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Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings

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HIGHLIGHTS

- The experimental platform provides the hydrothermal behavior data for green roof.
- The albedo of the green roof was measured and implemented in the numerical model.
- A coupled heat and mass transfer model for green roof behavior was validated.
- Comparison was undertaken between green and conventional roofing.
- Green roofing reduces energy demand and outside air temperature in canyon streets.

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ABSTRACT

In the present work, an experimental urban canyon (scale 1:10) with 4 cm concrete wall thickness and full scale green roof was used to evaluate the impact of green roof inside and outside the buildings. The platform was equally used to validate a coupled heat and mass transfer model for green roof behavior. The albedo of the green roof was measured and implemented in the numerical model. The developed model has been coupled to a building thermal code (TRNSYS). Then, simulations were conducted for the experimental urban canyon studied where a comparison was undertaken between green and conventional roofing. A reduction of the maximum roof surface temperature by 20 °C was found in summer due to the green roof. Green roof protects the roof membrane from high temperature fluctuations increasing the roof longevity and delay the timing of the peak membrane surface temperature by several hours. Also, the presence of vegetation permits to reduce the outside air temperature of the street canyon by 0.8 °C. Hence, green roofing is an effective solution to reduce the total energy demand and to improve the urban microclimate in the street canyon for an oceanic temperate climate.

1. Introduction

In horticultural and architectural sciences, planting roofs and walls is one of the faster growing sustainability practices, with high potential for innovation. Indeed, green roofs have innovative characteristics, more technical than aesthetic which makes green roofs different than garden roofs. One of the most cited reasons for green roofs is the benefit to the building through thermal insulation [1–4]. Green roofs play an insulating role introducing a reduction in the consumption of heating and cooling. However, the insulation characteristics of this type of roof depend on a number of parameters such as substrate thickness, building insulation thickness, climate zone, moisture in the substrate, cooling caused by evaporation from the substrate, transpiration of the vegetation and the shadows on the roof due to the foliage layer. The variation of all these factors can have very different effects on the roof insulation behavior.

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 [5]. Two types of green roof exist: intensive and extensive. Extensive green roofs have a thin growing medium between 10 and 15 cm, require minimal maintenance, and in general do not require irrigation (some require irrigation initially). They are generally less costly to install than intensive green roofs. Intensive green roofs have a deep growing medium (more than 20 cm) which allows the use of trees and shrubs. The depth of the growing medium requires extra loading requirements within the holding structure and requires a complex irrigation system for maintenance. They are generally quite costly and require extra structural design to the building [6–10]. Hence, the first type is suitable for green roof constructions [8].

The choice of the type of vegetation appropriated to the green roof and different components characteristics depend strongly on which climate the building is constructed. Green roof characteristics

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(vegetation, substrate, drainage, etc.) could not be the same in Australian and European climates [11]. A study of green roof drainage layer with rubber crumbs is presented in [12]. Researches were performed in Midwestern US climate in order to appropriate suitable vegetation species for green roof constructed in this climate. The study concludes that for all substrate depths and solar levels, the most abundant species were Sedum acre, Allium cernuum, Sedum album and Talinum calycinum [13].

Modeling a green roof and including it in a dynamic code to predict the thermal behavior of buildings is essential to build useful tools for prediction of energy savings intended for engineering construction. In addition the integration of a green roof model in a simulation tool of urban climate will also provide information on the impact of green roofing on climate phenomena encountered in urban areas.

In this study, an experimental platform was developed and deployed to validate a green roof coupled model of heat and mass transfer [14]. This green roof model is coupled to a building model to evaluate the impact of green roof on building energy performance through a comparison with conventional roof building. The experimental platform provides data for the hydrothermal behavior of green roofs and their interactions with building energy performance. Different experimental results with their detailed analyses of thermal and hydrological green roof behavior are presented and the experimental validation was performed for the periods of summer and winter. Furthermore, a detailed implementation of different sensors in the platform is presented. Afterwards, a comprehensive analysis of the impact of green roofs on the building thermal performance is presented, from the foliage and green roof soil temperature to the effect on cooling and heating energy demand.

2. Mathematical model

The heat transfer in a green roof was analyzed by several studies [6,9,15–18]. Many green roof models are available in the literature, stating by simple approaches with simplified assumptions to a detailed and complicated green roof model behavior where more phenomena are taken into account. The most simple is an approach in which the green roof is represented simply by a decrease of the roof U-value [19–21]. Many other researchers presented a green roof heat balance considering the important effects of foliage solar shading and cooling by evapotranspiration [3,6,16,22–25]. Actually, the green roof model developed by Sailor [6], based on Frankenstein and Koenig works [16] and implemented in Energy plus, seems to be of well adaptation to evaluate the impact of green roof in the energy performance of buildings. We noticed that many simplifications are still applied (foliage optical properties and geometry, mass transfer, etc.) but this model take in consideration several thermal heat transfer phenomena at the level of green roof components permitting a well adaptation for coupling it with a dynamic thermal simulation code.

The experimental validation in this study is performed for a coupled heat and mass transfer model of the green roof [26] where the thermal modeling part was based on the work of Sailor [6] and Frankenstein and Koenig [16]. The thermal modeling part consists of two balance equations; One at the level of the soil and the other at the level of the foliage. The energy balances for both of soil and foliage surfaces were given respectively on the following equations

$$F_f = \sigma_f\left[I_s(1-\alpha_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4\right] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_f + \varepsilon_g - \varepsilon_f \varepsilon_g}\left(T_g^4 - T_f^4\right) + H_f + L_f \quad (1)$$

$$F_g = (1-\sigma_f)\left[I_s(1-\alpha_g) + \varepsilon_g I_{ir} - \varepsilon_g \sigma T_g^4\right] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_f + \varepsilon_g - \varepsilon_f \varepsilon_g}\left(T_g^4 - T_f^4\right) + H_g + L_g + K(\theta)\frac{\partial T_g}{\partial z} \quad (2)$$

here T_g and T_f are respectively the soil and foliage temperature (Kelvin), ε_g and ε_f are respectively the soil and foliage emissivity, H_f is the sensible heat and L_f is the latent heat. I_s and I_{ir} are respectively the short and long-wave radiation (W/m^2). α_f is the canopy albedo, σ is the Stefan–Boltzmann constant (5.6710×10^{-8} W/m^2 K^4), σ_f is the density of the foliage and $K(\theta)$ represents the thermal conductivity of the soil depending on the water content.

In addition, a water balance model was developed and coupled to the previous thermal balance model integrating the evapotranspiration process [25]. Indeed, the moisture transfer process accompanies energy transfer through the building envelope and has a significant influence on indoor air humidity and air-conditioning loads, especially latent cooling load [26–28]. The present study is more interested in what happens at the soil level taking into account several properties of this medium. The green roof substrate is a medium with high porosity so that the properties change with the presence of water which can affect the heat transfer through the roof.

To evaluate the energy performance of a green roof building, the developed numerical model of green roof components must be coupled to a building thermal code; this allows an objective comparison with conventional roofs and to predict the total heating and cooling energy demand of buildings equipped with green roofs. In fact, a detailed calculation of the building thermal behavior is done using building thermal software for dynamic simulation like TRNSYS and EnergyPlus. This part of calculation includes the heat transfer through the roof support (that considers the thermal mass) and the heat transfer between the inside surface of the roof membrane and the inside of the building.

The developed model was coupled with TRNSYS software where a new green roof component was created; it can be used in the same way as any other component in TRNSYS software. The model source code was developed using the C++ programming language. At this phase of work, evaluating the energy performance and predicting the total energy consumption of a building equipped with green roof is possible.

3. Experimental validations

3.1. Arrangement of the canyon streets in the experimental platform

An experimental platform with green roofs (scale 1:10) with 4 cm concrete wall thickness and real green roof scale was constructed on the campus of the University of La Rochelle. The objective of this installation is to collect experimental data for the hydrothermal behavior of green roofs and their interactions with building energy performance. It is also used to undertake comparisons with the numerical results and thus validate the developed mathematical models. This work is part of the ANR-Habisol AGROBAT project funded by the Poitou–Charentes region (France), it consists to evaluate the incidence of green roofs on the energy performance of building according to multidisciplinary approach.

To reflect a real urban setting, the conception of the reduced models requires both physical and geometrical similarities with reality. Reaching a geometric similarity is not fundamentally complicated. For our case of study, we focused on a simple repetition of street canyons (ratio $W/H = 1$) formed by rectangular buildings without windows. The experimental platform was set up on the soil, on a 10 m by 20 m terrace of concrete tiles. It consists of 15 buildings forming 5 rows and therefore 4 street canyons. Each row contains 3 adjacent buildings with a total length $L = 4H$