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Assessment of green roof thermal behavior: A coupled heat and mass transfer model

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ABSTRACT

Green roofs have a positive effect on the energy performance of buildings, providing a cooling effect in summer, along with a more efficient harnessing of the solar radiation due to the reflective properties found inside the foliage. For assessing these effects, the thermodynamic model was developed as well as the thermo-physical properties of the green roof components were characterized. Its typologies and vegetation styles should also be studied. The proposed model is based on energy balance equations expressed for foliage and soil media. In this study, the influence of the mass transfer in the thermal properties and evapotranspiration were taken into account. We then added the water balance equation into our model and performed a numerical simulation. By assuming the outdoor conditions, the roof support temperature and the drainage water as inputs, the model evaluates the temperatures evolution at foliage and soil ground levels. A parametric study was performed using the proposed model to classify green roofs depending on the considered climate condition. Comparisons were undertaken with a roof slab concrete model; a significant difference (of up to 30 °C) in temperature between the outer surfaces of the two roofs was noticed in summer. The model was experimentally validated according to green roof platform, which was elaborated. The mass transfer effect in the subtract was very effective in reducing the model errors. Simulation results show that the use of vegetation in the roof building improves not only thermal comfort conditions, but the energy performance of a building.

1. Introduction

The building has, by the multiplicity of involved actors, a complex financial questions and growing environmental issues. In Europe, it represents 40% of the overall final energy consumption and 36% of the overall CO_2 emission. This high impact puts the energy savings in buildings at the heart of the strategy against economical problems and global warming.

To overcome these problems, various innovative construction solutions can be implemented. The use of vegetated land roofing is an appealing solution to improve a building energy performance, esthetic purposes, sustainability and environment in urban areas, especially regarding air quality and mitigation of urban heat islands.

In fact, with an insulation role [1–3] associated with an evaporative cooling [4] and better capturing of the solar radiation by the phenomena of inter-reflections within the foliage [5], green roofs have a very positive impact on the energy performance of buildings [4–8]. It also improves the longevity of roofing membranes [9–13].

The principle of a green roof is to cover a flat or a low sloped roof with a vegetated substrate. A green roof consists mainly of five components from the bottom to the top: a roof support, a roofing membrane (membrane protection and roof barrier), isolation, a drainage layer, a growing media and vegetation. Two types of green roofs are generally distinguished: extensive (low soil thickness, less than 10–15 cm) and intensive (high soil thickness, more than 15–20 cm) [12,14,15]. The integration of a green roof in a building is more successful during the initial stages of the building design process, but it is, nevertheless, feasible on existing buildings [16].

Motivated by the recent importance given to green roofs, several studies were done to model or measure the thermal impact of green roofs on building energy performance. The heat transfer in a green roof was analyzed by several studies [7,9,17–19].

The green roof, as an energy efficient solution compared to a conventional roof, was studied by many authors [4–8]. In this context, Wong [6] concluded experimentally that vegetation has the ability to stop up to 60% of external energy contributions in a tropical climate in Singapore. According to [5], about 40% of a building cooling load was saved with green roof in Athens. In the climate of Chicago, a high value of a green roof foliage density reduces the cooling energy consumption during the summer due to

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the shading effect; however, this may increase the heating consumption in winter by stopping the solar radiation arriving on the surface of the vegetation [7]. In Toronto, Martens [8] found that the building overall energy consumption was reduced by 73%, 29% and 18% for a building top floor, first and second floors below. Spala et al. [5] showed research results for a building in Athens, during the end June, that green roofs reduced the cooling consumption by 39% for the entire building and 58% for the top floor in comparison with a conventional roof. The impact on the heating demand was found insignificant [5].

Green roof thermal insulation role was studied by many authors [1–3]. According to Del Barrio [2], insulation is the main thermal role of green roofs. However, green roofs could never replace the role of the insulating layer [3]. The capacity of green roofs' subtracts for containing water, increases their thermal conductivity and thus reduces their thermal performance [1]. When the roof is frozen, the insulation role of green roofs is effective, but their performance doesn't differ significantly of those of conventional roofs in the presence of snow [1].

In the case of materials with very high porosity, such as substrates of green roofs, the moisture transfer phenomenon has a very significant impact [20–23]. The gravity effect on the roofs also has a considerable repercussion on the prediction of water exchange [24]. In addition, a water balance to evaluate the water content in the green roof subtract is essential to assess the vegetation thermal behavior [25]. Hence the importance of taking into account these phenomena in modeling the behavior of green roof components by coupling heat and mass transfer in the model.

For this reason, in the present work we developed an approach dealing with the assessment of green roofs' thermal behavior in which a moisture transfer model was developed and coupled with a green roof thermal model. The developed model can be coupled with building and urban climates simulation tools in order to help building designers in the assessment the impact of green roof as energy demand and the thermal comfort as well as their impact on the weather experienced in urban areas.

2. Mathematical model

2.1. Physical phenomena

Before the model development, we presented each physical phenomenon in order to propose a model that would appear accurate and feasible at the same time. To establish the energy balance on a green roof, the main heat fluxes (Fig. 1) taken into account in the literature [2,4,7,17,26] were:

- The incident solar radiation reaching the soil surface called global radiation. The short-wave radiation reflected from the surface of green roof.

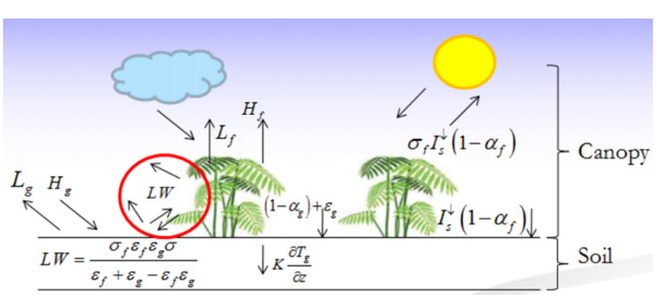

Fig. 1. Main heat flow on a green roof. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- The long-wave radiations emitted by the green roof.
- The heat flow of radiations emitted by the roof.
- The sensible heat exchange by convection.
- The latent heat flux derived from evapotranspiration.
- The sensible heat flux by conduction through the roof soil.

The evaporative and conductive heat fluxes are very dependent on its water content [23,26], which implies the necessity of the study of the moisture transfer in the green roof soils. The moisture transport results in condensation-evaporation processes which accompany energy transfer through building envelopes, and has a significant influence on indoor air humidity and air-conditioning loads, especially latent cooling load [20–22]. Recently [23], indicated that the use of suitable hygroscopic materials has the potential to reduce the energy consumption of buildings, and the most promising energy savings are for buildings with mechanical cooling equipment located in hot and humid climates, but there are potential savings in all climates if the HVAC system can be optimally controlled to regulate the indoor climate and comfort. They showed that through the moisture transfer phenomena, the indoor relative humidity stays below 70% during the HVAC system shut-off period and no additional dehumidification is needed. According to the current simulations, the potential energy savings are relatively small for heating (6% of the heating energy, 16% of the cooling energy) with whole building hygrothermal transfer than without taking into account the moisture transfer.

2.2. The developed approach

The process of mass and heat transfer through a green roof was different from that encountered in the case of a conventional roof. The temperature, relative humidity and solar radiation changed in a different way because of the presence of vegetation on the roof. To make this effect clearer, we were led to study in the first instance the thermodynamic phenomena across the canopy which consisted of vegetation and the air which can circulate inside (vegetation and air). First, the models were detailed for each physical phenomenon in order to propose a model that would appear both accurate and feasible at the same time. Several green roof models have been proposed in the context of this topic. These vary according to the criteria of accuracy, performance and feasibility.

Development of a mathematical model that describes the energy balance across the green roof is based on the model of Frankenstein and Koenig [17] and Sailor [7]. This model takes into account the major thermal phenomena that can occur in our system (vegetation and soil). This model divides the analysis of energy balance in two, analysis of the leaf surface F_f and analysis at the soil surface F_g. This method made modeling details of our equations clearer and more understandable. For us, we were interested in introducing a water balance and introducing it through the term of the thermal conductivity, which has not been taken into account in the model by of Frankenstein and Koenig [17]. Taking in to account the heat balances at the canopy and at the ground level per unit area, the energy balance equations were performed. However, the results were still valid with this method, but under specific conditions, like the results found with the model of thermal conductivity [27]. The model of thermal conductivity cannot be generalized because of the choice of a single type of vegetation.

Afterward, we realized a water balance at the component (soil and vegetation) and we integrated it in heat balance equations from the thermal conductivity, the latter being a function of water content. The water balance was given by the quantity of rain water, the quantity of water drained by the green roof and the quantity of water given by evapotranspiration (ETP). This evapotranspirated water used the Penman–Monteith equation [26].