Vegetative (Green) roofs in urban areas for the improvement of the outdoor and indoor comfort

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ABSTRACT

The need for cooling buildings for the comfort of inhabitants has an impact on urban heat island phenomenon and also on the energy consumption of buildings. Vegetation can be considered as a renewable heat sink for cooling purposes. Vegetative (Green) roofs have always been presented as an efficient solution to reduce the energy consumption. But few experimental studies exist, too limited and too specific. The energy saving by Vegetative (Green) roofs has to be assessed for implementation in the French building thermal rule (RT2012). Because Vegetative (Green) roof is part of the building envelope, its capacity to dissipate energy through evapotranspiration can be a solution especially during summer season and heat waves, in association with watering devices. The assessment of the evapotranspiration due to Vegetative (Green) roofs is important for the evaluation of the latent heat flux, part of the surface energy balance that influences the urban microclimate. Experimental studies have been conducted in order to assess the actual evapotranspiration of several Vegetative (Green) roof platforms and to propose a simplified model for the thermal rule. This paper presents reserved results. On the one hand, it confirms the importance of vegetation as a very promising approach. The thickness and the vegetation type improve the evapotranspiration of Vegetative (Green) roofs. On the other hand, at the building scale, it seems that other parameters are more influential on the cooling consumption, e.g., glass surfaces. But in both cases the water supply is important.

Keywords: Vegetative (Green) roofs, Urban Heat Island, Thermal Performance, Field measurements, France.

1. Introduction

The concentration and expansion of urbanized areas induce the Urban Heat Island (UHI) phenomenon. It occurs mainly during summer periods, increases air temperature on urban areas and could generate increased energy consumption due to air conditioning requirements, and hence, could also contribute to global warming. To achieve this objective,

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a solution could be reflecting solar radiation by using high reflective roofs known as “cool roofs” which can reduce heat flux through to roof in summer. Authors' show that the efficiency of these cool roofs decreases when the roof is insulated (Desjarlais et *al*., 2007). Vegetative (Green) roofs in urban areas could be an opportunity to reduce the UHI effects by increasing the evapotranspiration of water (Mentes et *al.*, 2006; Dimoudi and Nikolopoulou, 2003; Wong et *al.*, 2003; Bass et *al.*, 2002; Rosenfeld et *al.*, 1998; Von Stülpnagel et *al.*, 1990). Indeed, Vegetative (Green) roofs allow a reduction of the surface temperature amplitude with the modification of the surface albedo (Susca et *al.*, 2011; Akbari and Konopacki, 2005). Moreover, Vegetative (Green) roofs can also enhance the insulation in the buildings, and act as an efficient barrier against solar radiation permitting to reduce energy consumption from air conditioning and improve thermal comfort (Alexandri, 2007; Lazzarin et al, 2005; Niachou et al, 2001; Zinzi and Agnoli, 2011, Liu et al, 2003).

Many authors pointed out that vegetation contributes to the reduction of the outflow volumes at the annual scale due to evapotranspiration (Gregoire and Clausen, 2011; Palla et al. 2010; Stovin 2010; Bengtsson 2005, Köehler 2005). Only a few studies quantified the actual evapotranspiration (AET) by experimental measurements (Gregoire and Clausen, 2011; MacIvor and Lundholm, 2011). Few studies calculate the AET from numerical modeling (Metselaar, 2012; Hilten et al., 2008). Temperature reductions at the Vegetative (Green) roof surface compared to classical roof were shown in many studies (Jaffal et al., 2012; Susca et al., 2011; Teemusk and Mander, 2009; DeNardo et al., 2005; Wong et al., 2003). The main purpose of this study is to quantify and qualify the evapotranspiration with experiments.

Since the publication of the 2000 thermal French rule (RT2000), Vegetative (Green) roofs have been presented as an efficient solution to reduce the energy consumption but neither experiments nor models have been proposed to support this. To assess thermal behavior of Vegetative (Green) roofs in the new RT2012 French thermal rule, an experiment has been done to quantify and qualify those solar thermal fluxes through roofs.

2. Material and methods

2.1 Experimental Vegetative (Green) roofs structure

2.1.1 Nantes experiment

Six experimental Vegetative (Green) roofs (see Table 1) with overall dimensions of 1500 mm x 1500 mm were constructed by CSTB (Nantes, France). All platforms were built on wooden support and protective paint coating was used. Experimental roofs were constructed by following the French rules in roof construction. The wood support was recovered with a commercial bituminous vapour barrier (5 mm). The insulation layer was made using polystyrene blocks of 60 mm high. PVC membrane of 5 mm high was used for waterproofing. The discharge outlet was done with a PVC tube of 30 mm diameter placed at one corner of the roof platform (120 mm from the borders).

Table 1: Experimental roofs in Nantes

Roof number	Media thick (mm)	Vegetation
1	80	No
2	120	No
3	80	Sedum *album*
4	120	Sedum *album*
5	120	Festuca *glauca*
6	120	Dianthus *deltoïdes*

Experimental roofs were placed on a path with a slope of 1.5° at CSTB site in Nantes, France (see Figure 1). A meteorological (weather) station (MET) records the air temperature, the relative humidity of air, atmospheric air pressure, global and net radiation, wind speed and its direction at one minute frequency (see Figure 2) and at the same time to characterize the rainfall, a rain gauge and a Parcivel Disdrometre are also installed. All mean data are recorded every 10 minutes on a data logger (CR3000, Campbell Scientifics).

Commercial extensive Vegetative (Green) roof media were used (Star Forges, France). The growing media was composed of 70% minerals materials and 30% organic matter. The minerals were a mixture of pumice stones of 3/20 mm calibrate, Pozzolana of 3/7 and 7/15 mm calibrates. The organic matters contained composted bark of maritime pine, black peat with 3/20 mm calibrate and blond peat with 3/20 mm.

The plants commonly used in Vegetative (Green) roof are variety of succulent plants. Their metabolisms allow the plants to be more resistant in dry period. As a result, they are the most appropriate for Vegetative (Green) roofs (Emilsson, 2008). The CRITT Horticole, a French association which is helping the research and development of Vegetative (Green) roofs in France has tested several plants in a roof environment. Three species of plants have been selected with its help. The first plant variety is *Sedum album*. The second variety of selected plants is *Festuca glauca*. Both varieties are commonly used in Vegetative (Green) roofs. The third variety of plants is *Dianthus deltoids*. This species has never been used for Vegetative (Green) roofs; it's a perennial plant, aesthetically interesting with a large flowering period from June to September.

Figure 1: Experimental Vegetative (Green) roofs in Nantes, France.

Figure 2: Meteorological station in CSTB Nantes, France.

Rainfall flowing from experimental roofs is discharged to a tipping bucket mechanism. Two temperatures probes are placed in the middle and on the surface of the growing media. Four water content probes (Figure 3), based on domain frequency response are used for estimating volumetric water content inside the growing media.

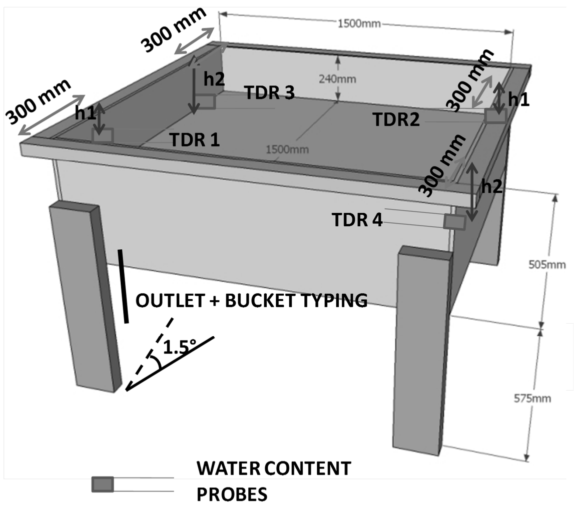

Figure 3: CS616 water content probes location.

The water volumetric probes are calibrated using the method of Rüdiger et al. (2010). The average volumetric water content is calculated from the average value of four probes.

2.1.2 Champs/Marne experiment

The main objective was to study the thermal fluxes through the roofs, with and without Vegetative (Green) roof configuration during summer season to determine energy consumption. For that, three platforms (2000x2000mm) representing different Vegetative (Green) roofs were built: a semi-intensive (A) and an extensive (B) Vegetative (Green) roof with a concrete structure (heavy roof) and an extensive Vegetative (Green) roof (E) with a steel structure (light roof) plus two reference platforms without Vegetative (Green) roof configuration, one with a steel structure (D) and the other with a concrete structure (C) (see Figure 4). The different layers are described in Figure 5.

With theses thermal fluxes through the roofs, all boundary conditions are measured, such as external temperature, solar flux and rain, in order to validate a thermal model which has been developed.

Figure 4: Experimental Vegetative (Green) roofs in Champs/Marne, France.

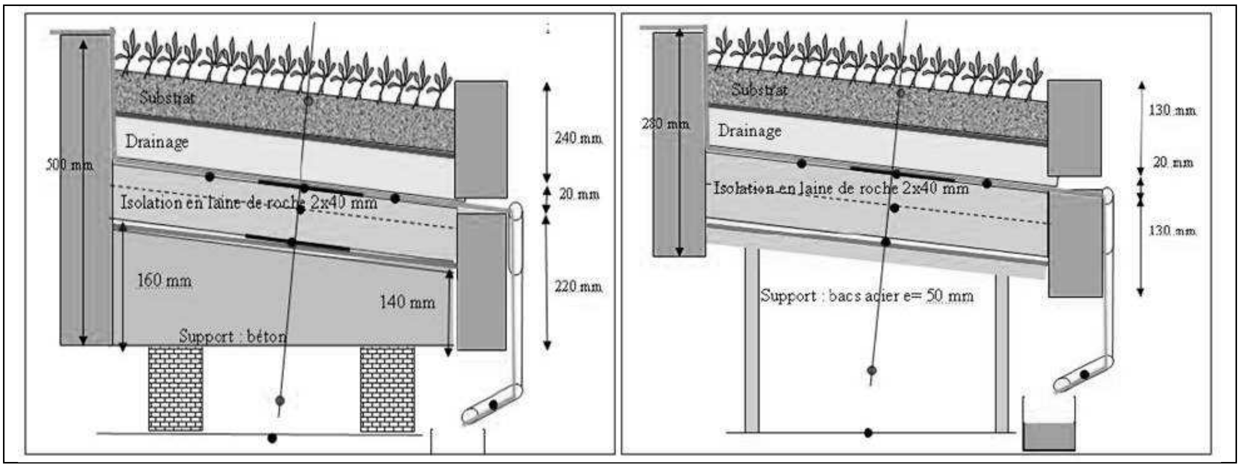

Figure 5: Scheme of experimental Vegetative (Green) roofs in Champs/Marne, France (left: semi-extensive with heavy structure; right: extensive with light structure).

2.2 Evapotranspiration calculation

Actual Evapotranspiration (AET) in mm was calculated from daily water balance through the following equation:

$$\boldsymbol{AET = P - R - L.\Delta\theta.\rho_b/\rho_w} \qquad (1)$$

where P is the daily cumulated precipitation (mm), R is the daily cumulated runoff (mm), L is the thickness of the growing media (mm), ρ_b and ρ_w are respectively the bulk density of the growing media and the mean density of water (g.cm^{-3}) and $\Delta\theta$ is the daily variation of volumetric water content (-). Cumulated AET (CumAET) for the monitoring period corresponds to the sum of daily cumulated runoff.

The evapotranspiration (ET) is calculated from hourly energy balance using the Penman-Monteith equation (it needs a relatively large number of input parameters, which is inconvenient in many applications):

$$ET = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (2)$$

where Δ (kPa.°C^{-1}) is Clausius-Clapeyron relation, R_n (MJ.m^{-2}.h^{-1}) is the net radiation, G (MJ.m^{-2}.h^{-1}) is the sensible heat flux into the soil, ρ_a (kg.m^{-3}) is the mean air density at constant pressure, c_p (MJ.kg^{-1}.°C^{-1}) is the specific heat of the air, e_s and e_a (kPa) are respectively the saturation and actual vapour pressure of the air, r_a (s.m^{-1}) is the aerodynamic resistance, r_s (s.m^{-1}) is the bulk surface resistance, γ (kPa.°C^{-1}) is the psychometric constant and λ (MJ.kg^{-1}) is the latent heat of vaporization. The daily ET is the sum of hourly ET.

All the parameters needed for the calculation have been directly measured where possible or from the literature. The hydrological performance of experimental roofs is analyzed with regards to the variables affecting Vegetative (Green) roof behaviour, including: media type, growing media thickness, presence of vegetation cover, vegetation type, evolution of the vegetation cover and category of rain.

2.3 The French thermal rule for building code

The French thermal regulation (RT 2012) is based on a simplified RC thermal modelling described in the European standard EN 13790. In this model, opaque building components are described with two parameters: its thermal transmission coefficient Up (W/m².K)) and its solar factor Sp (-). The thermal transmission represents the insulation ability of the component and is important to avoid thermal loss in winter conditions. The solar factor represent the ability of the component to transmit solar flux into the building: the solar factor is the ratio between thermal flux going through the component and solar incident flux, with the same ambient temperature on both sides of the component.

For opaque components, the solar factor can be deducted from the following equation:

$$S_p = \alpha_e \frac{U_p}{h_e} \tag{3}$$

where α_e is the absorption coefficient of the external side of the component, strongly linked to their colour (the whiter the colour is, the lower α_e is), h_e is the thermal superficial transfer coefficient of the external side, linked with wind speed and thermal emissivity and Up is the thermal transmission coefficient.

This formula does not consider evapotranspiration aspect and the goal is to correct it for Vegetative (Green) roofs applications.

3. Results

3.1.1 Hydrological performances

The results for Nantes experiment presented here correspond to the period from 1st July 2011 to 30th September 2011. The monthly mean temperature, rain, relative humidity, wind speed and net radiation for 2011 summer period are shown in Table 2. The characteristics of the rain during the study period are illustrated in Figure 6.

Table 2: Experimental roofs in Nantes

2011	July	Aug	Sept
T(°C)	18.0	18.5	17.6
Rain (mm)	70	125	43
Hr (%)	68	75	77
U (m/s)	1.9	1.6	1.5
Rn (W/m²)	358	367	356

The daily mean temperature for the studied period was 18.1 ± 2.2 °C. The maximum temperature recorded was 30.9 °C and the minimum was 7.2 °C over this summer season. The cumulated rainfall amount was 238 mm for the same period. In comparison from July to September, for Nantes from 1971 to 2000, the mean air temperature was 18.5 °C and mean cumulated rainfall was 156 mm (Meteo France, 2009). The measured air temperatures are consistent, but the amount of precipitation is higher in comparison to the previous years. Rain events are considered when rain intensity is higher than 0.2 mm/h and the end of a rain event is considered when no rain is recorded after one hour. A total of 62 rain events were recorded during this period – 35 events were classified as light (<2 mm), 16 as medium (2-6 mm) and 11 as heavy (>6 mm) rain events.

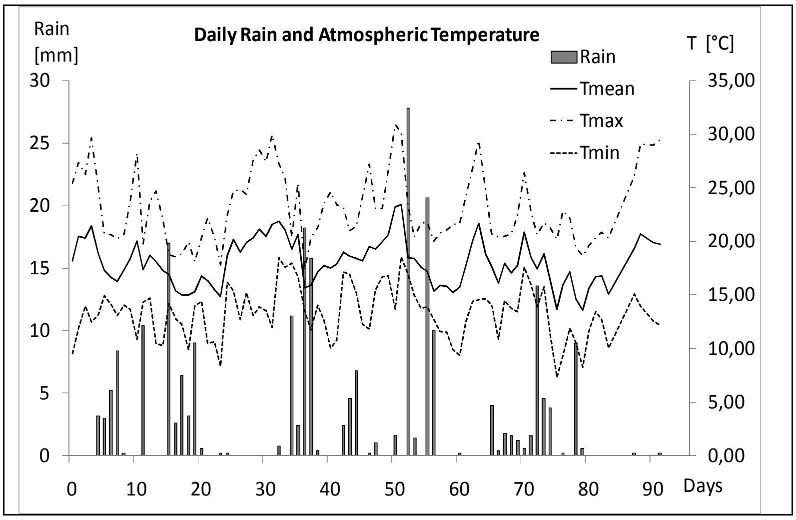

Figure 6: Daily precipitation (mm), mean, max, min daily temperatures (°C) (day 0 = July 1st 2011; day 92= September 30th 2011) from the MET station of the CSTB site.

Cumulated AET calculated from water balance (equation 1) is shown in Table 3.

Table 3: Cumulated AET in Nantes

Roof number	Cumulated AET (mm)
1	115*
2	160
3	180
4	203
5	202
6	216

**The tipping bucket mechanism of roof n°1 started recording data from the 30th July 2011. This explains the lower value for AET of roof n°1 in comparison with the others roofs.*

CumAET from roofs with bare surface (roof n°1 and n°2) is lower than those of roofs with vegetation cover (roof n°3 vs. 4). This is mainly due to the benefits of transpiration of the vegetation. Roofs with greater thickness of growing media have higher values of CumAET (roof 3 vs. 4, 5 and 6). The vegetation specie also has an impact on the value of CumAET. In this case, CumAET for *Dianthus deltoïdes* (roof n°6) is higher than the ones of *Sedum album* or *Festuca glauca* (roof n° 4 and n°5, respectively).

Reference ETo for grass and crop ETc for Sedum roof n°4 were calculated through equation 2. The correlation between ETo and ETc defines the crop coefficient K_c for sedum as estimated to 0.71 ($K_c = ETc/ETo$). Cumulated ETo and ETc are respectively 324 mm and 232 mm.

3.1.2 Thermal performances

The results for Champs experiment presented here correspond to two months – August and September 2009. Compared to the bare surface platform, the main result is a significant decrease of the fluxes through the Vegetative (Green) roofs, when they are wet. As an example, see below (Figure 7) the incident solar flux and the thermal flux through the light structure, with and without extensive vegetation.

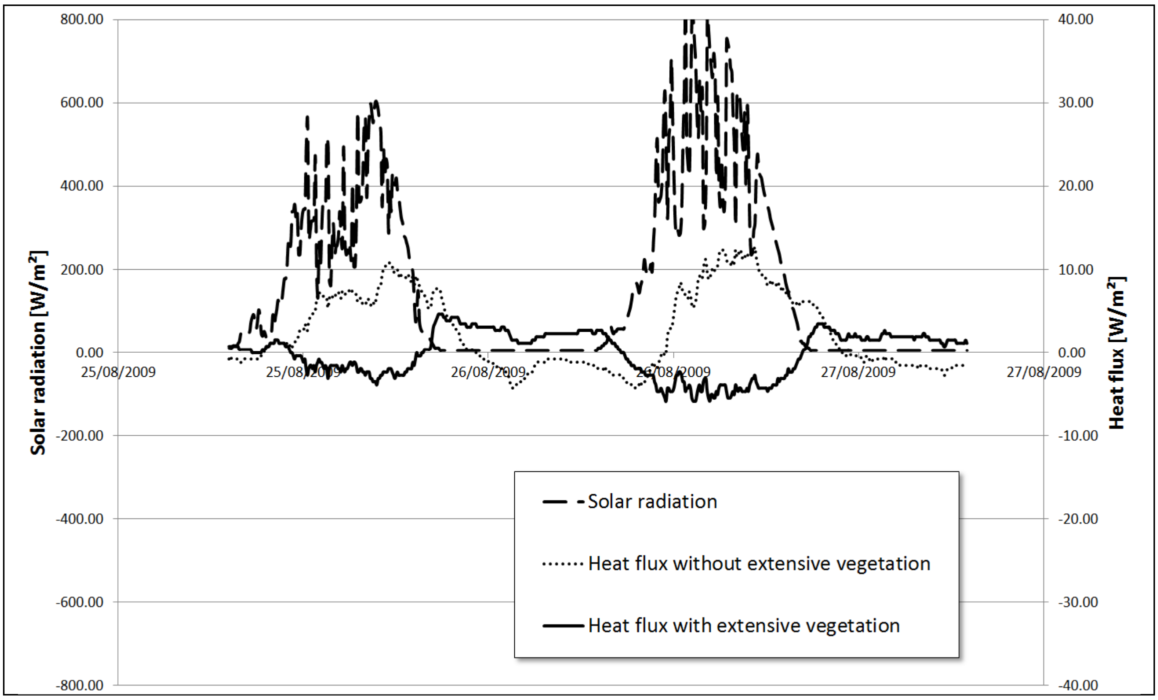

Figure 7: Platforms D and E radiation and fluxes form 25-27 of august 2009.

A thermal model was developed and validated with these experiments (Besbes et al, 2012). Using this model, influent parameters has been shown. A wet Vegetative (Green) roof can absorb a large amount of solar incident flux by evapotranspiration. When the Vegetative (Green) roof is dry, the solar incident flux is not absorbed but is limited by the mask effect of the plants. In all cases, thermal insulation of the roof is important to limit thermal flux through the component. A simple formula has been validated to describe the solar factor of a Vegetative (Green) roof:

$$S_{p,GR} = \alpha_{e,GR} \frac{U_p}{h_e} . (100 - \Delta t_{wet}) \quad (4)$$

where $\alpha_{e,GR}$ is the equivalent absorption coefficient which has been assessed by simulation, and Δt_{wet} is the percentage of time during which the Vegetative (Green) roof is wet in summer season, assessed by simulation and for the French meteorological climates.

This solar factor has been used then to simulate the summer thermal behaviour of an entire building. Despite a strong ability to limit solar flux transmission through the roof, the effect of the Vegetative (Green) roof on the global energy consumption of the building is quite limited. A lot of parameters have more influences on the thermal behaviour and energy consumption of an entire building, such as:

- Numbers of windows: solar factors of windows are higher than solar factors of opaque components

- Insulation of the building: the effect of Vegetative (Green) roofs will be lower on well insulated buildings

- Surface ratio between roof and other walls: for a collective dwelling, the thermal effect of the Vegetative (Green) roof will be efficient only for the last floor

- Climate: if the limitation of solar flux transmission provided by Vegetative (Green) roofs reduces energy consumption for cooling in summer, it increases the energy consumption for heating in winter and a Vegetative (Green) roof could has no effect on annual energy consumption in cold climate.

4. Conclusion

These studies point out the role of Vegetative (Green) roofs with regards to their hydrological and energy mitigation performance. However, using Vegetative (Green) roofs with a very low growing media thickness is debatable because it could prevent satisfactory vegetation growth. Another point concerns the maintenance of those systems, because well-maintained vegetation seems to be necessary to ensure steady storm water mitigation and to keep high evapotranspiration rates for better performances. The requirement of watering or irrigation seems to be mandatory, which may decrease their global environmental benefits (unless grey water is used).

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