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Abstract

Installation of intensive or extensive green roofs increases in Western European and North American cities. It is estimated that 12% of all flat roofs are green in Germany and the roof industry is growing at a rate of 10% per year in the EU. Apart from the aesthetic point of view, the main objective is to reduce heating (by increasing thermal resistance value) during winter and cooling (by evaporation) during summer. Most researches are conducted on specific plant species for green roof establishment. The major purpose of this work is to evaluate the theoretical approach of thermal properties (heat capacity and thermal conductivity) of wet substrates and to propose a simulation modelling of the interactions of the processes of water transport and heat flow and exchanges. Water flow properties using the van Genuchten approach and heat flow equation are applied in 1D simulation to different substrates and configurations. The main result is that the water retention properties of the substrate are the main parameter to consider but with different effects between winter and summer. The geometry of installation (height, support) is an important aspect of installation. Heat diffusion phenomena stay limited vs. latent heat exchanges in summer.

INTRODUCTION

Installation of green roofs has several advantages including: limitation of heat exchange, rainwater management, and aesthetic properties. Very popular in Europe, particularly in Germany for twenty years, green roofs have become very popular in North America in recent years, as a result, a reduction of the urban heat island effect (Saiz-Alcazar et al., 2006) of up to 2°C with an increase of the urban global Leaf Aera Index (Hardin and Jensen, 2007). New developments study their effect on the mitigation of urban air pollution (Currie and Bass, 2008).

Building energy simulations (Martens et al., 2008) will evaluate the percentage energy savings as a result of green-roofs and show that the principal effect is the cooling generated by latent heat flux during hot periods and that green-roofs are only a complement to the insulation layer during cold seasons. Most research has been conducted on specific plant species for green-roof establishment and performance of substrates vs. these plants (Durhman et al., 2007; Getter and Rowe, 2007), but only a few studies have evaluated substrate properties vs. their specific thermal properties and their influence on water content on the heat transfer.

The objective of this study is to evaluate the theoretical approach of thermal properties of wet substrates and to propose a simulation to model the interactions of water transport and heat flow and exchange.

THEORETICAL APPROACH

Water Retention and Transfer

The water balance in the substrate volume considers precipitation, evapotranspiration and drainage. Water transport in a small substrate element is described using the Richards equation:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta\psi}{\delta z}\right] \quad (1)$$

where ψ represents the water potential (m or kPa), θ is the volumetric water content (m^3 m^{-3}), t the time, z the vertical coordinate and K the hydraulic conductivity (m s^{-1}).

The water retention curve of substrate is described by the nonlinear function of van Genuchten (1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha\psi)^n\right]^{-m} \quad (2)$$

where S_e is the saturation degree, θ_r and θ_s are the residual volumetric water content and the volumetric water content at saturation (m^3 m^{-3}) respectively, α (m^{-1} or kPa^{-1}) n and m are fitting constants reflecting the steepness of the retention curve.

Unsaturated hydraulic conductivity is represented by the van Genuchten-Mualem model (van Genuchten, 1980):

$$K(S_e) = K_{sat} S_e^{0.5}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (3)$$

Evapotranspiration is considered as a sink function inside the volume of substrate.

Heat Transfer

The heat transfer inside the substrate considers convection and diffusion phenomena. Diffusion is modelled by the classic heat flow equation:

$$C_h \frac{\delta T}{\delta t} = \frac{\delta}{\delta z}\left[K_h(\theta)\frac{\delta T}{\delta z}\right] \quad (4)$$

where T is the temperature, C_h (J m^{-3} K^{-1}) the volumetric heat capacity and K_h (J m^{-1} s^{-1} K^{-1}) represents the thermal conductivity of the medium.

Thermal conductivity of the growing medium could be expressed as a composite of the thermal conductivities of the different phases pondered by their volumetric content in the medium with:

$$K_h(\theta) = K_{hsolid}(1 - \theta_s) + K_{hwater}\theta + K_{hair}(\theta_s - \theta) \quad (5)$$

where K_{hsolid}, K_{hwater} and K_{hair} (J m^{-1} s^{-1} K^{-1}) are respectively the thermal conductivity of the solid, water and air. Values of K_h for water and air are very common but inexistent for organic solids except wood. As a first degree approximation, we could assume that thermal conductivity of organic component in substrate is equal to wood thermal conductivity.

In the same way, the volumetric heat capacity of the wet substrate could be expressed as:

$$C_h(\theta) = C_{hsolid}\rho_{solid}(1 - \theta_s) + C_{hwater}\rho_{water}\theta + C_{hair}\rho_{air}(\theta_s - \theta) \quad (6)$$

where C_{hsolid}, C_{hwater} and C_{hair} are respectively the specific heat capacities (J kg^{-1} K^{-1}) of the solid, water and air and ρ_{solid}, ρ_{water}, ρ_{air} (kg m^{-3}) the densities of the solid, water and air. Specific heat capacities for air, water and media also used for building isolation are well-known. For organic matter in soil or for peat, only a few references could be found in the literature (Burwash, 1972; Weiss et al., 2006).

Initial and Boundary Conditions

For water, the upper boundary condition is the atmospheric infiltration and the bottom condition is a free drainage with the possibility to manage the potential value and simulate drainage spacing between the bottom of substrate and the roof.

The same time and space discretisation is used for water flow and heat transport and the problem is solved numerically by finite difference technique.

RESULTS AND DISCUSSION

Water Retention vs. Geometry

Figure 1 describes the variation in water retention along the perpendicular height of the substrate. A drainage layer is managed between the growing media and the concrete roof to facilitate the horizontal water transfer. Drainage layer and growing media heights have a direct influence on the water retention capacity of the system. Using the parameters of Table 1, we could see in Figure 1 that the installation of a 10 cm drainage layer reduces the average water retention capacity which could be called "green-roof water capacity" (amount of water held after rain and drainage) from 0.85 (0 kPa) to 0.73 (-1 kPa) and causes a decrease of 40% of the available water capacity. Values of α, θ_r and θ_s parameters are predominant for the water retention capacity of the system. A gentle slope facilitating the drainage under the substrate can lead to a great horizontal heterogeneity in the water retention capacity.

Variation of Thermal Properties vs. Water Retention

Comparing the values of thermal properties of the different constituents of the system (Table 2) and assuming that the volume of solid phases are very low in growing media, shows that the thermal properties of the growing layer are directly dependent on the air/water ratio. For the tested material, values of thermal conductivity are intermediate between a traditional brick and an insulation material as rockwool. With the variation of water content, thermal conductivity varies between 0.5 J m^{-1} s^{-1} K^{-1} at retention capacity and 0.25 (5 times the value of rockwool) when the water content is near θ_s. The volumic heat capacity C_h (not presented) follows similar variations.

Simulation of Water and Heat Transfer

The simulation presents the variation of water content and heat transfer during 60 h for a 16 cm height of substrate and 10 cm drainage layer, the water content of substrate is near θ_r (67 L m^{-2}) at t=0. Rain simulation began at t=24 h for 5 h and a total of 35 mm. The amount of water applied was sufficient to bring the substrate back to "green-roof water capacity" (110 L m^{-2}). In addition, two different climatic conditions are tested:

- wintertime conditions with temperature varying between 0 and 10°C daily and a low evapotranspiration of 0.5 mm per day; temperature of the rain was fixed at 5°C and temperature at the bottom of the substrate was maintained at 15°C.
- summertime conditions with temperature varying between 28 and 36°C daily and a high evapotranspiration of 7 mm per day; temperature of the rain was fixed at 15°C and temperature at the bottom of the substrate was maintained at 25°C.

Dependence of evapotranspiration on water content is described with a non-dimensional multiplication factor varying with Se.

Figures 2 and 4 present the variation of water content along the height of substrate during the two seasons. For the simulated substrate, a new equilibrium is rapidly reached after the rain and the substrate could be considered at the maximal retention capacity in these conditions. For the winter conditions when the temperature is 10°C outside, heat flow at the bottom of the substrate (Fig. 3) varies from 2 W m^{-2} to a maximum of 25 W m^{-2} during the rain. The rain and the increase of the water content has a significant effect on the average value of heat flow between the building and the substrate with the value of 6.4 for a water content near θ_r and 10.5 W m^{-2} for the substrate at "green-roof water capacity". High transfer values during the rain are due to the low rain temperature and water content higher than "green-roof capacity".

Summertime conditions (Fig. 5) lead to comparable values for the inverse sensible heat flow from outside towards the building with an average flow of 4.7 W m^{-2} for water content near θ_r. Rain inverses the heat flow and has an important and durable cooling effect. After drainage of the rain, a new regime of heat transfer is attained at 60 hours with an average heat flow of 5.2 W m^{-2}. But whatever the water content or the time of day, the flow is lower than the latent heat flow due to evapotranspiration which presents maxima from 230 W m^{-2} when the substrate is near θ_r to 630 W m^{-2} near saturation.

Horticultural substrates generally present a value of α>0.5 and the thickness of the layer will have a great influence on the air/water ratio at the top of the substrate. Figure 6 presents the heat flow under a constant 10°C temperature gradient between the two faces of the substrate maintained at the "green-roof water capacity". Thickness of substrate has a great influence on the limitation of heat flow towards atmosphere which could be divided by 50% when the thickness of the layer increases from 10 to 15 cm. However, the performance of substrate stays lower than traditional insulation material.

CONCLUSION

Some substrates used in horticulture can potentially be good materials for green-roof installation. They present low bulk density and good water retention, a main advantage for plant consumption and rain buffering in urban water management. Although green-roof substrates have an effect on heat transfer with a sufficient thickness, their insulation properties are limited particularly near "green-roof water retention capacity" and they cannot totally substitute insulation material.

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Tables

Table 1. Parameters of the van Genuchten water retention function used in the simulation.

α	1.3	$(kPa)^{-1}$
θ_s	0.95	$m^3\ m^{-3}$
θ_r	0.35	$m^3\ m^{-3}$
n	1.82	
m	0.45	
K_{sat}	3.6E-04	m/s
λ	0.5	

Table 2. Thermal properties of constituents.

	Density ($kg\ m^{-3}$)	Heat capacity ($J\ kg^{-1}\ K^{-1}$)	Heat conductivity ($J\ m^{-1}\ s^{-1}\ K^{-1}$)
Air	1.2	1000	0.0257
Water	1000	4200	0.57
Quartz	2650	840	2.926
Solid brick	1700	1050	0.64
Wood	1200	2000	0.1
Peat	1460	1400	

Figures

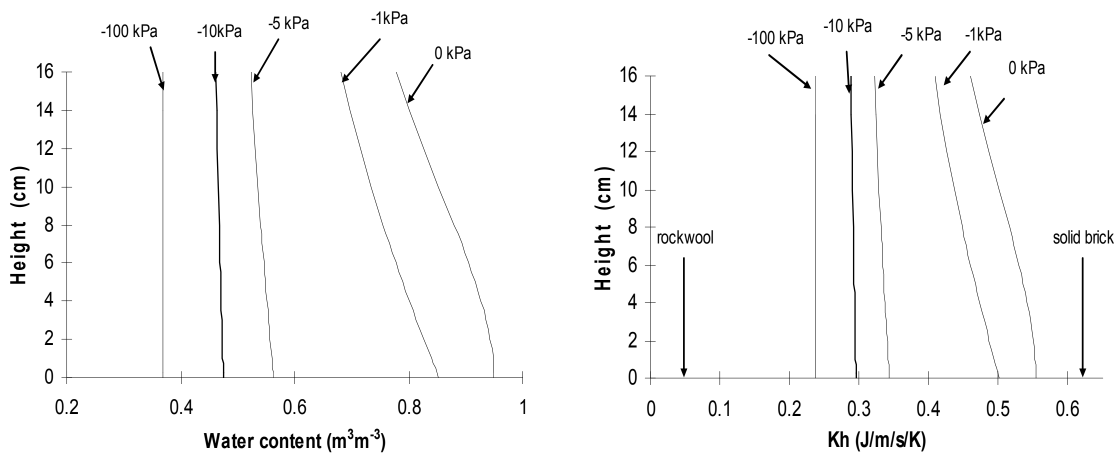

Fig. 1. Water content and thermal conductivity along the perpendicular height for different values of water potential at the bottom of a growing medium (VG parameters of Table 1).

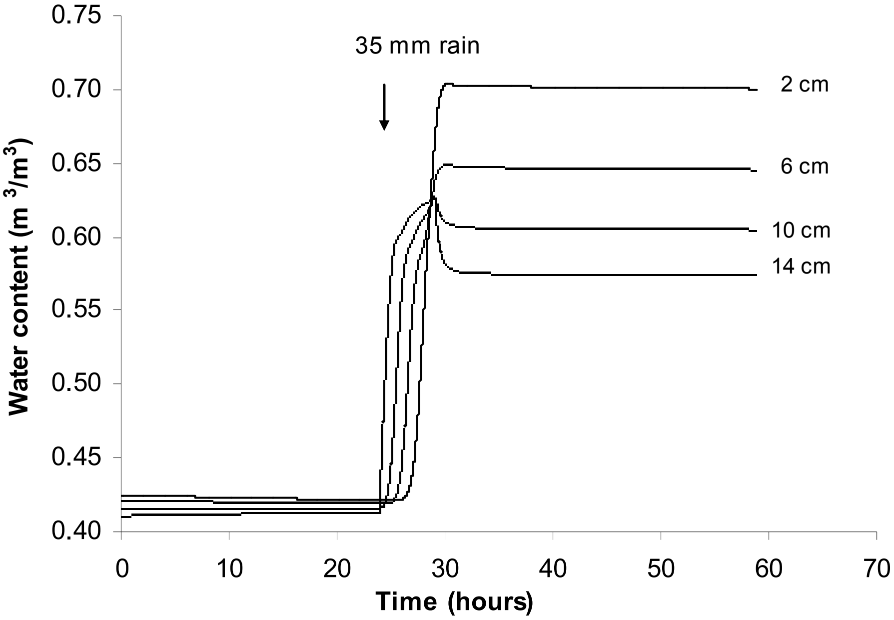

Fig. 2. Wintertime simulation: water contents vs. time at different levels from bottom in a 16 cm deep substrate.

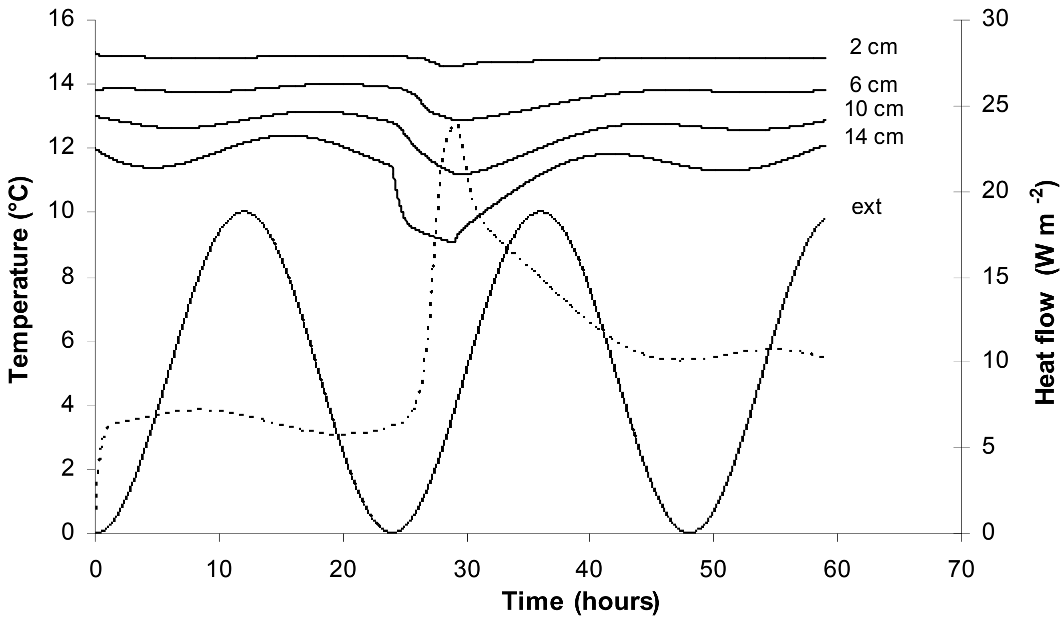

Fig. 3. Wintertime simulation: temperatures (continuous lines) at different level from bottom and heat flow at bottom of the substrate (dashed line) vs. time in a 16 cm deep substrate. Temperature of rain is 5°C and temperature at the bottom is maintained at 15°C.

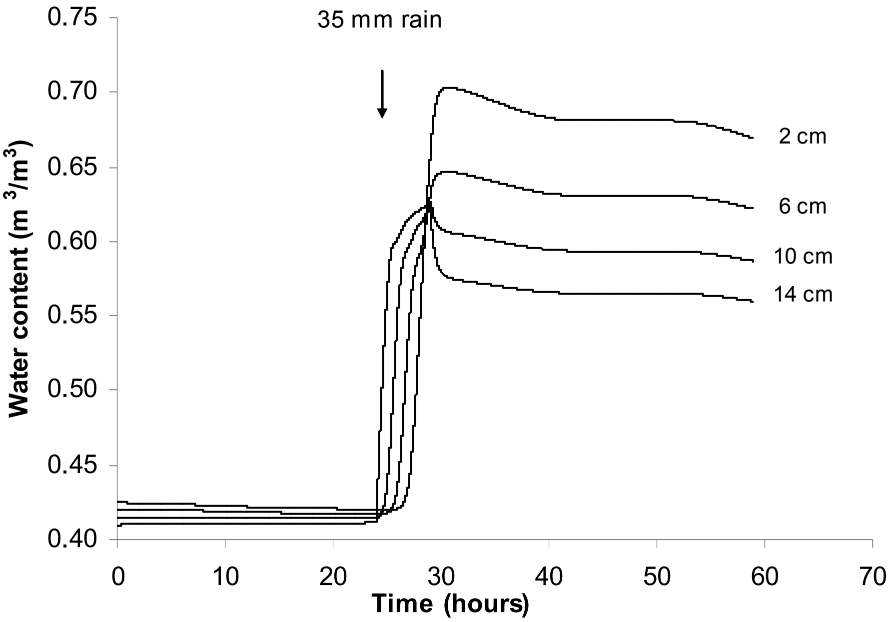

Fig. 4. Summertime simulation: water contents vs. time at different levels from bottom in a 16 cm deep substrate.

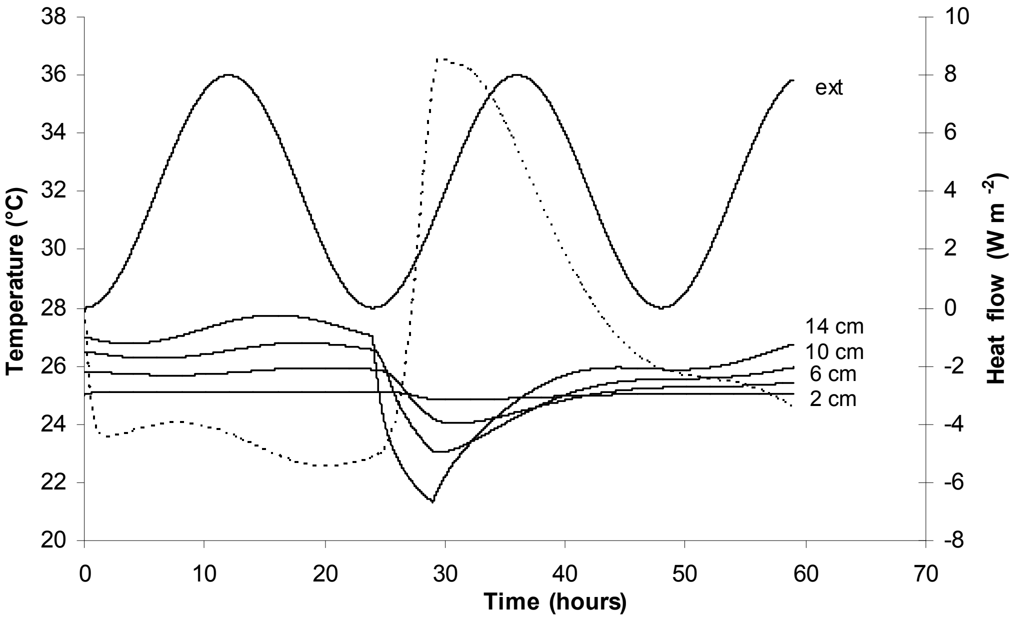

Fig. 5. Summertime simulation: temperatures (continuous lines) at different level from bottom and heat flux at the bottom of the substrate (dashed line) vs. time in a 16 cm deep substrate. Temperature of rain is 15°C and temperature at the bottom is maintained at 25°C.

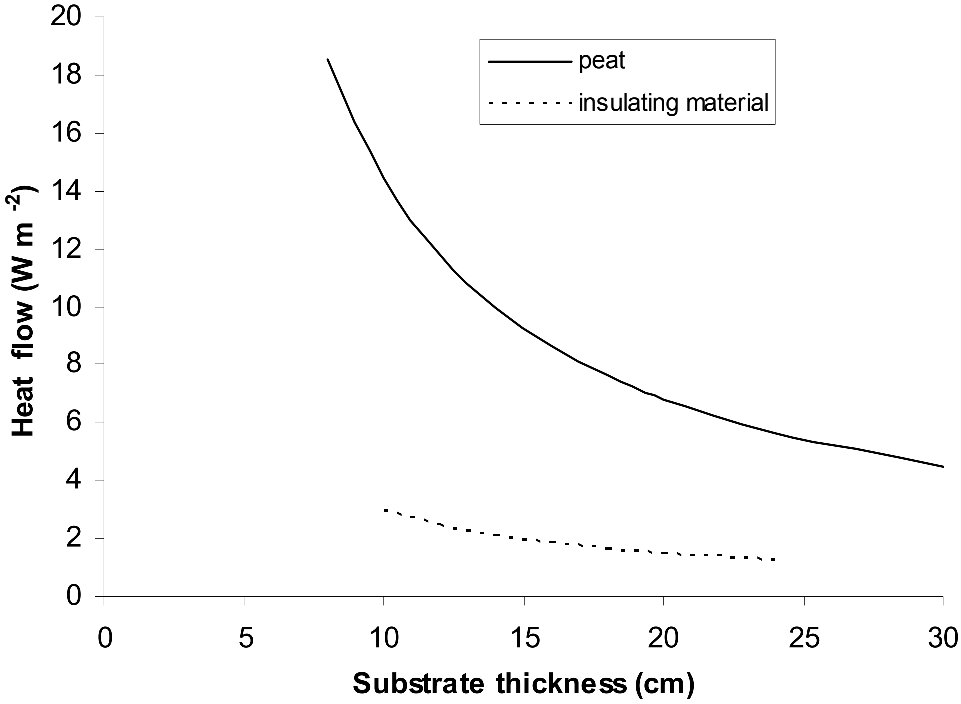

Fig. 6. Stationary heat flow for a constant temperature difference of 10°C between the two faces vs. thickness of substrate (continuous line) or insulating material (dashed line).