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Developing a one-dimensional heat and mass transfer algorithm for describing the effect of green roofs on the built environment: Comparison with experimental results

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Abstract

This paper investigates the mathematical modelling of the effect of green roofs on mitigating raised urban temperatures. A dynamic, one-dimensional model is developed, describing heat and mass transfer in building materials, considered as capillary-porous bodies, the vegetated canopy, modelled as a combined plant–air canopy layer, the soil and the air. The model is validated with an experiment, conducted in the Welsh School of Architecture, in Cardiff, in summer 2004. The right choice of parameters that affect the accuracy of the model (such as the expression of the convective heat transfer coefficient and stomatal resistance) is discussed. Special attention is given to the comparison between the experimental results and the outputs of only heat transfer algorithms and heat and mass transfer expressions. Taking these comparisons into consideration, conclusions are drawn about developing an accurate algorithm describing the thermal effect of green roofs on the built microclimate.

Keywords: Green roofs; Heat and mass transfer; Dynamic microclimatic model

1. Introduction

Green roofs and walls have been gaining popularity over the last years as a solution to the environmental problems that modern cities face. They are believed not only to improve aesthetics and urban psychology, but also to lower pollutant concentrations, noise and urban temperatures (mitigating the heat island effect), the latter being the subject of this study.

In order to assess the potential of green roofs for lowering urban temperatures for climates with different relative humidity characteristics, a tool has been developed in the Welsh School of Architecture, Cardiff University, based on heat and mass transfer algorithms. The tool describes heat and mass transfer in the air, soil, plants and building materials.

In most building-simulation tools the effect of water vapour diffusion on heat is omitted as too small. However, as will be argued in this paper, for outdoors simulations, where thermal and vapour gradients can be significantly large, the exclusion of this term may lead to less accurate results. Apart from that, the choice of the expression of physical factors, such as the convection heat transfer coefficient or stomatal resistance is quite crucial for the accurate predictions of temperature and water vapour concentrations, which is also discussed in this paper. In order to calibrate this tool, an experiment was conducted in August 2004, measuring temperatures and humidity at a test cell. This paper presents the results from the comparison of the measured with the calculated values for the air nodes, regarding the combination of heat and mass transfer and the choice of the convection heat transfer coefficient.

From a thermal modelling point of view, four components can be distinguished in a green roof: the structural part, the soil medium, the canopy (leaf cover) and the air above the roof. For a plain roof, these components are diminished into two, with only the structural part and the air participating in the thermal and mass exchanges of the

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Nomenclature

Latin letters

a_c	albedo of the surface structural material
a_l	leaf albedo
a_s	soil albedo
b	coefficient, depending on the soil type
c_1	isobaric specific heat of component 1 (moisture) of the mixture (J/kg K)
c_2	isobaric specific heat of component 2 (air) of the mixture (J/kg K)
c_c	building material specific heat capacity (J/kg K)
c_G	specific heat of the soil–water–air mixture (J/kg K)
c_{pa}	isobaric specific heat capacity of air (J/kg K)
c_{pl}	specific heat capacity of the leaf tissue (J/kg K)
c_s	specific heat of solid soil (J/kg K)
c_w	specific heat of liquid water (J/kg K)
D	binary diffusion coefficient (m^2/s)
D_g	diffusion coefficient of water through soil (m^2/s)
D_υ/D_q	the ratio of the molecular diffusion of water vapour to that of gas q
$e_s(T_l)$	saturation water vapour pressure at leaf temperature (Pa)
e_a	water vapour pressure in the bulk air (Pa)
h	crop height (m)
h_a	specific enthalpy of phase a (water) (J/kg)
h_b	specific enthalpy of phase b (steam) (J/kg)
h_D	external convective diffusion coefficient (m/s)
$h_{D,in}$	internal convective diffusion coefficient (m/s)
h_{in}	internal convective heat transfer coefficient (W/m^2 K)
h_{out}	external convective heat transfer coefficient (W/m^2 K)
I	solar radiation on the surface (W/m^2)
I_1	source of component 1 (moisture) of mass (kg/m^3 s)
I_{max}	the noon incoming solar radiation under a cloudless, clear sky
K_g	coefficient of permeability of liquid water through soil (hydraulic conductivity) (m/s)
$K_{g,s}$	hydraulic conductivity at saturation (m/s)
k_o	extinction coefficient
K_s	thermal conductivity of the soil–water–air mixture (W/m K)
$K_s \partial T_s/\partial z$	conductive heat flux through the soil–water–air mixture (W/m^2)
LAI	the leaf area index is the leaf area (upper side only) per unit area of soil below it (dimensionless quality)
LAI_{active}	the index of the leaf area that actively contributes to the surface heat and vapour transfer. It is generally the upper, sunlit portion of a dense canopy
Le	Lewis number
P	function of time of year ($P = 0$ during the growing season and $P \gg 0$ at other times)
r_a	aerodynamic resistance (s/m)
r_{aH}	convective heat resistance (s/m)
r_c	resistance expressing the plant type and measuring the biological (surface) resistance of a canopy to losses of water (s/m)
r_g	aerodynamic resistance of heat transfer between soil and air (s/m)
r_{min}	minimum bulk stomata resistance for water vapour
r_s	total stomatal resistance of the canopy (s/m)
r_{si}	stomatal resistance of a leaf (s/m)
P	function of time of year ($P = 0$ during the growing season and $P \gg 0$ at other times)
q_a	relative concentration of component 1, expressed as specific humidity (kg/kg)
q_c	building material moisture content (kg of the substance/kg of the dry body)
T	temperature (K)
T_a	air temperature (K)
$T_{a,c}$	surface air temperature at the foliage (°C)
T_l	leaf surface temperature (K)
T_{sky}	sky temperature (K)
t	time (s)
U	wind speed (m/s)
$(1-\omega_{g,s})$	volumetric content of solid soil

Greek letters

α_a	coefficient of thermal diffusivity of air (m^2/s)
α_m	diffusion coefficient of moisture in the building material (m^2/s)
γ	psychrometric constant (Pa/K)
ε	ratio of vapour diffusion coefficient to total moisture diffusion coefficient or evaporation number of building material
ε_c	emissivity of the surface structural material
ε_l	leaf emissivity
ε_s	soil emissivity
η_{eroot}	the minimum value of soil moisture occurring in the root zone of the plant (equal to the minimum value of ω_g of the model)
η_{wilt}	the level of soil moisture below which permanent wilting of the plant occurs
λ	heat of phase change (latent heat of evaporation of water) (J/kg)
ρ_α	total concentration of the mixture (kg/m^3)
ρ_c	density of the structural material (kg/m^3)
ρ_g	density of the mixture of soil (kg/m^3)
ρ_l	density of the leaf tissue (kg/m^3)
ρ_s	density of solid soil (kg/m^3)
ρ_w	density of liquid water (kg/m^3)
σ	Stefan–Boltzmann constant (5.67×10^{-8} $W/m^2 K^4$)
ψ_p	moisture potential of soil tension (cm)