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Development and validation of a coupled heat and mass transfer model for green roofs☆

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A R T I C L E   I N F O

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A B S T R A C T

This paper describes a dynamic model of transient heat and mass transfer across a green roof component. The thermal behavior of the green roof layers is modeled and coupled to the water balance in the substrate that is determined accounting for evapotranspiration. The water balance variations over time directly impact the physical properties of the substrate and the evapotranspiration intensity. This thermal and hydric model incorporates wind speed effects within the foliage through a new calculation of the resistance to heat and mass transfer within the leaf canopy. The developed model is validated with experimental data from a one-tenth-scale green roof located at the University of La Rochelle. A comparison between the numerical and the experimental results demonstrates the accuracy of the model for predicting the substrate temperature and water content variations. The heat and mass transfer mechanisms through green roofs are analyzed and explained using the modeled energy balances, and parametric studies of green roof behavior are presented. A surface temperature difference of up to 25 °C was found among green roofs with a dry growing medium or a saturated growing medium. Furthermore, the thermal inertia effects, which are usually simplified or neglected, are taken into account and shown to affect the temperature and flux results. This study highlights the importance of a coupled evapotranspiration process model for the accurate assessment of the passive cooling effect of green roofs.

1. Introduction

Green roofs can be valuable for building energy performance and for urban microclimate mitigation. Urban surfaces, especially roof coatings, contribute to the urban heat island effect. Green roofs have direct impacts on the urban environment [1–4] and reduce building cooling energy demand. The thermal impact of green roofing that motivates the present work has been extensively studied using different experimental measurements performed on residential and commercial buildings. For example, Liu and Minor [5] found that a green roof improves the thermal insulation of a building, thereby reducing solar heat gain by approximately 70–90% in the summer and reducing heat loss by approximately 10–30% in the winter. In addition, the durability of the waterproof membrane of the roof is increased following the reduction of the peak temperature by approximately 30 °C, as observed by Teemusk and Mander [6]. Indeed, the leaf temperature remains similar to the ambient air temperature because of the evapotranspiration process, whereas the temperature of paved urban surfaces exposed to the sun can exceed the ambient air temperature by approximately 30 °C [7].

These results are specific to the types of buildings studied and depend on the specific vegetation and growing medium that are used. The change in these parameters varies; for example, the decline in annual energy consumption can range between 0.6 and 14.5% [8] and is primarily observed in the top floor of buildings [9]. In addition, the magnitude of the thermal impact of green roofs is strongly correlated with weather conditions [10]. These findings show the need to develop models that assess the thermal behavior of green roofs in different climates under various configurations.

The assessment of the impact of green roofs on building energy performance under different climatic conditions requires a detailed modeling of the heat and mass transfer phenomena that occur within the different layers of the green roofs. These phenomena depend not only on weather conditions but also on the physical properties of the green roof layers, such as the thermal and radiative properties, the water content and the type of vegetation. All of these properties also depend on each other. Indeed, the thermal conductivity, density, heat capacity and radiative properties vary with the water content of the growth medium [11,12]. Conversely, the water content of the growth medium depends on the intensity of the evapotranspiration process, which in turn depends on the type of vegetation, the leaf area index (F) and the fractional vegetation coverage.

Hydric modeling of the water content variations in the growth medium is therefore equally as important as the thermal modeling of the green roof, especially for long periods of simulation. Furthermore, the thermal inertia of the green roof can have a significant impact on heat transfer through the building envelope and on the

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Nomenclature

d_0	Displacement height, m
d_f	Average leaf thickness, m
D	Drainage, kg m^{-2} s^{-1}
E	Evapotranspiration, kg m^{-2} s^{-1}
F	Leaf area index
g	Gravitational constant, m s^{-2}
h	Height, m
H	Sensible heat flux, W m^{-2}
k	Thermal conductivity, W K^{-1} s^{-1}
l_v	Latent heat of vaporization, J kg^{-1}
L	Latent heat flux, W m^{-2}
p_{atm}	Atmospheric pressure, Pa
p_v	Vapor pressure, Pa
P	Rainfall, Pa
r_a	Aerodynamic resistance to sensible heat transfer, s m^{-1}
r_c	Resistance to heat flow from soil surface displacement height, s m^{-1}
r_{sub}	Substrate surface resistance to mass transfer, s m^{-1}
$r_{s,\min}$	Minimum leaf stomatal resistance, s m^{-1}
R_n	Net radiation flux, W m^{-2}
S_r	Saturation ratio
t	Time, s
T	Temperature, K
u	Wind speed, m s^{-1}
z	Altitude or depth, M
z_{oh}	Roughness length scale for heat, M
z_{om}	Roughness length scale for momentum, M

Greek letters

γ	Thermodynamic psychometric constant, Pa K^{-1}
ε	Emissivity
κ	Von Karman's constant
ρ_s	Leaf shortwave reflectance
ρ_g	Soil shortwave reflectance
ρ_{soil}	Substrate apparent density, kg m^{-3}
ρc_p	Specific thermal capacity, J m^{-3} K^{-1}
σ	Stefan–Boltzmann constant, W m^{-2} K^{-4}
σ_f	Fractional vegetation coverage
τ_s	Leaf shortwave transmission
φ	Incident radiation on the horizontal, W m^{-2}
ψ_{sh}	Stability correction for heat
ψ_{sm}	Stability correction for momentum
ω	Volumetric water content

Subscripts

a	Air
b	Bottom of the substrate
c	Leaf canopy
f	Foliage
g	Ground (soil) surface
s	Solar/shortwave
sat	Saturation value
sky	Sky/longwave
w	Water

estimation of the thermal loads of heating and cooling. In addition, the effect of inertia will depend on the type of growth medium and the drainage layer that is used and on whether the study is analyzing extensive or intensive green roofs.

The aim of this paper is to develop a thermo-hydric model that considers the inertia of all parts of the green roof and permits an explicit calculation of the evapotranspiration. To validate the model experimentally, the numerical results are compared with experimental data obtained from a one-tenth-scale model built at the University of La Rochelle in France.

2. Green roof model

Table 1 summarizes various existing green roof models [13–20], which differ in their approaches. For example, some models treat the air inside the foliage canopy as a thermal zone that is renewed by urban air [18] or as a mixture with constant proportions below the aerodynamic boundary layer that is formed by the air flow over the vegetation [15,21]. Although they are based on different approaches, these models all have the disadvantage of considering the heat and mass transfer to be in a quasi-steady state or neglecting the effect of water transfer on heat transfer. Such assumptions may distort the prediction of the temperatures reached over time and the conducted heat flux throughout the green roof support.

The proposed model in this paper considers two structural parts of the green roof: the leaf canopy and the substrate (the growing medium). The leaf canopy is characterized by its fractional coverage σ_f, its leaf area index F and its foliage distribution, which gives it semi-transparent radiative properties (Fig. 1). The substrate is a porous medium with physical properties that depend on its water content.

The input data of the model are from the external and internal sides of the green roof component. The external conditions generated by the local climate include the incident longwave radiation, incident shortwave radiation, air temperature, air humidity, wind speed and

Table 1
A bibliographic review of green roof models.

Model	Assumptions	Description
(P. C. Tabares-Velasco, 2011) [13]	Steady-state regime and negligible thermal inertia of the substrate	Model based on experimental observations of a laboratory setup
(S.-E. Ouldboukhitine, 2011) [14]	Negligible thermal inertia of the substrate and constant proportions of the air mixture within the foliage	Based on a modified version of Sailor's model that accounts for the effects of water transfer on the thermal properties of the substrate using the Penman–Monteith equation
(H. He and C. Y. Jim, 2010) [20]	A multilayer foliage canopy with semitransparent radiative properties	Development of an efficiency shading model (SEM) based on the theory of propagation of electromagnetic waves
(C. Feng et al., 2010) [19]	Photosynthesis is significant, and the leaf temperature is known	An overall heat balance throughout the extensive roof
(E. Alexandri and P. Jones, 2007) [16]	Non-uniformity of the temperature and humidity fields throughout the foliage canopy	Solving a reduced form of the partial differential equations of transfer
(D. J. Sailor, 2008 and S. Frankenstein and G. Koenig, 2004) [15,17]	Negligible thermal inertia of the substrate and constant proportions of the air mixture within the foliage	The model is based on two balance equations for the foliage and soil surface
(E. Barrio, 1998) [18]	Renewable thermal air zone within the foliage	The model is solved for a constant temperature and the water content of the soil