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Modelling within-canopy heat exchanges of green roofing

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Abstract. The mathematical modelling of green roofs is deeply limited by the poor knowledge of the thermal exchanges occurring within canopies of the vegetated apparatus. These exchanges, in fact, affect the whole performance of the roofing and, in turn, the comfort conditions for occupants of the green covered building. In this work a critical review of the literature algorithms for the simulation of the within-canopy heat exchanges is presented in the aim of providing, on one hand, a contribution toward the singling out of a more accurate modelling of this important component of the envelope and, on the other hand, toward the definition of some simplified, but reliable, algorithm to be usefully included in the typical scheme of the energy certification of buildings. First results of a field experiment are also reported, aimed at defining the thermal boundary conditions of the canopy volume of control.

1. Introduction

In the current building design and practice, green roofs are becoming more and more popular, mainly due to an increasing environmentally conscious behavior of people.

Anyway, apart from their aesthetical characteristics, vegetated roofs can play a relevant role in the thermal balance of buildings they belong to. Particularly in Mediterranean mild climates, their importance in reducing the energy demand of buildings for summer climatization has been several time pointed out in literature as they reduce the summer roof surface temperatures and the outdoor air temperature [1÷3]. This, in turn, results in a relevant reduction of the request of electric energy for climatization purposes, with a general benefit on the country energy balance.

Clearly, a widespread diffusion of such building components should be supported by the availability of reliable (and simple to manage) calculation tools, in order to allow technicians to evaluate their thermal and energy effects.

Talking of canopy, it is worth mentioning that there exists a consolidated theory on heat exchanges in plant canopies [4÷16]. Specifically, canopy physical and physiological processes (radiative exchanges, photosynthesis and transpiration) are generally described by researchers by adopting either a "big-leaf" approach [11÷14] or a "two leaf" approach [15, 16] or a "multilayer" approach [10, 17, 18]. The big leaf approach to plant canopies is commonly recognized by the scientific community as the simplest one compared to the other two approaches because of the few parameterization, but it is also a common opinion among researchers that it provides errors [15] that may be overcome using a multilayer approach or a two leaf approach.

In this paper, after a brief description concerning plant canopies typically available in green roofs along with some notes concerning dominant heat exchanges occurring in this green roof component, a critical review of the calculation methods adopted in the scientific literature for the mathematical description of the within-canopy exchanges is presented. This review is aimed at investigating, on the one hand, the manner in which within-canopy thermal exchanges in green roofs are currently approached in literature and by which simplifications they are affected, and on the other hand their feasibility for an inclusion in the scheme for the energy certification of buildings. Afterwards, first results of an experimental measurement campaign concerning a green roof installed in Sicily and composed by different vegetal species and substrates are reported. The experiment is mainly intended for the definition of the thermal boundary conditions of the volume of control represented by the canopies, to be analysed.

2. Plant canopies in green roofs: typologies and thermo-physics

Generally speaking, a green roof is a green space created by adding layers of growing medium and plants on top of a traditional roofing system. More specifically, components involved in a vegetated roof are: a structural support, an high-quality waterproofing membrane, an anti-root barrier, a drainage layer, a water storage layer, a filtration layer, a substrate and, finally, a plant canopy.

The canopy or vegetation layer is basically a layer of a certain height made of air and leaves. Plants constituting this layer depend on the green roof types, whether intensive or extensive. In fact, intensive green roofs typically use a wide variety of plant species that may include trees and shrubs, while extensive ones typically use plants such as herbs, grasses, mosses and drought-tolerant succulents as Sedum [19].

From a thermo physical point of view, main physical phenomena contributing to determine the thermal status of leaves (figure 1) include: the absorption of solar radiation by leaves (a); the thermal radiation exchanges among leaves and the surroundings (sky and substrate surface) and among leaves (b); convective heat transfer between leaves and the air within the canopy (c); convective heat transfer between leaves and the air outside the canopy (d); and latent heat exchanges due to leaves' transpiration (e).

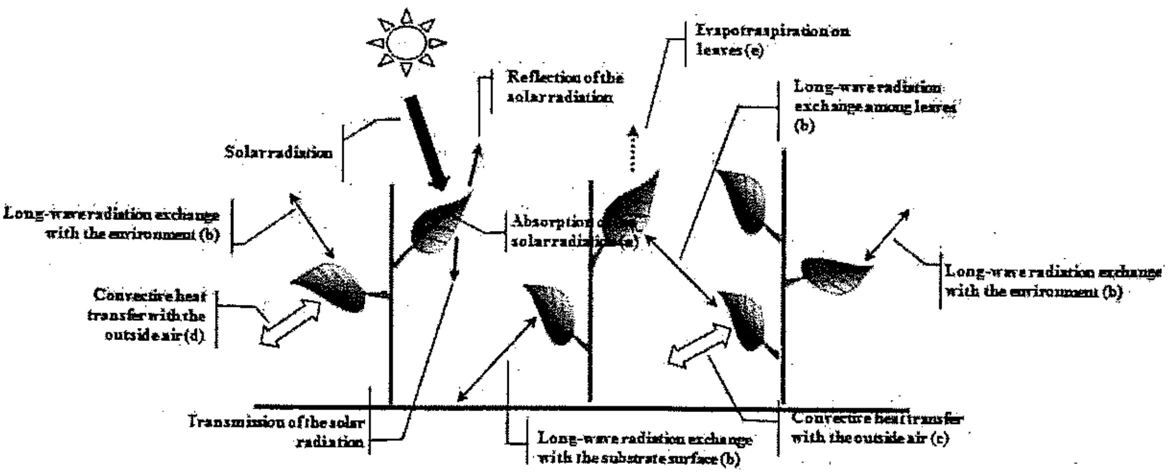

Figure 1. The energy balance of the foliage in green roofs canopies.

Whereas dominant processes contributing to determine the thermal status of the air within the canopy are: convective heat exchanges between leaves and the air within the canopy and between the substrate surface and the air within the canopy; and convective heat transfer between the air within the canopy and the air outside the canopy.

Obviously, the presence of the plant canopy represents one of the factors contributing to render the modelling of a green roof more complex compared to a traditional roof; a mathematical description of the solar radiation absorbed by leaves, for example, would require a precise knowledge of the solar radiation distribution within the canopy and this, in turn, would require a detailed knowledge of either the canopy architecture, the angle distribution of the incident radiation, and the optical properties of leaves. As regards the simulation of the radiation distribution within plant canopies in order to describe the radiative heat exchanges, it must be mentioned that there exist in literature various radiative transfer models within plant canopies [8, 17, 18, 20, 21]. However, these models result to be more or less complex and high computational demanding as they include the processes of radiation penetration through gaps between leaves, radiation reflection and transmission from and through leaves (scattering processes), and absorption by the leaves relying on a multilayers-type canopy approach.

Based on this considerations, it is therefore evident that an exact modeling of heat exchanges happening in the canopy layer of a green roof is almost impossible.

To investigate the manner in which within-canopy thermal exchanges in green roofs are currently approached in literature and by which simplifications they are affected, in the following relevant canopies models to estimate the energy balance of green roofs are reported. This review could provide an useful information to estimate also their feasibility for an inclusion in the scheme for the energy certification of buildings.

3. Canopy's models to estimate the energy balance of green roofs

Over last decades, several authors have turned their attention to these promising building components, proposing a set of simulation models of vegetated roofs thermal behavior.

Green roofs models proposed by Palomo del Barrio [22], Sailor [23] and Alexandri & Jones [24] have been selected for this study since they account for the vegetation layer.

The canopy's models embedded in their green roofs models, apart from the one proposed by Sailor that does not take into account the air within the canopy, consist of two equations: one expressing the energy balance of the foliage layer and one expressing the energy balance of the within-canopy air.

In the present study we turned our attention only to algorithms referred to the foliage layer of a plant canopy. Therefore, equations concerning the energy balance of the within-canopy air have not been discussed here.

All of the below described canopy's models embedded in the selected green roofs models are seemingly based on the same approach that is the "big leaf approach". The canopy is therefore treated as a single leaf or a single layer characterized by only one value of leaves temperature and air temperature and only one value of air humidity. Equations used to describe its energy balance generally refer to equations that are first developed for a single leaf but then scaled up to the canopy level.

In the following, algorithms to describe the energy balance of the foliage embedded in the selected canopy's models are presented, along with a brief description.

Palomo del Barrio approach. The energy balance equation of the foliage is:

$$(\rho c)_p d\, LAI \frac{dT_p}{dt} = \varphi_{rad,sol} + \varphi_{rad,TIR} + \varphi_{conv,p-a} + \varphi_{trans,p-a} \tag{1}$$

where: T_p is the leaves temperature (average in the control volume) (K); $(\rho c)_p$ is the specific heat capacity of leaves (J/m3 K); d is the average thickness of leaves (m); LAI is the leaf area index.

The first term on the right end side expresses the net radiative exchange of leaves with the sun (W/m^2). The second term expresses the net thermal radiation exchange of leaves with the surroundings (sky and substrate) (W/m^2). The third term refers to the convective heat transfer among leaves and the air within the canopy (W/m^2), while the fourth term takes into account the latent heat exchange due to leaves transpiration (W/m^2).

Alexandri & Jones approach. The energy balance equation for the foliage is:

$$\rho_l c_{pl} \Delta x \frac{dT_l}{dt} = \frac{\rho_a c_{pa}}{r_{aH}}(T_a - T_l) - \frac{\rho_a c_{pa}}{\gamma}\frac{e_s(T_l) - e_a}{r_a + r_s}$$
$$+ \left[I(1+\alpha_s)(1-\alpha_l) + \sigma T_{sky}^4 + \sigma \varepsilon_s T_s^4 - 2\sigma \varepsilon_l T_l^4\right] \times \exp[-k_o \mathrm{LAI}]. \quad (2)$$

where ρ_l is the density of the leaf tissue (kg/m3); c_{pl} is the specific thermal capacity of the leaf tissue (J/kg K); T_l is the leaf temperature (K); T_a is the air temperature (K); ρ_a is the air density (kg/m3), c_{pa} is the specific thermal capacity of air at constant pressure (J/kg K); r_{aH} is the convective resistance (s/m); r_a is the aerodynamic resistance (s/m); r_s is the "total stomatal resistance" of the canopy (s/m); $e_s(T_l)$ is the saturation at the leaf temperature (Pa); e_a is the vapor pressure in the "bulk air" (Pa); α_l is the leaf albedo; α_s is the substrate albedo; T_{sky} is the sky temperature (K); T_s is the surface soil temperature (K); k_o is the extinction coefficient; LAI is the leaf area index.

The first term on the right end side expresses the convective heat transfer between leaves and the air within the canopy (W/m^2). The second term refers to the latent heat exchange between leaves and air due to leaves traspiration (W/m^2). The third term expresses the net radiative exchange (shortwave e longwave) of leaves with the surrounding environment (W/m^2).

Sailor approach. As Palomo del Barrio and Alexandri&Jones, also Sailor seems to adopt the same approach to the canopy. However, he divides the surface roof area in the two following areas: one entirely covered by leaves that occupies a roof fraction equal to σ_f, and an area totally exposed to the sun that occupies a roof fraction equal to 1- σ_f. The energy balance for the foliage is therefore the following:

$$F_f = \sigma_f\left[I_s^{\downarrow}(1-\alpha_f) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^4\right] + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1}(T_g^4 - T_f^4) + H_f + L_f \quad (3)$$

where F_f is the net heat flux into the vegetation (W/m^2); σ_f is the fractional vegetation coverage; $I_s^{\downarrow}$ is the solar radiation incoming (W/m^2); α_f is the canopy albedo; ε_f is the canopy emissivity; ε_g is the soil emissivity; ε_1 indicates the quantity ($\varepsilon_g + \varepsilon_f - \varepsilon_g \varepsilon_f$); $I_{ir}^{\downarrow}$ is the longwave radiation incoming (W/m^2); σ is the Stefan-Boltzmann constant (5,67 x10^{-8} W/m^2 K^4); T_f is the foliage temperature (K); T_g is the soil surface temperature (K).

The expression on the right end side is composed of four terms: the first and the second one express the net radiative exchange of leaves with the surrounding environment. In more detail, the first one expresses the balance of radiation fluxes (shortwave e longwave) incoming and radiation fluxes outgoing, as that it provides the net radiation absorbed by the foliage. In this term the presence of the soil is neglected. the presence of the substrate is taken into account in the second term that represents the equation commonly used for the radiative exchange between infinite and parallel surfaces. In other words, it expresses the radiative exchange between leaves and the substrate. The third term expresses the sensible heat flux between the vegetation and the air within the canopy (W/m^2). The fourth term refers to the latent heat exchange due to leaves transpiration (W/m^2).

As observed, each of these foliage models consists of sub-models describing respectively radiative exchanges (shortwave and longwave), convective exchanges and latent heat exchanges due to transpiration occurring in the vegetation.

In the following a critical comparison among the algorithms proposed by Palomo del Barrio, Sailor and Alexandri & Jones for each of these components of the energy balance of a canopy is presented.

4. A comparison among canopy's models by components of the canopy's energy balance

Solar radiation absorbed by leaves. As far as the shortwave radiation exchanges between leaves and sun is concerned, Palomo Del Barrio distinguishes among the solar radiation transmitted by the canopy; the solar radiation reflected by canopy, and the solar radiation absorbed by the canopy.

The shortwave radiation absorbed by the canopy that is responsible of the thermal status of the leaves is calculated as a fraction equal to [1 – (canopy shortwave transmittance)-(canopy albedo)] of the global solar radiation that the canopy receives. This one, on turn, is a summation of the solar radiation at the top of the canopy and of the solar radiation reflected by the soil surface after having been transmitted by the canopy.

Sailor instead, simply distinguishes between solar radiation reflected by the canopy and solar radiation absorbed by the canopy. There is no reference in the algorithm proposed to the shortwave radiation transmitted by the canopy. Therefore, the shortwave radiation absorbed by the canopy is simply estimated as a fraction equal to [1- (canopy albedo)] of the total incoming shortwave radiation.

This might be due to the use of the fractional vegetation coverage (σf) that represents the area of the roof which is directly covered by one or two leaves, instead of LAI.

Alexandri and Jones propose an algorithm apparently not very clear. More precisely, the shortwave radiation absorbed by the canopy is calculated by multiplying two terms, that is: one term refers to one leaf and represents the fraction of the solar radiation absorbed by one insulated leaf which, by the way, doesn't transmit (only the leaf albedo is considered) while the second term referring to the foliage density of the canopy (LAI) is supposed to take into account the presence of the other leaves. This algorithm is quite similar to that one proposed by Palomo del Barrio as regards parameters involved except for the fact that they consider the leaf albedo instead of the canopy albedo.

Radiative heat exchange among leaves and between leaves and environment. As far as the thermal exchange of leaves with the surroundings (sky, soil, leaves) is concerned, Palomo Del Barrio distinguishes between the long-wave radiation transmitted by the canopy and the long-wave radiation absorbed by the canopy. Since the leaves of the canopy typically behave as black bodies towards the long-wave radiation [25], the canopy will transmit only the thermal radiation which is not intercepted by the leaves. While what is intercepted, will be totally absorbed. The long-wave radiation absorbed by the canopy, responsible of the thermal status of the leaves, is thus calculated by Palomo del Barrio as a fraction equal to [1 – (canopy longwave transmittance)] of the long-wave radiation that the canopy receives. This one, on turn, is a function of the net thermal radiant exchange between the leaves and the surfaces that the leaves see, that is: the sky and the soil. In the algorithm proposed by Palomo del Barrio to estimate such contribution to the energy balance of leaves the emissivity coefficients of leaves and soil are assumed equal to 1. In other words, they are not input parameters of this model.

The algorithm proposed by Sailor to estimate the net long-wave radiation absorbed by the vegetation is formally different; it consists of two terms: one takes into account the radiant exchange between leaves and the atmosphere and the other one the radiant exchange between leaves and the soil surface. More precisely, regarding the first term, the equation usually used for the radiant exchange between a horizontal surface and the surrounding environment has been utilized. Regarding the second term, the equation usually used for the radiant exchange between two flat infinite parallel surfaces has been adopted. In this algorithm the emissivity coefficients of leaves and soil represent input parameters.

Alexandri and Jones propose an algorithm apparently not very clear. More precisely, the longwave radiation absorbed by the canopy is calculated by multiplying two terms, that is: one term refers to one leaf and represents the longwave radiation absorbed by one insulated leaf while the second term, $e^{(-ko\ LAI)}$ referring to the foliage density of the canopy (LAI) is supposed to take into account the presence of the other leaves. This algorithm is quite similar to that one proposed by Palomo del Barrio as regards parameters involved except for the fact that they consider the emissivity coefficients of leaves and soil represent input parameters.

Convective heat exchange between leaves and the air inside the canopy. As far as the evaluation of the convective heat transfer between the leaves and the air within the canopy is concerned, Palomo del Barrio applies the well-known Newton's law for heat convection. In case of convection within the canopy a new parameter is introduced in such law, that is: the "canopy external resistance" that represents a sort of mean canopy resistance to the sensible heat transfer (this parameter should refer to various boundary layer resistances to sensible heat transfer of leaves). Such parameter is linked to the well known convective coefficients, commonly indicated with "h" (W m^{-2} K^{-1}) in literature, by means of the following relationship:

$$h = \rho cal / raH. \qquad (4)$$

Moreover, in case of convection heat transfer within the canopy another parameter is introduced to account for the exchange surface between leaves and the surrounding air, that is: LAI index.

Sailor applies instead the "bulk formulae" which relate the thermal fluxes (both latent and sensible) with directly measurable variables. In particular, based on this other algorithm, such thermal exchange is basically influenced by the difference in temperature between foliage and near canopy air, by the leaf area index (LAI) and by the wind speed.

Alexandri and Jones propose an algorithm that is analogous to the one proposed by Palomo del Barrio. More precisely, parameters involved are the same of those present in the Palomo del Barrio one for the convective heat transfer LAI apart which is not present.

Evapotranspiration in canopy leaves. The algorithm for estimating the energy flux consumed to let water evaporate in leaves (known as "leaves evapotraspiration") proposed by Palomo del Barrio is analogous to the one used for determining the convective exchanges between the leaves and the canopy air, but in this case the flux is influenced by the difference of vapour pressure at the leaf surface and at the canopy air. The algorithm further introduces a new parameter, that is: the mean canopy resistance to latent heat transfer. It is given by the sum of the "canopy external resistance", previously introduced, and the so called internal resistance to vapour transfer of the canopy or "bulk stomatal resistance" . It seems remarkable to note at this point, that actually it is not really clear the reason why for calculating the mean canopy resistance to latent heat transfer this algorithm reports the "canopy external resistance" which was introduced for estimating the sensible heat transfer between canopy and canopy air. A new parameter that is the aerodynamic canopy resistance referring to the latent heat transfer should be used instead.

Sailor proposes again the "bulk formulae" but, in this case, the flux is influenced by the difference of vapour pressure at the leaf surface and at the canopy air. Furthermore, this algorithm introduces a new parameter, the so called "surface wetness factor" (r'') which takes into account both the stomatal resistance (rst) and the aerodynamic resistance (ra). More specifically, it is a ratio of the aerodynamic resistance to the total resistance.

Alexandri and Jones propose an algorithm that is analogous to the one proposed by Palomo del Barrio. Parameters are the same of those present in the Palomo del Barrio algorithm apart from LAI which is not present. Furthermore, another difference is represented by the aerodynamic canopy resistance referring to the latent heat transfer which is used in their algorithm, unlike in Palomo del Barrio one.

We report in the following section first results of an experiment concerning a green roof in Sicily and composed by different vegetal species and substrates. The experiment is mainly aimed at defining the proper thermal boundary conditions to which a canopy apparatus is subjected, in terms of outdoor air and ground temperatures, during the year.

5. An experimental approach to the green roofs canopy

The experimental green covering has been realized in the framework of the ARCOVERDE project, funded by the Ministry of Agricultural and Forestry Policies. It is located in Bagheria (Palermo), Italy, in a small office building of the CRA (Agricultural Research Centre) [26].

The roof is divided in 6 sectors to study the influence of two different parameters: the thickness of the water storage layer and the type of vegetation. Three different types of vegetation have been utilized, that is: a) Halimione portulacoides, b) Rosmarinus Officinalis Prostratus, c) Crithmum Maritimum.

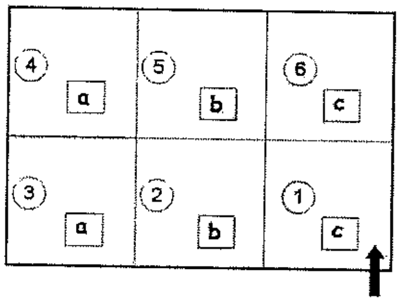

Figure 2. Coupling of vegetable species with the sector.

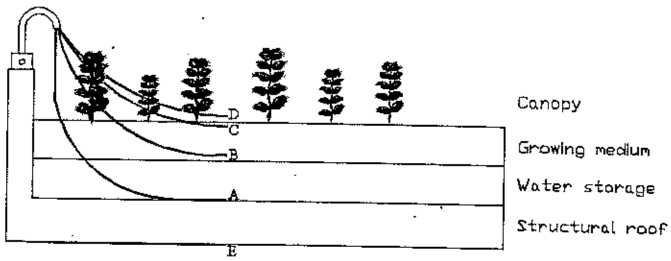

Figure 3. Different depths of the thermocouples.

The system has been installed on March 2010, while it has been monitored from October 2010 to March 2012. The monitoring system consists of 30 copper-constantan thermocouples, 5 for each sector, located at different deepness, as shown in figure 3. Furthermore a weather station records the outdoor air temperature.

Results are presented for two sectors of the experimental apparatus that differ by the covering intensity of the leaves. In particular, sector 1 refers to a more intense foliage (nearly 100% of coverage), while the third sector refers to a foliage that covers almost 70% of the sector surface.

Results are reported for typical months respectively of the winter (January) and summer (July) seasons. Each graph of figures 4 and 5 reports the monthly behaviour of temperatures referring to air, the inter-canopy space and the ground.

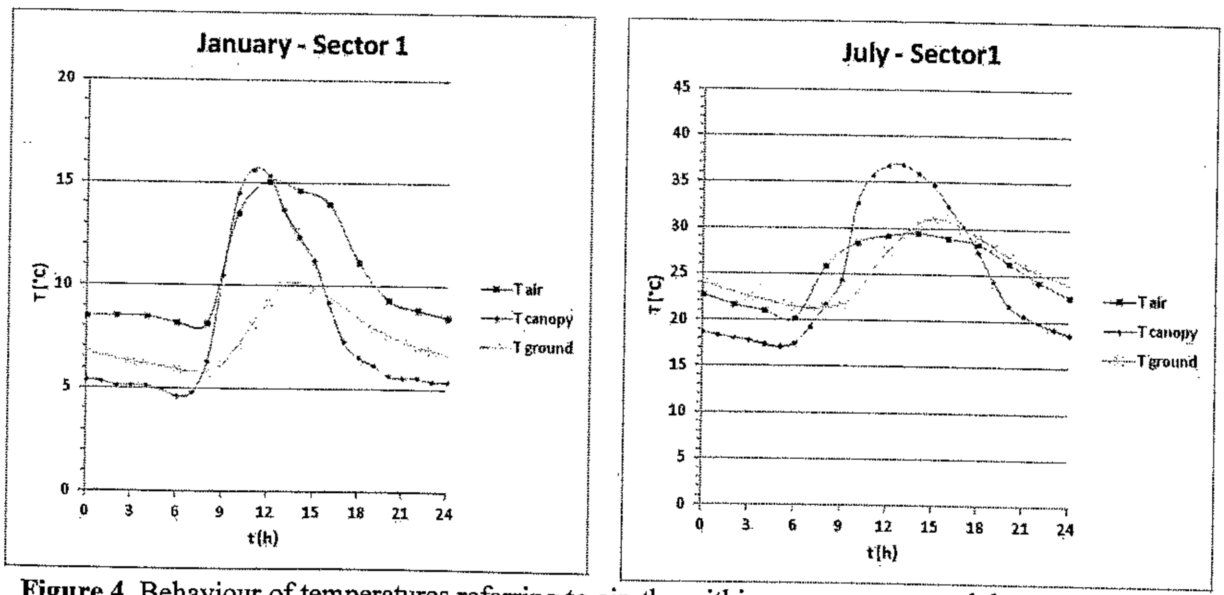

Figure 4. Behaviour of temperatures referring to air, the within-canopy space and the ground during the mean monthly days of January and July in the sector 1.

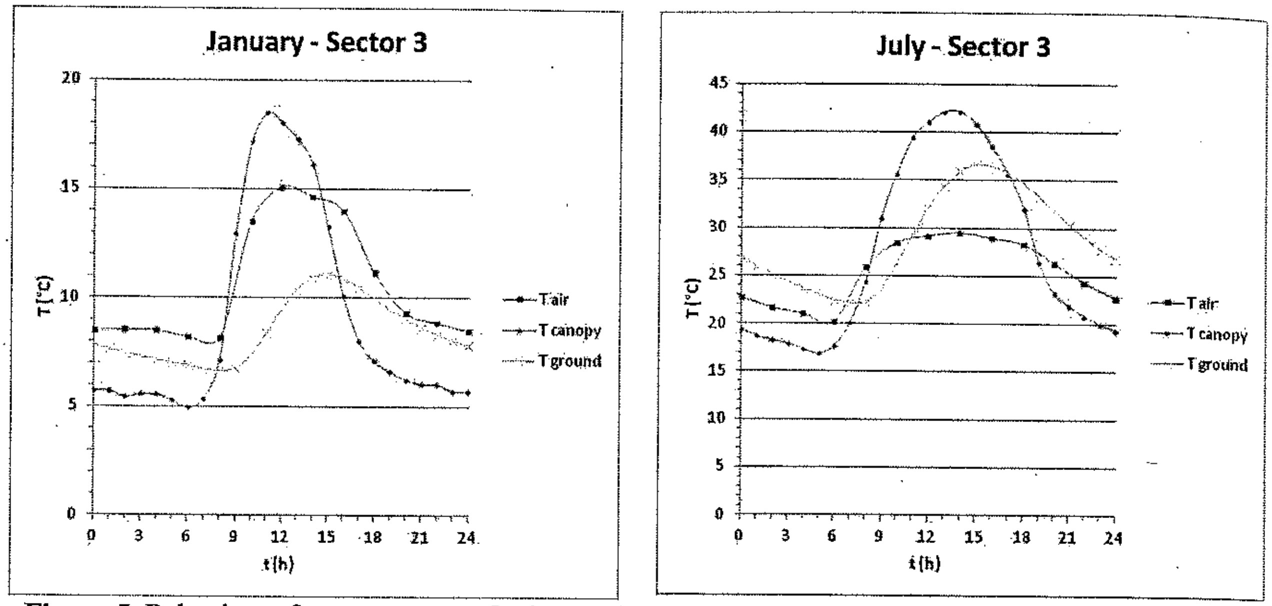

Figure 5. Behaviour of temperatures referring to air, the within-canopy space and the ground during the mean monthly days of January and July in the sector 3.

Air and ground temperatures can be here assumed as the thermal boundary conditions for the control volume represented by the canopy apparatus.

As it is possible to see, the most foliage intense sector shows a smoother behaviour of temperatures in July, due to shadowing effects of the leaves, with respect to the less intense one. On the other hand, in winter a less intense foliage allows sun to better reach the surface, in this way inducing higher temperatures to the ground that, in turn, will result in better indoor thermal conditions for occupants. In figure 6, a comparison is proposed between the inter-canopy temperatures of both sectors, in the months of January and July.

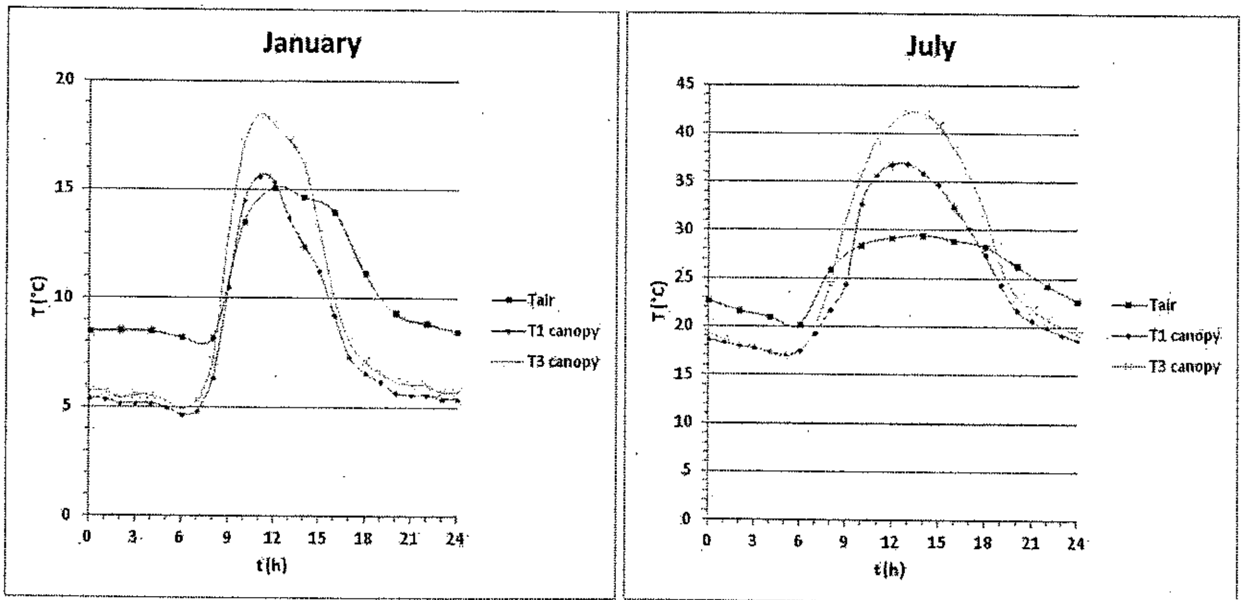

Figure 6. Comparison of the behaviour of temperatures referring to air and the within-canopy space during the mean monthly days of January and July in the sectors 1 and 3.

From these graphs, it is particularly evident the different behaviour of the two sectors, depending on their different shadowing properties of the direct solar radiation. In fact, the most intense foliage sector presents a maximum temperature in January about 3 °C lower that the less intense one; it also shows a maximum temperature about 5 °C lower in July than the less intense one. Clearly, this behaviours will induce different conditions to the indoor temperatures of the room on which the green roof is installed, since a less intense foliage presents a better performance in winter and a worse one in summer. These first results, apart the need for further verifications, suggest interesting considerations concerning the choice of the vegetation to be adopted for green coverings that can be assumed as an effective issue in buildings design.

6. Conclusions

Through this work a critical review is presented of the most effective algorithms aimed at the modelling of the thermal exchanges within the canopy of green roofs.

Despite the complex appearance of these algorithms, they are actually based on a very simplified approach that, for example, does not take in due account the radiation profile occurring within the foliage apparatus. On turn, the detailed analysis of this radiation profile, would enable a better knowledge of the whole thermal exchanges of this building component.

At this stage of the research, it is not possible to select an effective algorithm to be included in the mathematical models of the energy performance of buildings. In fact, on one hand, the level of detail of the available algorithms is too low compared with the ones concerning the modelling of the other parts of a building; on the other hand, if one would select a simplified algorithm in order to include green roofs in the typical energy certification schemes, the available ones are actually too complex for the simple approach required by the certification procedures. In other words, the level of the research in this field seems to be in the middle of a river. Clearly further researches and analyses are required on purpose.

With the aim of providing a contribution in this attempt, we report here first results of an experimental concerning a green roof installed in Sicily and composed by different vegetal species and substrates. The experiment is mainly intended for the definition of the thermal boundary conditions of the volume of control represented by the canopies, to be analysed. Early results of this experiment suggest interesting considerations concerning the behaviour of different green roofing in summer and in winter, so calling for a deep attention in the selection of the vegetal species in the design of these building components.

On the other hand, these results, compared with those provided by the current mathematical models, can offer some contribution toward the definition of a simplified, but accurate enough, algorithm for vegetated roofs to be included in the (simplified) methods for the energy certification of buildings.

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