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Thermal inertia assessment of an experimental extensive green roof in summer conditions

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ABSTRACT

Passive solutions for building envelopes such as green roofs are regarded as promising tools to reduce the energy demand for buildings air-conditioning and to improve the thermal comfort of indoor spaces. It is therefore necessary to quantify and assess properly the summer thermal performance and to determine how a green roof cover can attenuate and delay the temperature and heat flux acting on its surface. The paper deals with an experimental investigation of the dynamic thermal characteristics of a vegetated roof situated on a university building roof in south Italy. An analysis of the daily values of dynamic parameters showed a quite stable trend of the decrement factor with variation in the range 0.0982–0.1920. The time lag exhibited a trend ranging from 7.2 h to 8.5 h. A successive analysis was developed decomposing the trends of temperature into Fourier series to assess the response of the vegetated systems to solicitations of different frequencies and to assess the deviations, in the calculation of the dynamic parameters, arising from considering a sinusoidal variation with a 24 h period of the external forcing, in accordance with the International Standard EN ISO 13786, compared to the experimental values. The green roofs showed a behaviour similar to a high-pass frequency system, and relative errors, by using only the fundamental harmonic under 10% were found for 72.9% of the cases for the decrement factor and for 93.8% of the data for the time lag. Results demonstrated that when climatic conditions of the location are more irregular then the predictions of the dynamic parameters considering only the fundament harmonic instead of the real trend of the forcing can provide more relevant errors.

1. Introduction

Environmental issues related to greenhouse emissions and climate change are nowadays a cardinal concern in worldwide national policies. In this context it is reported that in the European Union, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions and also that approximately 35% of the EU building stock is over 50 years old, therefore improving the energy efficiency of buildings can significantly contribute to lower CO_2 emissions [1]. The quest for the reduction of primary energy demand for buildings air-conditioning has spurred researchers and companies to investigate innovative energy systems and passive technologies to improve the thermal performance of building envelopes [2]. An important passive solution is represented by green roofs. Even though they have been used since ancient times mainly for aesthetical reasons and for their resistance to natural elements such as rain precipitation and fire, in recent years vegetated roofs have drawn attention because of the numerous benefits that they are able to produce. They improve stormwater management and reduce urban runoff [3,4] [5–7]. Vegetated surfaces are believed to actively contribute to Urban Heat Island mitigation [8–10] as also demonstrated by Alexandri et al. [11] which showed that covering a building envelope with vegetation can produce important potential lowering of urban temperatures. Green roofs present additional benefits, often difficult to quantify in technical and economical assessment such as the ability to improve of buildings aesthetical appearance and to create new and pleasant recreational areas in workspaces. They can contribute to the liveability of urban areas strengthening social cohesion, providing space for everyday renewal and restoration, softening the hard cityscape and increasing the biodiverse nature in the middle of built environments [12]. Most importantly, green roofs can produce important energy saving of the heating and cooling demand for a building air-conditioning [13,14]. In this regard, several authors have investigated the thermal performances of vegetated surfaces with different approaches in different climate conditions. In Ref. [15] the authors conducted simulations of a single-family house with both a conventional and a green roof. They found a maximum reduction of the mean indoor air temperature of 2.6 °C in Athens and a total energy demand reduction of 32% in the Mediterranean climate, of 6% in a

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temperate climate and of 8% in a cold climate. Getter et al. demonstrated how an extensive green roof influences temperatures and heat fluxes in the roof during different seasons of the year, with a reduction of heat fluxes, through the building envelope, by an average of 13% in winter and 167% in summer compared to a traditional gravel insulated roof [16]. Gagliano et al. [17] conducted an investigation to evaluate and compare the energy saving potential of different retrofitting strategies involving green roofs. They found that green roofs can reduce the energy demand for cooling more than for heating. Furthermore, their results highlighted that green roofs guarantee indoor thermal comfort and generate a lower outer surface temperature being an effective tool for UHI mitigation. In a cold climate, the results of [18] showed that an extensive green roof is sufficiently capable of protecting the roof membrane from extreme temperatures and provides effective thermal insulation in winter. Also in Ref. [19] the analysis showed that green roofs are effective in reducing heat flow through the roof and reducing the energy demand for building space conditioning.

What ultimately emerges from the literature is that the performance of a green roof strongly depends on the climatic condition of the locality and on the properties of the building envelope. It may occur that, in summer, the additional thermal resistance of the green layers limits the night heat exchange of the indoor environment toward the outdoors through the roof surface, especially in the case of high-insulated buildings, generating a higher temperature of the bottommost layers and impeding the night cooling of the interior spaces. This can consequently result in an increased energy load for cooling in the summer season [20]. In this regard in Ref. [21], the authors proposed and analysed the performance of an active green roof capable of producing variable insulation thanks to a plenum between the green roof and the indoor space and fans operated with a temperature control. They also performed parametric simulations of green roofs with different leaf areas, soil depth, and insulation thickness in different climates to assess the energy saving potential for cooling and heating purposes. The results demonstrated the validity of the proposed system in terms of both indoor air temperature and energy saving potential. In Ref. [22] a novel solution that employ the use of a water-to-air heat exchanger to improve the indoor thermal comfort in buildings with green roofs was presented and tested. The analysis showed very promising results with the system able to reduce the building cooling energy demand.

Although the research conducted in the last few years has demonstrated the undisputed beneficial summer performance of vegetated roof beyond doubt, however, the performances in winter period are reported to be controversial where some authors claim no benefits [15] or even a worsening of the building thermal load [23,24]. Conversely, in hot summer days, when solar irradiation is relevant, the shading of the vegetation layer and the evapotranspiration phenomena lead to considerable low surface temperatures with consequent impact on the thermal load of the underlying indoor spaces and on the surrounding air temperature. In warm climates, an additional advantage of a vegetated roof is the increased thermal inertia that markedly influences the thermal behaviour of the building since the energy performance depends significantly on the thermal mass of the building envelope components. The high thermal mass and heat capacity induces a reduction and a time delay of the cooling load peaks.

In summer conditions indeed, the building external surface temperature fluctuates with a wider amplitude around the set point temperature maintained in the indoor environment. In this condition, the external forcing generates an irrelevant value of the steady heat flux component but a conspicuous fluctuating heat flux component instead. Consequently, the thermal capacitive effects of the building envelope play a cardinal role rather than the thermal resistive effects. In winter, conversely, the elevated difference between the steady component of the external surface and indoor air temperature produces a relevant steady heat flux through the envelope. In this case, the thermal capacity does not play a main role.

It is therefore important to quantify the summer thermal performance of a green roof determining the dynamic thermal characteristics appropriately. In this context, for traditional envelope components, the dynamic characterization procedure is given by the International Standard EN ISO 13786 [25]. The properties considered by the Standard are thermal admittances and thermal dynamic transfer properties, namely the periodic thermal transmittance, the decrement factor and time shift. These parameters are determined considering a sinusoidal variation of the external air temperature or a heat flux, of unitary amplitude and period equal to 24 h. Thermal dynamic transfer properties relate physical quantities relevant to one side of the component to those relevant to the opposite side. Many authors have dealt with the dynamic thermal characterization of the building envelope both theoretically and experimentally. The main objective of these works was to evaluate the influence of the thermophysical properties, thickness and placement of the wall layers, of the wall orientation, of the surface heat transfer and surface optical properties of the wall, and of the location on the dynamic parameters defined in terms of temperature or heat flux [26–31]. In other studies, the analysis of the dynamic behaviour of the external walls was extended in actual operating conditions, by using the actual trends of the convective and radiative heat fluxes acting on the internal and external surfaces of the wall [32,33].

Although different investigations on green roofs performances have been reported, only few studies consider and quantify the dynamic thermal characteristics of vegetated roofs. In Ref. [34] the authors calculated an equivalent dynamic thermal parameter for green roofs through a mathematical approach, based on the standard EN ISO 13786. Through the calculation model implemented in EnergyPlus they obtained the conductive heat flux through the inner surface and considering an equivalent external temperature they calculated the equivalent dynamic thermal transmittance. Results demonstrated that design parameters influencing the equivalent parameter were LAI value and soil thickness. They also found that the thermal transmittance was always lower than $0.12\ W/(m^2\ K)$. Gagliano et al. [35] calculated the time lag and decrement factor starting from experimental data measured on a prototype of an extensive green roof installed on an existing roof in Southern Italy. Their measurements, carried-out during a summer period, were used as input to perform simulations to obtain the outer surface temperature for the existing traditional roof and the green roof prototype. Simulations results were also used to determine the dynamic parameters in free floating conditions during the warmest day of the period considering the sol-air temperature as external forcing. For the green roof, the results showed a decrement factor almost exactly double that of a traditional roof.

In this context, the present work deals with a comprehensive experimental dynamic characterization in summer condition, in a Mediterranean climate, of an extensive green roof with the aim of assessing thermal inertia properties. Measurements carried out during four summer months were used to determine experimentally the dynamic parameters of three different green roof solutions installed in the experimental site and to evaluate the daily variations according to the weather conditions. The same parameters were also evaluated for characteristic days obtained as an average of weekly values of the main thermal variables of the layers. Finally, the temperature trends were decomposed as Fourier series in order to assess the influence of the different harmonics of the signal in the determination of the dynamic parameters of the whole green roof system.

2. Methods

2.1. Experimental site and climatic conditions

The experimental site is located on the roof of a building of the Department of Mechanical, Energetic and Management Engineering of the University of Calabria in Cosenza (Italy). Cosenza is situated in Southern Italy, where the climatic conditions are typically