling load of the reference building. For Athens city, the simulations findings are almost the same. However, because Athens climate is hotter than La Rochelle climate, the cooling load is more important (up to 2.7 kWh/m^2 on July and August). Thus, the energy savings due to the green walls are very important although the relative reduction seems less than the relative reduction in La Rochelle city.

The reduced cooling energy demand is due to the heat flux decrease on the vegetated parts of the building envelope. When the green walls are implemented the additional green walls layers decrease the *U*-value of the building envelope. Moreover, the shading effect of the foliage and the evapotranspiration process decrease significantly the external surface temperature. This temperature may reach very high values in summer, so when it is reduced, the inside surface temperature is also decreased. Consequentially, the operative temperature of the building decreases, the cooling demand is reduced and the thermal comfort is enhanced.

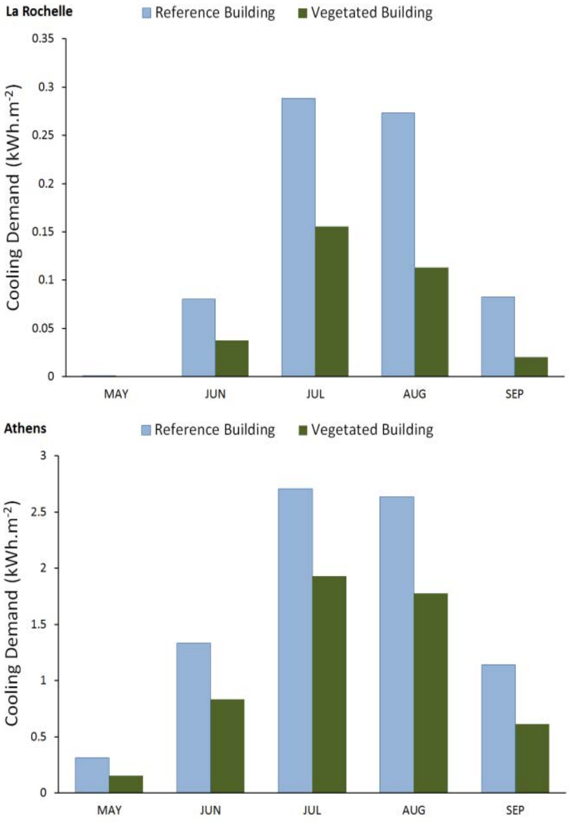

Figure 6 Comparison between the cooling thermal load for the reference building and for the vegetated building in La Rochelle and in Athens

The additional *U*-value, the shading and the evapotranspiration effects operate together and their specific effects are coupled and difficult to separate. Indeed, the evapotranspiration affects the substrate's water content and consequently the thermophysical properties of the vegetated component. Then, the overall *U*-value of the wall is modified. Besides, the increase of the shading effects should involve higher coverage ratios or higher leaf area index. However, higher foliage density involves more plant transpiration and less soil evaporation. So this will change the surfaces temperature and affect the sensible and the longwave heat fluxes. In this paper, we don't discuss the contribution of each thermal effect. A detailed study will focus, subsequently, on a breakdown between these different effects.

Figure 7 shows the diurnal variation in summer time of the mean operative temperature in the building located at Athens city. This temperature depends on the air temperature and on the temperature of the surfaces. The difference in the operative temperature reaches up to 1.5 °C between the reference building and the vegetated building.

The only drawback of green walls in summer days is associated with water management. Indeed these green systems require considerable quantities of water for irrigation. This can be a challenge in water-scarce regions. However, recovery of rain water and reusing a part of wastewater can help to remedy this problem. For instance, the estimation of the water use through performed simulation is 10 L.m^2.day^{-1} for the east façade and 7.3 L.m^2.day^{-1} for the west facade.

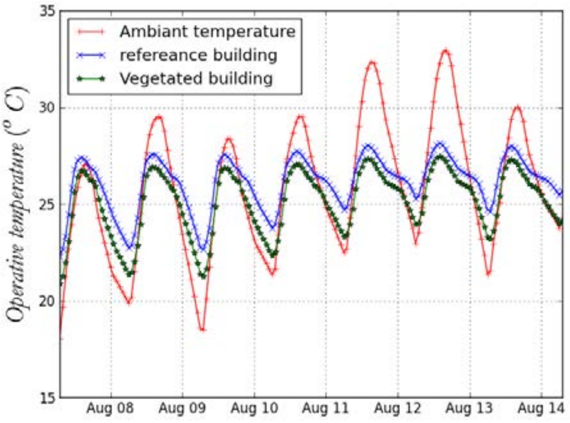

Figure 7 Building mean operative temperature variations for the reference building and for the vegetated building

CONCLUSION

A green envelope model was integrated in the transient building simulation program TRNSYS. The model, already validated alone with experimental data, is coupled to a building model. The coupled model developed here gives good agreement with summer conditions' experimental data.

The thermal dynamic simulation study done for various conditions, with the proposed model, highlights the significant impacts on cooling energy demand, especially in Mediterranean climate. The green walls decrease the surface heat transfer from indoor to outdoor and the façade surface temperature. As a result, the green walls will contribute, also, to the urban microclimate mitigation. In addition, real meteorological data should be used to be able to make absolute comparisons. This work is ongoing, and a specific model of urban canyon is under development so as to use realistic microclimatic data. Moreover, the model will be validated for winter in order to perform reliable simulations to quantify the thermal effects of the green envelopes on building heating demand for an all year period.

NOMENCALTURE

T = Temperature (K)
φ_s = Horizontal shortwave irradiance (W m^{-1})
k = Thermal conductivity
ρc_p = Specific thermal capacity (J m^{-3}K^{-1})
ω_g = Volumetric water content (–)
F = Leaf area index (–)
σ_f = Fractional vegetation coverage (–)
d = Thickness (m)
ε = Emissivity (–)
γ = psychometric constant (Pa K^{-1})
p_v = Vapor pressure (*Pa*)
r_a = Aerodynamic resistance (s m^{-1})
r_s = Leaf stomatal resistance (s m^{-1})
r_c = Leaf canopy resistance (s m^{-1})
r_{sub} = Substrate surface resistance (s m^{-1})
Rn = Net radiation flux (W m^{-2})
H = Sensible heat flux (W m^{-2})
L = Latent heat flux (W m^{-2})
P = Latent heat flux (kg m^{-2} s^{-1})
A = Latent heat flux (kg m^{-2} s^{-1})
D = Latent heat flux (kg m^{-2} s^{-1})
E = Latent heat flux (kg m^{-2} s^{-1})
t = Time
z = Altitude or height

Subscripts

a	Air
c	Leaf canopy
f	Foliage
g	Substrate surface (Ground)
w	Water
sat	Saturation value
s	Solar/ Shortwave

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