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THERMAL CHARACTERIZATION OF GREEN ROOFS THROUGH DYNAMIC SIMULATION

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ABSTRACT

The aim of this study is to evaluate a simplified parameter to characterize green roofs summer dynamic thermal performance through a mathematical approach.

The inside face surface conduction in a green roof component is calculated through the Fast all-season soil strength (FASST) model. A parametric analysis is carried out to evaluate which roof design options have the greatest effect on the green roof thermal behavior during the summer period. The results show the relevance of the leaf area index of the vegetation layer and of thickness of the soil, which is the key factor regarding the growing media characterization.

INTRODUCTION

During the last years, green roofs have been frequently applied in the Mediterranean regions for passive cooling of buildings. According to the Italian Presidential Decree 59/2009 (Italian Government, 2009) the adoption of this solution is advised because it is considered a proper technical solution for reducing building cooling needs, through the mitigation of solar gains.

In fact the planted roofs mitigate solar radiation by the shading effect of plants on the soil layer and by their biological functions, such as photosynthesis, respiration, transpiration and evaporation from soil and vegetation.

Whereas on the one hand the added thermal mass, the evaporative cooling and the higher time lag effect are positive effects, on the other hand the maintenance costs are quite elevated, above all due to the artificial watering which should be considered in a global feasibility analysis.

In warm climates, the green roofs play a significant role on the building cooling need and on its peak load, as underlined by Florides et al. (Florides et al., 2002). In general the percentage of solar radiation absorbed by the green roof for performing the vegetation biological functions is high, and only a minimal part is transfered to the ground and thus to the indoor space (Ekaterini and Dimitris, 1998).

Several studies investigated the energy performance of green roofs. In summer, with a poorly wet soil, the attenuation of the entering heat flux is significant compared to traditional roofing technologies. As regards the heating season, the energy performance should be properly evaluated, considering the entity of evapotranspiration, the kind of use of building, the insulation rate of the building (Theodosiou, 2003). For a dry green roof Lazzarin et al. (Lazzarin et al., 2005) found out that of the incident solar irradiation, 23% is dissipated by solar reflectivity, 39% by solar absorption, 24% by outside adduction, 12% by evapotranspiration and 1,3% by thermal accumulation. In general through a green roof only 1,8% enters the underneath room versus 4,4% of a traditional roof.

Green roofs have several benefits: they can mitigate the urban heat island effect (Takebayashi and Moriyama, 2007), improve energy efficiency of buildings (Theodosiou, 2003; Wong et al., 2003), reduce storm water runoff, increase biodiversity, purify water and air. Other benefits as improved air quality, acoustic insulation, aesthetic value, reduction of the solar gain absorbed by roof-structure (Ayata et al., 2001) could be achieved.

In some research papers also the contribution of green roof in thermal insulation is investigated in particular when the bare roof has no insulation layer (Nichau et al., 2001), while other works revealed that even if green roofs contribute to thermal protection, they cannot replace the insulation layer (Eumorfopoulou and Aravantinos, 1998).

Several calculation methods have been developed to evaluate the thermal behaviour of green roofs: Barrio (Barrio, 1998) and Sailor (Sailor, 2008) studied the energy balance of green roofs taking into account long wave and short wave radiation, plant canopy effects on convective heat transfer, evapo-traspiration from soil and plants and heat conduction and storage in the soil layer. Feng, Meng and Zhang (Feng et al., 2010) also considered photosynthesis phenomena. In some papers sensitivity analyses were carried out to evaluate the most important green roof design variables. LAI (Leaf Area Index) has been found as one of the most relevant variables through mathematical analysis (Del Barrio, 1998; Kumar and Kaushik, 2005) and by means of field measurement (Wong et al., 2003; Kumar and Kaushik, 2005). Even if there are various calculation methods to determine the thermal behaviour of a green roof, few investigations for the evaluation of a simplified thermal parameter to be used by designer have been carried out.

Dynamic simulations have been used by a number of authors in order to predict energy performances of buildings, with reference to both building envelope components and HVAC systems, (Ascione et al., 2013; Fabrizio, 2012; Sailor, 2008; Kumar and Kaushik, 2005).

In the present paper, first a simplified thermal parameter to characterize thermal behaviour of green roof during summer period is defined and evaluated through dynamic energy simulation. Then a sensitivity analysis to evaluate the most important design variables influencing the proposed parameter is performed.

CASE STUDY

In order to evaluate the thermal performance of a flat green roof, a test-room has been considered.

The test room is surrounded by an adiabatic opaque envelope except for the green roof. Nor ventilation, nor internal heat gain have been considered. The indoor air temperature has been set constant at 26°C.

For each simulation, only the thermo physical properties of the green roof have been changed while the characteristics of the adiabatic components have been set as constant.

Green roof

The green roof analyzed in this paper is a multi – layers flat roof composed of a common structural layer made of concrete; a thermal insulation layer covered by a waterproof layer and laid on a moisture barrier; a drainage layer; a filter layer; a soil layer and vegetation layer as shown in Figure 1.

Three different thicknesses of the thermal insulation layer have been considered: 0 cm; 5 cm and 10 cm corresponding to a not insulated, a medium insulated and a high insulated roof respectively.

The thermal properties of the green roof layers are shown in Table 1.

Two types of vegetation roofs have been considered: an extensive and a semi-intensive one. The first type is characterized by a thin soil layer on which generally shrubs and grass grow; the second one is characterized by greater thickness of soil layer and higher plants. As intensive green roofs are rarely used because their high level of maintenance and cost, they haven't been considered in the present work.

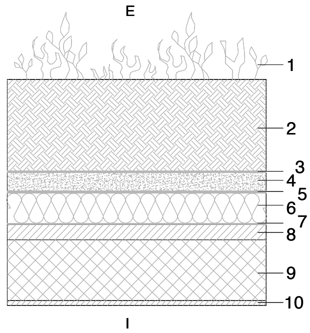

Fig. 1. Layers of the considered green roof.

Table 1. Thermo physical characteristics of green roof layers

	LAYERS	S	λ	ρ	c_p
	outside - inside	[m]	[W/(m K)]	[kg/m^3]	[J/(kg K)]
ROOF	1. Vegetation layer	-	-	-	-
	2. Soil layer	See Table 5			
	3. Filter layer	0,005	0,06	160	2500
	4. Drainage layer	0,06	0,08	800	920
	5. Waterproof layer	0,007	0,17	1200	920
	6. Thermal insulation layer	0	0,035	90	990
		0,05			
		0,10			
	7. Moisture barrier	0,003	0,055	2500	840
	8. Concrete slab	0,05	1,16	2000	880
	9. Concrete floor	0,20	0,39	1680	848
	10. Plaster	0,015	0,35	1200	840

CALCULATION METHODS

Green roof modeling

The technical literature proposes several calculation procedures for the green roofs.

The quantification of the evapotranspiration is quite complicated. Some models (Takakura et al., 2000) evaluate the state of vegetation as an equivalent uniform material, composed by air and foliages. Zhang et al. (Zhang et al., 1997), Alexandri and Jones (Alexandri and Jones, 2007), consider the heat exchange between plant leaves and the surrounding air.

The analysis developed in this article is based on the fast all season soil strength (FASST) model developed by Frankenstein and Koenig (Frankenstein and Koenig, 2004) for the US Army Corps of Engineers. This model has been implemented in EnergyPlus which is the tool selected for the numerical analysis. The results obtained from EnergyPlus have been used to calculate the conductive heat flux through the inner surface of the green roof by means of the conduction transfer function calculation method.

The green roof is modeled as a single vegetation layer on a soil surface. The vegetation layer model is a steady-state semi-infinite plane panel characterized by an emissivity, albedo, height and foliage fractional coverage that influence the heat exchange between the soil layer and the adjacent air. Soil is modeled as an homogeneous layer through which sensible and latent heat flux pass.

The green roof model takes into account the following phenomena:

- long wave and short wave radiative exchange within the vegetation layer including the effect of multiple reflections between vegetation and soil layers;
- vegetation layer effects on convective heat transfer;
- evapotraspiration from the soil and plants;
- heat conduction (and storage) in the soil layer.

In order to calculate the heat flux through a green roof, two energy balance equations are simultaneously solved for each time step at the soil (Φ_g) and foliage (Φ_f) level involving soil surface temperature (θ_g) and foliage temperature (θ_f).

The energy balance equation at the foliage level is reported in Equation 1.

$$\Phi_f = \sigma_f \left[I_s (1 - a_f) + \varepsilon_f \sigma \theta_f^4 \right] + \\ + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(\theta_g^4 - \theta_f^4 \right) + H_f + L_f \qquad (1)$$

In equation (1) σ_f is the foliage fraction coverage; I_s is the total solar irradiance; a_f is the shortwave albedo of the foliage layer; ε_f is the foliage emissivity; σ is the Stefan-Boltzman constant; θ_f is the foliage surface temperature; ε_g is the ground emissivity; ε_1 is a function both of the ground and of the foliage emissivity; H_f is the sensible heat flux and L_f is the latent heat flux.

The sensible heat flux (H_f) considers the convective heat exchange between the foliage and the adjacent air while the latent heat flux (L_f) takes into account the heat exchange due to the evaporation at the foliage level as a function of the air and of the stoamatal resistance to vapour diffusion.

The energy balance equation at the soil level is reported in Equation 2.

$$\Phi_g = (1 - \sigma_f) \left[I_s (1 - a_g) + \varepsilon_g I_{ir} - \varepsilon_g \sigma \theta_g^4 \right] - \\ + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(\theta_g^4 - \theta_f^4 \right) + H_g + L_g + \lambda_g \cdot \frac{\partial \theta_g}{\partial z} \qquad (2)$$

In equation (2) a_g is the shortwave albedo of the ground; I_{ir} is the total infrared irradiance; H_g is the sensible heat flux, L_g is the latent heat flux, λ_g is the ground thermal conductivity and z is the depth of the soil.

The terms of energy balance equations are shown in Figure 2.

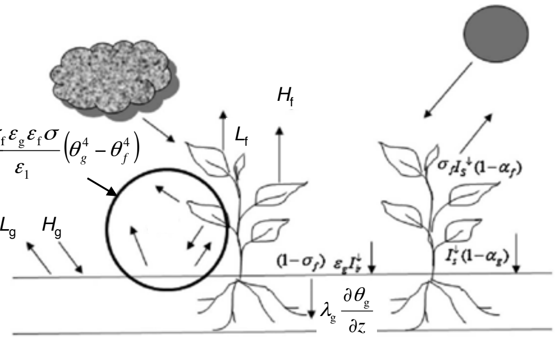

Fig. 2. The energy balance for a green roof. (EnergyPlus manual, 2009)

Input data

In order to evaluate the influence of different green roof typologies and configurations on the thermal behaviour of the green roof, the properties of soil and vegetation layers have been changed considering a range of variation that covers most of the current design solutions. In Tables 2 and 3 the ranges, the calculation steps and the average values of the parameters used for each simulation are shown. In particular, for each simulation, each parameter varies within its range while the remaining parameters are set as constant to their average value.

For each green roof configuration, the conductive heat flux through the inner surface is calculated and the corresponding equivalent dynamic thermal parameter is obtained as explained in the following paragraph. A sensitivity analysis is conducted in order to identify the most relevant green roof design variables affecting the defined dynamic thermal parameter.

As Table 2 shows, different ranges of height of plants have been considered varying from 10 to 20 cm for extensive roofs and from 20 to 50 cm for semi-intensive roofs.

The range of leaf area index (LAI) values, the projected leaf area per unit area of soil surface, varies from 0,0015 to 5, in order to cover the corresponding validity range considered by the model. The same assumption has been made for leaf reflectivity, leaf emissivity and stoamatal resistance, that is the resistance of the plants to moisture transport.

Different soil thicknesses have been considered varying from 0,05 to 0,15 m for extensive green roofs and from 0,15 to 0,35 m for semi-intensive ones. Moreover different levels of soil roughness have been considered according to the model.

Table 2. Input parameters of vegetation layer.

		RANGE	STEP	AVERAGE VALUE
Height of plants	Extensive roof	10-20 [cm]	1 [cm]	15 [cm]
	Semi-intensive roof	20-50 [cm]	1 [cm]	35 [cm]
Leaf area index (LAI)		0,0015-5 [-]	0,5 [-]	1,5 [-]
Leaf reflectivity		0,1-0,4 [-]	0,025 [-]	0,22 [-]
Emissivity		0,8-1 [-]	0,025 [-]	0,95 [-]
Minimum stoamatal resistance		50-300 [s/m]	20 [s/m]	180 [s/m]

The definition of the input parameter is reported in the text

Table 3. Input parameters of soil layer.

		RANGE	STEP	AVERAGE VALUE
Roughness		VeryRough, Rough, MediumRough, MediumSmooth, Smooth, and VerySmooth	-	Rough
Thickness	Extensive roof	0,05-0,15 [m]	0,01 [m]	0,10 [m]
	Semi-intensive roof	0,15-0,35 [m]	0,01 [m]	0,25 [m]
Absorptance (thermal)		-	-	0,9 [-]
Absorptance (visible)		-	-	0,7 [-]
Saturation volumetric moisture content		-	-	0,5 [m^3/m^3]
Residual volumetric moisture content		-	-	0,01 [m^3/m^3]
Initial volumetric moisture content		-	-	0,15 [m^3/m^3]
Thermo-physical properties (see Table 5)		DH01, DH02, DH03,DH04, DH05,DH06,DH07,DH08	-	DH01

In order to study the behavior of the typology of soils generally used for green roofs, a literature review has been made. Generally few data about green roof soils are available: technical standard EN ISO 13370 (CEN 2007) provides thermal characteristics of few common soils while FASST model provides thermal properties of several soil types which are not used as ecoroof growing media. On the other hand Sailor et al. (Sailor et al., 2008) monitored eight types of ecoroof soils commonly used for green roofs in the United States with different moisture levels in order to obtain values of density, thermal conductivity, specific heat and albedo. Moreover Farouki's database of soils (Farouki, 1981), which uses Johansen's method for predicting soil thermal conductivity from existing data, has been examined. In Figure 3 a correlation between thermal conductivity and density multiplied by specific heat for different kind of soils is presented according to Sailor's data, Farouki correlation model and EN ISO 13370. While technical standards data overestimate thermal conductivity, Sailor's monitored data and Farouki correlation seem to provide comparable results.

In fact, compared to the common types of soil, the ones used for green roofs are characterized by a low quantity of organic compost, by a relevant quantity of sand and a very high quantity of light material such as pumice or expanded shale. For this reason this kind of soils are generally characterized by low value of thermal conductivity.

As the present work aims to analyze soil types used for green roof, only the eight typologies of soil common in the western U.S monitored by Sailor et al. have been selected for the sensitivity analysis.

The composition of the eight types of soil is reported in Table 4 while the thermal properties of soils characterized by zero per cent of moisture level content are reported in Table 5. In this paper different configurations of green roofs for summer design day condition have been performed without taking into account the moisture content of soil.

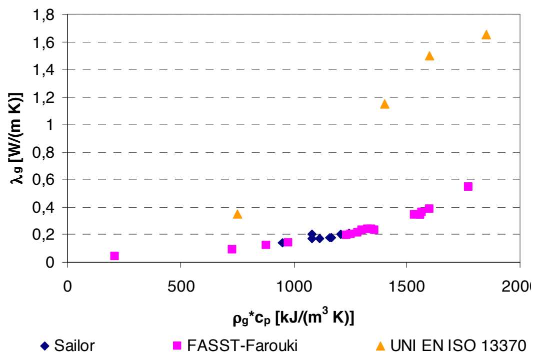

Fig. 3.Correlation between soil thermal conductivity (λ_g) and soil density per specific heat ($\rho_g \cdot c_p$for three database of soils

Table 4. Composition of green roof soils (Sailor et al., 2008).

SOIL CODE	PUMICE	EXPANDED SHALE	COMPOST	SAND
	[%]	[%]	[%]	[%]
DH01	50	0	10	40
DH02	50	0	0	50
DH03	75	0	0	25
DH04	75	0	10	15
DH05	0	50	10	40
DH06	0	50	0	50
DH07	0	75	0	25
DH08	0	75	10	15

Table 5. Thermo-physical properties of green roof soils for 0% of moisture level (Sailor et al., 2008).

SOIL CODE	ρ_g	λ_g	c_p	a_g
	[kg/m^3]	[W/(m K)]	[J/(kg K)]	[-]
DH01	1020	0,17	1093	0,28
DH02	1130	0,18	1032	0,41
DH03	880	0,17	1227	0,38
DH04	760	0,14	1251	0,39
DH05	1360	0,20	887	0,17
DH06	1400	0,21	890	0,19
DH07	1117	0,20	966	0,18
DH08	1060	0,18	1093	0,18

Equivalent dynamic thermal parameters

In order to calculate an equivalent dynamic thermal parameter for green roofs, EN ISO 13786 (CEN 2007) has been considered. This technical standard is based on the admittance method introduced by N.O. Milbank and J. Harrington-Lynn (Milbank Harrington-Lynn, 1974), and supplies a simplified calculation model that considers 24 h sinusoidal boundary conditions.

In order to represent in a more realistic way the boundary conditions influencing the heat flow through the roof, an equivalent external temperature has been considered ($\theta_{e,eq}$) as in equation below (3).

$$\theta_{e,eq} = \theta_{ae} + \frac{I\alpha + h_{ir,g}(\theta_g - \theta_{ae}) + h_{ir,sk}(\theta_{sk} - \theta_{ae})}{h_e} \quad (3)$$

The equivalent external temperature takes into account the outside air temperature (θ_{ae}) as well as the solar irradiance I on the component, the long wave radiative exchange between the component and the ground, $h_{ir,g}$ (θ_g - θ_{ae}), between the component and the sky, $h_{ir,sk}$ (θ_{sk} - θ_{ae}), where θ_g is the surface temperature of the growing media and θ_{sk} is the temperature of the sky. h_e is the outdoor surface heat transfer coefficient, given by (4):

$$h_e = h_{conv} + h_{ir,air} + h_{ir,g} + h_{ir,sk} \quad (4)$$

where h_{conv} is the convective heat transfer coefficient and $h_{ir,air}$, $h_{ir,g}$ and $h_{ir,sk}$ are the radiative heat transfer coefficients respectively with air, ground and sky.

As the green roof is a flat roof, the radiative heat transfer coefficient with the ground is equal to zero.

In Figure 4 the daily trend of external air temperature is compared with the equivalent external temperature considering a ground solar absorption of 0,7.

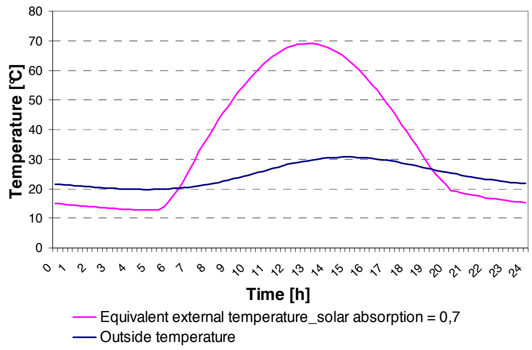

Fig. 4.Comparison between external air temperature and equivalent external temperature trend.

In order to calculate the equivalent dynamic thermal properties of a green roof, a summer design day has been considered for the city of Torino. In Table 6 the geographical data of the location and the climatic data of summer design day are shown.

Table 6. Geographical data and climatic data of summer design day for Torino

	LOCATION	TORINO	
PLACE	Latitude	45,08	[°]
	Altitude	239	[m]
SUMMER DESIGN DAY	$\theta_{max,bs}$	30,7	[°C]
	$\Delta\theta_{ae}$	11	[°C]
	$I_{m,g,North}$	80	[W/m^2]
	$I_{m,g,South}$	150	[W/m^2]
	$I_{m,g,East}$	177	[W/m^2]
	$I_{m,g,West}$	212	[W/m^2]
	$I_{m,g,horizontal}$	326	[W/m^2]

Through the calculation model based on the transfer function (CTF), implemented in EnergyPlus, the heat flux through the green roof for each time step has been evaluated. Knowing the equivalent outside temperatures and the heat fluxes, an equivalent periodic thermal transmittance has been defined to characterize the thermal behavior of a green roof, calculated as (5):

$$Y_{ie} = \frac{(\Phi_{cond,si,\max} - \Phi_{cond,si,\min})_{si}^{dyn,CTF}}{(\theta_{e,eq,\max} - \theta_{e,eq,\min})} \quad (5)$$

Since the analysis carried out by EnergyPlus is in dynamic conditions the thermal inertia of the component has been taken into account. Thus density and specific heat of the soil become influencing factors of primary importance.

RESULTS

The results in term of equivalent dynamic thermal transmittance (Y_{ie}) are here presented for each considered green roof configuration. In Figure 5 Y_{ie} variation is presented for an extensive green roof for different insulation thickness levels. The design parameters of soil and vegetation layers mainly affecting Y_{ie} values are the LAI value and the thickness of the soil layer. Moreover, the more the green roof is thermally insulated, the more the design parameters of soil and vegetation become negligible. In fact, for a not insulated roof, a variation of soil thickness induces a variation of Y_{ie} quite high, from 0,03 to 0,12 W/(m^{2}K); for a medium insulated roof, Y_{ie} varies from 0,01 to 0,04 W/(m^{2}K) while for a well insulated roof Y_{ie} varies from 0,01 to 0,02 W/(m^{2}K). The thermal resistance of the green roof, mainly affected by the thermal insulation layer, is then the parameter that mainly affects the Y_{ie} values of a green roof. Whenever an extensive green roof is not or is poorly insulated, LAI values and soil thickness are very important to determine a green roof thermal behavior.

All the considered green roof configurations meet the Y_{ie} limit value of 0,12 W/(m^{2}K) set by the Italian legislation for the opaque envelope components subject to solar radiation.

In Figure 6 the Y_{ie} variation is presented for a semi-intensive green roof for different insulation thickness levels. In this case the variation of Y_{ie} due to the variation design parameters is negligible, as Y_{ie} values are very low, generally less that 0,01 W/(m^{2}K).

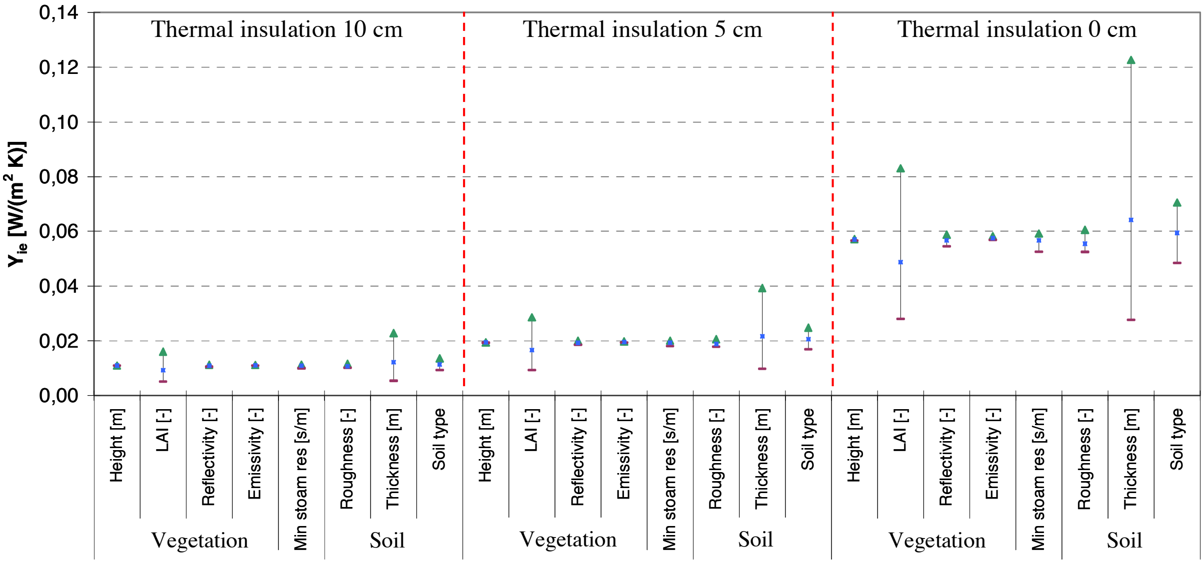

Fig. 5. Equivalent periodic dynamic thermal transmittance variation for each design parameter. Extensive green roof.

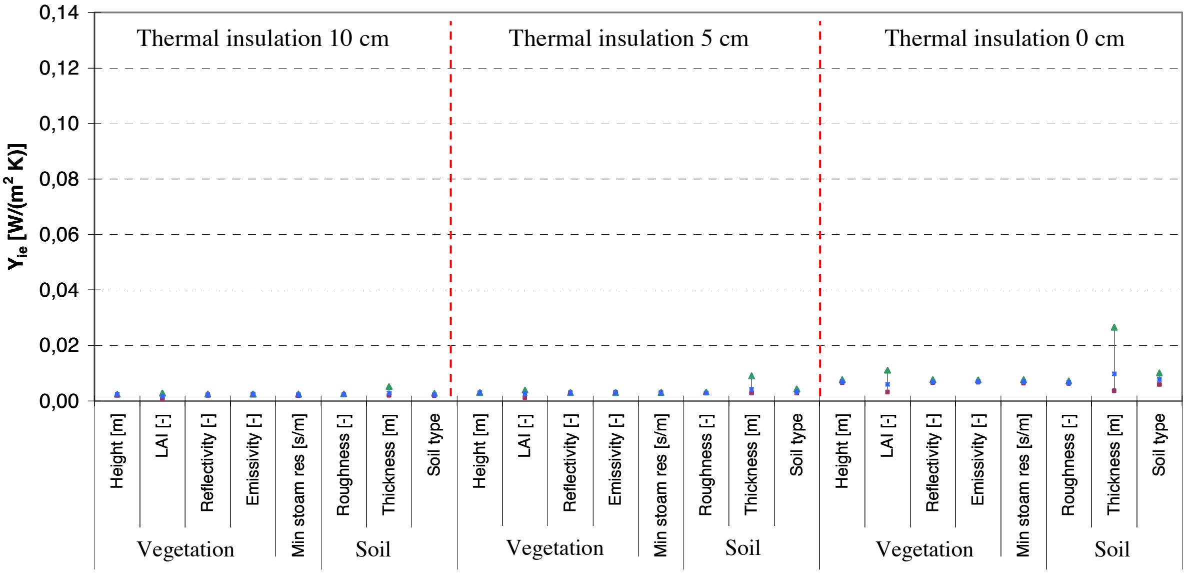

Fig. 6. Equivalent periodic dynamic thermal transmittance variation for each design parameter. Semi-intensive green roof.

Generally, neither thermal insulation thickness, nor soil and vegetation design variables influence Y_{ie} values for a semi-intensive green roof. This is due to the fact that a semi-intensive green roof is generally characterized by an deeper soil layer.

In order to evaluate the Y_{ie} trend versus the soil thickness, for the three thermal insulation levels and for extensive and semi-intensive green roof, Figure 7 is shown.

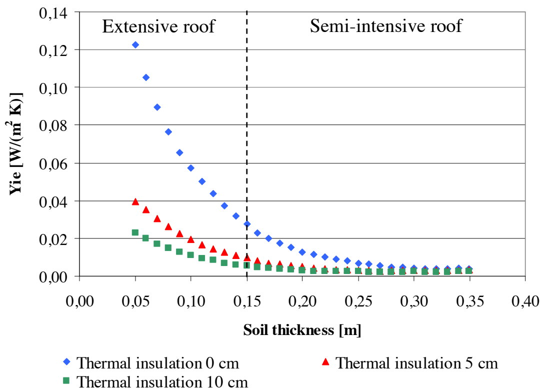

Fig. 7. Y_{ie} versus soil thickness for three level of thermal insulation thicknesses.

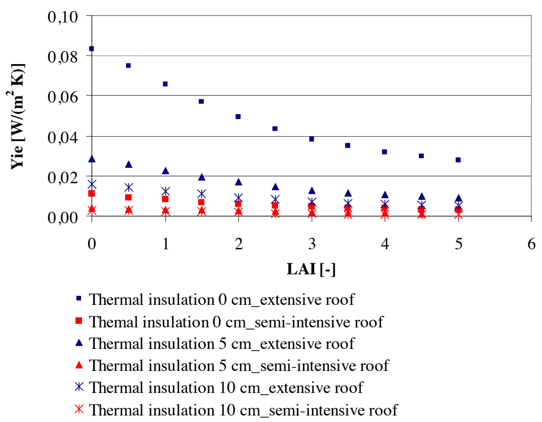

Fig.8 Y_{ie} versus LAI for three level of thermal insulation thicknesses

In Figure 8 is shown the Y_{ie} trend versus LAI values for the three thermal insulation levels and for extensive and semi-intensive green roof.

The more LAI values are low, the more Y_{ie} values increase. In fact, high values of LAI means a higher vegetation shading effect but also higher evapotranspiration effects.

The typology of soil has generally a not negligible influence on Y_{ie} for non insulated extensive roofs while, in all other cases (insulated extensive roofs and insulated or non semi-intensive roofs) is quite unimportant. These results have been obtained considering for all the selected soils the absence of moisture and water content. Other simulations will be performed in order to evaluate the impact on the Y_{ie} of soils considering also a different moisture levels.

Other vegetation characteristics, such as height of plants, foliage reflectivity and emissivity and minimum stoamatal resistance don't affect Y_{ie} values as well as the roughness of the soil.

CONCLUSION

In the present work, a simple methodology to evaluate the energy behavior of different green roof configurations has been carried out. A simplified parameter to characterize green roofs dynamic thermal property through a mathematical approach for summer period hase been analyzed.

A parametric analysis has been carried out for extensive and semi-intensive green roofs in order to evaluate which roof design options are mainly involved in the characterization of a green roof thermal behavior during the summer period.

Regarding the extensive green roofs, the results show the importance of the leaf area index of the vegetation layer whereas for the growing media thermal characterization the key factor is the thickness of the soil. However, the more the roof is thermally insulated, the more the other design options become negligible. For semi-intensive green roofs, as the thickness of the soil layer is higher, the influence of the other design variables on Y_{ie} values is very low.

Generally, Y_{ie} values for all the considered green roof configurations are very low because of the soil layer that is characterized by a high thermal inertia.

The proposed methodology can be a simple tool useful for industries or designers to easily perform different configurations of green roofs. The configuration of the green roof can be optimized taking into account the effect of the design variables on the proposed simplified parameter Y_{ie}. The critical aspect is the lack of information about green roof soil compositions and characteristics as well as vegetation characteristics influencing the energy behavior of this technology.

NOMENCLATURE

a	[-]	albedo (reflection coefficient)
c_p	[J/(kg K)]	heat capacity
H	[W/(m^{2}K)]	heat transfer coefficient
H	[W/m^2]	sensible heat flux
I	[W/m^2]	solar radiation
L	[W/m^2]	latent heat flux
LAI	[-]	leaf area index
S	[m]	thickness
Y_{ie}	[W/(m^{2}K)]	periodic thermal transmittance
α	[-]	solar absorption
ε	[-]	emissivity
Φ	[W/m^2]	heat flux
λ	[W/(m K)]	thermal conductivity
θ	[K]	temperature
ρ	[kg/m^3]	density
σ	[W/(m^{2}K^4)]	Stefan-Boltzman constant
σ_f	[-]	foliage fractional coverage

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