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Numerical simulation of the dual effect of green roof thermal performance

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ABSTRACT

Green roof is one of technologies applied in reducing energy consumption when cooling of a building is of concern. The heat and mass transfer in green roof is expressed by the complex system of coupled nonlinear differential equations which should be solved with respect to the four elements of air, plants, soil and structure, simultaneously. Numerical solution is applied through finite difference method. Over 40 models among 100 are adopted for the evaluation of thermal, physical and biological parameters in order to achieve best accuracy. Modeling of photosynthesis and plants' response to environmental change is simulated for the first time in green roof modeling history. Grid independency has been checked for two most challenging regions; plants and soil. The average difference between numerical results and experimental measurements is below 8%, indicating a good agreement. The shading effect of plants and drought of soil layers due to solar radiation are shown. The results, obtained through comparison of green and concrete roofs indicate that the green roof represents 77% reduction in heat flux transmission and 13 K reduction in air temperature at one meter above the roof compared to conventional roof, revealing a significant effect in reducing the energy consumption required for cooling the buildings and urban heat island effect simultaneously.

1. Introduction

The population problem is not just a matter of the number of people. People consume food, fresh water, wood, minerals, and energy as they go about their daily lives. Producing food, pumping out groundwater, harvesting wood, mining minerals, and burning fossil fuel all deplete the natural resource bases. One indicator of environmental impact is to measure the energy consumption. Unlike most of the environmental factors which are hard to measure, precise data on how to measure annual energy consumption are available. World energy consumption is on the rise where buildings are in the upper portion of the account (40% in the U.S.) [1]. The amount of energy consumed is increasing due to the factors such as population growth, economic growth and energy demand for the modified and new services, like electronics. An increase in energy consumption is not without an increase in air pollution, since, a big share of energy is produced by burning fossil fuels and releasing detrimental gases in the air.

A large portion of the total energy consumed in the buildings, is for air conditioning; therefore, finding a manner to reduce energy consumption with respect to cooling, can significantly reduce the burden directly, as well as the greenhouse gas emissions indirectly.

All of the negative contributions related to energy consumption have made human to resort to environment friendly technologies or so-called *green technologies*. One of these technologies is the *Green Roof* which is a special type of roof implementation system, where plants are grown on the conventional roof tops. Roofs on the buildings are one of the major elements cab be retrofitted to make energy-efficient structures. Many methods for roof implementation in green buildings have been suggested so far. Al-obaidi et al. have suggested a system consisting reflective and radiative materials combined with ventilation [2]. Ong has investigated thermal performance of several types of solar passive roofs [3]. Yew et al. have suggested a roof system using thermal insulation coating and moving air cavity [4]. Green roof is one of the newest and the most efficient methods among the previous ones because does not just reflect the solar radiation but rather dissipate it also by passive mechanisms using vegetation.

Plants on the roof, prevent direct sunlight incident on the roof surface. The plants have different radiative and thermal properties compared to the building materials and through their two main

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Nomenclature

b	soil type exponent (–)
c_{m1}	specific mass capacity of moisture (kg/J)
c_{pa}	isobaric specific heat capacity of air (J/kg K)
c	specific heat capacity (J/kg K)
d	zero plane displacement height (m)
D	diffusion coefficient (m^2/s)
ETP	rate of evapotranspiration (kg/m^2 s)
h	plant height (m)
I	radiation intensity (W/m^2)
k	von Karman's constant (–)
K	thermal conductivity (W/m K)
K_g	hydraulic conductivity of soil (m/s)
l	characteristic length (m)
$M_{C_6H_{12}O_6}$	molar mass of glucose (kg/mol)
q_{ph}	heat flux of photosynthesis (W/m^2)
q_{ETP}	heat flux of evapotranspiration (W/m^2)
Q^*	isothermal mass transfer heat (J/kg)
$R_{ph,net}$	rate of photosynthesis (kg/m^2 s)
r_{ad}	aerodynamic resistance (s/m)
r_c	convection resistance (s/m)
$r_{\min}$	minimum of stoma resistance (s/m)
r_s	stoma resistance (s/m)
T	temperature (K)
t	time (s)
v	wind speed (m/s)
v_z	wind speed at height of z (m/s)
z	dimension of solution (m)
z_h	height of humidity measurements (m)
z_{oh}	roughness, governing heat and vapor transfer (m)
z_{om}	roughness, governing momentum transfer (m)
z_v	height of wind measurements (m)

Greek letters

α_a	coefficient of thermal diffusivity of air (m^2/s)
ΔH_{reac}	enthalpy of photosynthesis reaction (J/kg)
φ	moisture content of air (kg of the substance/kg of the dry body)
λ	latent heat of vaporization (J/kg)
ψ_p	moisture potential of soil tension (m)
$\psi_{p,s}$	moisture potential of soil tension (saturated) (m)
ρ	density (kg/m^3)
ω_g	volumetric water content (m^3 of liquid water/m^3 of the soil–water–air mixture)
$\omega_{g,s}$	volumetric water content (saturated) (m^3 of liquid water/m^3 of the soil–water–air mixture)

mechanism of photosynthesis and transpiration, they contribute to disposal of the heat absorbed by the roof (Fig. 1) [5].

For modeling the heat and mass transfer in green roof, Barrio introduced a model based on the three elements of plant, soil and structure [6]. In her model, which is one of the first basic models in green roof, simplified representation of the dynamic thermal behavior of actualgreen roofs has been done and sensitivity analyses have been carried out to assess the cooling potential of green roofs in summer. In the model volumetric water content of soil is considered as a constant, while the air between the canopies is not accounted for separate analysis. In another model the governing equations related to plant and soil are solved, but the thermal inertia of soil is neglected in spite of improvement in soil modeling [7]. Alexandri and Jones have presented a model that includes heat and mass transfer equation and variable air humidity but the role of plant metabolism has been neglected [8]. In other study a physically-based model of the energy balance of a vegetated rooftop has been developed and the role of growing media depth, irrigation, and vegetation density has been investigated but the humidity of air has been considered to be constant in all vegetation layers [9]. Tabares-Velasco and Srebric have introduced a model based on the experimental observations and steady state solution applied for theoretical analysis [10]. Other research has been done based on Sailor's modified model [9] and the role of water transfer in soil layers has been accounted, but thermal inertia of growing medium and variable humidity of air have not been considered in the modeling [11]. Studies have been also carried out in recent years; in a study multilayer heat transfer scheme has been used [12] and in another heat transfer through a green roof has been partitioned into two stages of the heat budget of the plant layer and the substrate surface, and the conduction of heat through the substrate to the underlying structure and for each part different strategies has been utilized [13]. Both of the studies neglect the significant role of plant metabolism in their modeling. Feng et al. have shown that this phenomenon can't be ignored in green roof energy balance but their calculations in other mechanisms of heat transfer is very rough [14] so there is need for a study to calculate all of the heat and mass exchange phenomena by exact

Fig. 1. Comparison of surface temperatures of a green roof and a concrete roof [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)