Building and Environment 73 (2014) 187–197

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A hydrothermal model to assess the impact of green walls on urban microclimate and building energy consumption

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
15 December 2013
Accepted 22 December 2013

Keywords:
Green walls
Microclimate
Building energy consumption
Model
Simulation
SOLENE

ABSTRACT

Covering a building envelope with vegetation provides a solution capable of mitigating the urban heat island phenomenon and its impact on the energy consumption of buildings. Simulation tools to assess the efficiency of such a solution are lacking, especially for green walls. The present research aims to offer a hydrothermal model of green walls and green roofs for implementation in the urban microclimate simulation software *SOLENE-Microclimate*. To this end, a fast, efficient coupled heat–mass transfer model has been developed. Simulation results are compared with experimental data obtained from the LEEA Laboratory in Geneva for three green wall samples. Aside from the level of uncertainty found for the evapotranspiration calculation, these results confirm that the model accurately characterizes the temperature evolution of all three prototypes. Results also show good correlation between measured and simulated temperatures. The model is indeed able to reproduce water stress and characterize various types of living walls.

1. Introduction

The combination of global warming and the urban heat island effect raises concerns over health, energy consumption and discomfort that require quick realistic answers. One key consideration is how best to adapt city planning policy in order to mitigate the urban heat island phenomenon and its impact on the energy consumption of buildings. In a context of urban intensification, covering the building envelope with vegetation offers a potential solution. One objective therefore is to provide a simulation tool capable of describing how the greening of building envelopes affects the thermal behavior of buildings not only directly, but also indirectly through induced microclimate changes.

While green roofs have been widely studied for their impacts on both a building's thermal behavior and the urban microclimate, studies on green walls have mainly focused on building-related impacts.

After several pioneering works in the 1980's dedicated to the thermal effect of climbing plants [1,2], the scientific community was investigating this topic in depth by the end of the 2000's decade, with the emergence of innovative vertical greening techniques like living walls [3–18].

These recent papers have dealt with many different devices, which can be classified into three categories. The first, called "vegetated coverings" or "green facades", introduce climbing plants on a wall or support structure close to the wall without any irrigated substrate. The second category, which differs from the first by the presence of an air cavity with a different air temperature underneath the foliage, includes support grid systems far from the wall such that this air cavity cannot be observed. This category has been called a "sunscreen" since its effect is mainly radiative. The last category, known as the "living wall", includes a wide range of devices using an irrigated substrate that can be either natural or artificial.

Recent research has investigated vertical vegetated elements at various scales and for various purposes. The first and most commonly studied scale is that of the device, where intrinsic characteristics like thermal, hydraulic and radiative parameters are observed on standalone samples or a building facade. Some studies have extended their observations to the thermal impact on buildings, which has yielded three types of results:

- The decrease in indoor temperature, ranging from 0.5° to 7 °C, depending on the case under study [1,2,8,9];
- The decrease in energy consumption for cooling, observed between 5% and 68% [5,6,8,9];
- Heat flux transmitted through the external wall, which could be either positive or negative depending on climate [2,3,7,10].

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http://dx.doi.org/10.1016/j.buildenv.2013.12.012

Nomenclature

c_p	specific heat [J/K/kg]
C_i	heat capacity of node *i* [J/K]
d	zero displacement altitude [m]
d_f	thickness of a single leaf [m]
Dr	drainage water [l]
e_a	partial pressure of water vapor in the atmosphere [Pa]
e_{sat}	saturation vapor pressure [Pa]
Et_d	daily evapotranspiration rate [l]
Et_h	hourly evapotranspiration rate [l]
ETP	reference evapotranspiration [kg/m^3/s]
f	evapotranspiration rate [−]
F	view factor [−]
h_{i-j}	heat transfer coefficient between nodes *i* and *j* [W/m^2/K]
Ir	irrigation [l]
k_s	extinction coefficient [−]
L	thickness of the foliage coating [m]
LAI	leaf area index [−]
L_v	latent heat of vaporization of water [J/kg]
Pr	precipitation intercepted by the control sample [l]
r_a	aerodynamic resistance of the canopy [s/m]
r_{aero}	aerodynamic resistance of a single leaf [s/m]
r_l	stomatal resistance of an isolated leaf [s/m]
r_s	surface resistance [s/m]
R	air exchange rate within the canopy [s^{-1}]
R_{i-j}	thermal resistance between nodes *i* and *j* [m^{2}K/W]
R_n	net radiation balance [W/m^2]
T_i	temperature of node *i* [°C]
v	wind speed [m/s]
$V_{\max}$	maximum water content [l]
V_t	water content at time step *t* [l]
z_m	reference altitude for wind measurements [m]
z_0	roughness height [m]

Greek symbols

α_{lat}	repartition coefficient of latent heat flux [−]
α_R	weighting coefficient of wind speed for the air exchange rate [−]
γ	psychrometric constant [Pa/°C]
Δ	slope of the saturation vapor pressure–temperature relationship [Pa/°C]
Δm	hourly variation of mass [kg]
ε	thermal emissivity [−]
κ	von Karman constant, 0.41 [−]
λ	thermal conductivity [W/m^2/K]
σ	Stefan–Boltzmann constant, $5.67 \cdot 10^{-8}$ [W/m^2/K^4]
ρ	density [kg/m^3]
ρ_f	foliage albedo [−]
τ_f	foliage transmittance [−]
φ	heat flux [W/m^2]

Subscripts: Thermal fluxes

lat	latent
swr	short-wave radiation
lwr	long-wave radiation
conv	convection
cond	conduction

Subscripts: Nodes

f	foliage
a	air within the foliage
es	external surface
∞	outdoor air
n1	internal node

Moreover, two studies have focused on microclimate impacts according to various approaches. Alexandri and Jones [6] used a street canyon model with a finite element calculation method and a detailed representation of vegetated surfaces for different climatic contexts. Their results revealed an impressive decrease in air temperature inside the canyon, especially in hot dry climates but also in temperate and continental settings. Wong et al. [12] developed an empirical model dedicated to Singapore for comparing the effects of several greening scenarios on the local district. None of them however have validated their numerical results with local experimental weather data.

It has thus been verified that the thermal behavior of a green wall is very sensitive to its own configuration as well as to the characteristics of its green coating and to its climatic context. This verification is valid for impacts on both the building and its immediate environment, which leads to the conclusion that the green wall must be modeled in detail to enable an accurate representation of the three phenomena playing major roles in the thermal behavior of the green envelope, i.e. evapotranspiration, solar radiation and convective heat exchanges. Furthermore, to compare different technical solutions, the model must also allow representing the three categories of devices and taking into account the behavior of a wet substrate.

Some of the works cited above present a hydrothermal model of vegetated walls that has been directly inspired by modeling efforts on green roofs [3,5,6,8]. Wang et al. [9] only considered radiative effects, while Holm [1] used porous wood and a layer of water as an analogy for the green canopy.

Many green roof models have been developed; they typically comprise a dynamic thermal balance applied to each component of the green envelope (support, soil and vegetated canopy) and calculation of the coupled mass–heat transfer between them. These models are one-dimensional, without any transverse fluxes and based on a finite difference approach [19–22].

The main remaining distinctions consist of: calculation of the evapotranspiration rate, spatial discretization of the canopy and substrate, and a representation of moisture inside the substrate. Most authors represent vegetation by a single thermal node, while Alexandri and Jones [20] used three nodes. As for plants, the soil can either be considered as a homogeneous solid body with thermal parameters dependent on a saturation rate [19,21,22] or else represented by a porous medium with three phases (humid air, water and porous state) in taking into account the latent heat of phase transition [20].

Concerning model adaptation from the roof to the wall, it can be noted that none of the differences possibly expected between the horizontal and vertical surfaces have been treated, especially from the effect of gravity. Existing thermal models are in fact primarily intended to direct greening and double skin facades using plants without any growing medium.

One of the most significant differences to be taken into account when modeling the behavior of green walls is their interaction with