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ScienceDirect

Energy Procedia 78 (2015) 1556 – 1561

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Combined thermal effect of cool roof and cool façade on a prototype building

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Abstract

Recently, huge efforts were made to develop new passive solutions for optimizing building summer thermal-energy behavior. While cool roofs are well investigated, a lack of knowledge is detected about the benefits deriving from the combination of cool roofs and cool façades. This work aims at determining the thermal performance of innovative cool roofing membrane and cool façade painting when applied on a prototype building, through continuous monitoring. Additionally, sensitivity analysis is performed to investigate the thermal benefits of the coupled solutions. Results showed that the combined solutions generate significant passive cooling in terms of indoor operative temperature reduction.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Cool roof; Cool façade; Continuous monitoring; Building thermal-energy performance; Sensitivity analysis.

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1. Introduction

Urban Heat Island (UHI) is a well acknowledged urban microclimate phenomenon [1] characterized by higher temperatures in urban areas compared to the surrounding suburban and rural areas [2]. It is due to various factors, such as solar radiation trapping and wind shelters caused by urban street canyon geometry, urban greenhouse effect, diminution of evaporation surfaces and storage of sensible heat in the city fabric, and anthropogenic heat released [3]. Although mitigating the heating energy requirement in winter, UHI increases the cooling energy demand in

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.205

summer. Therefore, in last decades the contribution of air conditioning in buildings energy consumption has been growing [4]. Several studies focused on the development of techniques for mitigating the UHI phenomenon, such as smart materials with high optic-thermal performances [5], increased urban green areas [6], solar shading of urban surfaces [7], cool building envelope materials [8]. The potential of such cool materials has been widely investigated in roof applications, while their capability in mitigating UHI when applied in building façades is still not well acknowledged [2; 9-10]. Findings confirmed the potential of this technique in southern European climatic conditions. Considering cool roof applicability in cold climates, Mastrapostoli et al. [11] observed a decrease of 73% for cooling, with negligible heating penalties, as a result of the application of a cool roof fluorocarbon coating for an industrial building in Oss, Netherlands. In order to compare the performance of such innovative materials under different boundary conditions, dedicated building prototypes have been often used [12-13]. For instance, Doya et al. [13] employed reduced-scale building prototypes in a typical urban canyon configuration to assess the thermal effects of cool façade paints on both building and outdoor environment. Using five dedicated test cells, Revel et al. [14] monitored the thermal performance of cool colored ceramic tiles, acrylic paints and bituminous membranes for both roof and walls [13]. In this panorama, the purpose of this work is to evaluate the thermal effect of two innovative cool solutions for building envelopes, i.e. a cool roof membrane and a façade reflective painting. To this aim, such cool materials were previously experimentally characterized and optimized in-laboratory. Therefore, their performance in terms of achievable indoor comfort conditions was assessed when applied on (i) the roof and (ii) the South-facing façade of a dedicated test-room located in Perugia, Italy. The in-field continuous monitoring of the main thermal and optical parameters was performed. The final objective is to determine the enhancement of the test-room thermal performance associated to the application of the proposed cool coatings compared to traditional test-room building materials, i.e. bitumen membrane and red colored painting. In fact, while cool roof technologies are well investigated if compared to cool façades, a lack of knowledge and research effort is detected about the experimental measurement of benefits deriving from coupling the two solutions. Therefore, the sensitivity analysis of the two envelope strategies was carried out to compare the effects of the combined solutions, i.e. cool roof and cool façade. Finally, first results of the in-field measured albedo of the cool roof membrane were analyzed.

Nomenclature

T_{out}	Outdoor dry bulb Temperature [°C]
T_{op}	Indoor Operative Temperature [°C]
$T_{op, max}$	Maximum hourly value of indoor Operative Temperature [°C]
R^*	Equivalent Reflectance of the building envelope [-]
R_{solar}	Solar Reflectance [%]
A	Size of envelope surfaces, i.e. roof and façade [m^2]
VF	View Factor of the envelope surface to the sky [-]
OP, IP	Output and Input Parameters of sensitivity analysis [-]
OP_{max}, $OP_{min,}$ IP_{max}, IP_{min}	Output Parameter and Input Parameter extremes [-]
SC	Sensitivity Coefficient [-]

2. Materials and methods

The aim of this study is to compare the thermal behavior of the two innovative cool envelope solutions, i.e. cool roof membrane and cool façade painting. Therefore, the two solutions have been applied on a dedicated prototype case study building, i.e. test-room, located inside the university campus in Perugia, Italy. The in-situ continuous monitoring of the thermal-energy performance of the proposed solutions has been carried out under real dynamic boundary conditions during summer 2014. Both the indoor/outdoor thermal characteristics and the roof albedo have been monitored. Firstly, the case study building with non-cool envelope materials, i.e. bitumen membrane and red colored painting, has been monitored as base case scenario. Secondly, the cool membrane has been applied on the test-room roof in order to assess the specific contribution of the cool roof to the thermal performance of the test-room in summer conditions. Thereafter, the cool painting has been applied in the South-facing façade of the same case study building. In this way, the performance of the coupled solutions has been analyzed. Monitored data have been subsequently post-processed in order to compare the thermal effect of the two cool solutions. In particular, the sensitivity analysis has been performed to understand the coupled cooling contribution of the cool roof and the cool South-façade. Three different scenarios for the case study building envelope have been identified:

- Standard scenario (S): the materials implemented in the building envelope are construction techniques commonly used in recent buildings in Italy. In particular, the roof is covered with a bituminous black membrane and the walls with a red colored traditional painting;
- Cool Roof scenario (CR): the innovative cool roof membrane is applied over the existing membrane of the case study building Standard scenario;
- Cool Roof and Façade scenario (CR+F): the further innovative cool façade painting is applied on the South-facing façade of the case study building Standard scenario.

2.1. Cool roof membrane and cool façade painting

The innovative cool roofing membrane is a polyurethane-based waterproof liquid white membrane with high elasticity. The cooling potential of such membrane was optimized through iterative laboratory and in-field tests by increasing specific components such as the titanium dioxide (TiO_2) and hollow ceramic microspheres percentage. Therefore, the final optimized membrane presents almost 12% of TiO_2 and 4% of hollow ceramic microspheres.

The proposed cool painting for building façade applications is an almost white non-organic painting, mainly composed by potassium silicate with small percentage of resin. It is characterized by high vapor permeability. Also the painting was optimized through an iterative procedure by increasing TiO_2 and hollow ceramic microspheres percentage. The most performing combination is again with 12% of TiO_2 and 4% of hollow ceramic microspheres.

2.2. Sensitivity analysis

The sensitivity analysis has been performed to define the impact of each proposed solution on the building thermal performance. In fact, sensitivity analysis allows the identification of the more significant variables (high sensitivity) and strategies from both technical and economical point of view [15]. Therefore, the reflectance properties of the roof and the walls represent the input parameters (IP) of the thermal analysis multi-variable problem. The output parameter (OP) chosen for defining the sensitivity coefficient (SC) is the maximum hourly value of indoor operative temperature (T_{op}). T_{op} results are stated as a function (1) of the equivalent reflectance of the building envelope (R^*) that represents the sole IP variable. R^* for the envelope is expressed as the combination of the equivalent reflectance of the different envelope components. The variable R_i^* is a function (2) of the Solar Reflectance (R_{solar}), the surface area (A), and the view factor of surface to the sky (VF) of the *i-th* material. The considered VF for roof and wall are equal to 1 and 0.5, respectively. Such VF values have been defined assuming free field conditions to the sky, even if small obstacles are present. Therefore, the R^* value is slightly overestimated.

$$T_{op,\max} = f\left(x_1; x_2; \ldots; x_n\right) = f\left(R^*\right) \tag{1}$$

$$R_i^* = f\left(R_{solar,i}; A_i; VF_i\right) \tag{2}$$

The differential of the OP is calculated through the equations reported in [15] considering that each IP variable is independent from every other one. The SC expressing the IP role is obtained with (3), considering the maximum OP situation as the base case.

$$SC = \frac{(OP_{\max} - OP_{\min})/OP_{\max}}{(IP_{\max} - IP_{\min})/IP_{\max}} \quad [-] \tag{3}$$

3. Case study and monitoring setup

The case study building consists of a fully instrumented test-room (12 m^2) located in Perugia (Italy), and built following recent construction techniques [16]. Fig. 1 reports the pictures of the roof and the South-facing façade of the case study building before (Fig. 1a,c) and after (Fig. 1b,d) the application of the cool membrane and painting. The experimental setup [16] is composed by (i) an outdoor meteorological station located over the roof of the university building close to the test-room facility (Fig. 1e) and (ii) an indoor station positioned inside the same test-room (Fig. 1f). The meteorological station allows the continuous monitoring of the climate boundary conditions in terms of temperature, relative humidity, wind velocity and direction, rain fall, and solar radiation. The indoor station is meant to measure the main thermal-energy parameters inside the prototype building, i.e. walls and ceiling surface temperatures, air temperature, mean radiant temperature, relative humidity, energy consumption, etc., and the reflected roof radiation for the in-field measurements of albedo. Detailed information is reported in [16].

Fig. 1. Case study building: (a, b) roof configurations; (c, d) façade configurations; (e) outdoor and (f) indoor microclimate monitoring setup.

4. Results and discussion

4.1. Albedo

The analysis of the optical properties of the two roof coating solutions has been carried out by comparing the in-field mid-day albedo measured during summer 2014. The comparison between the black bituminous membrane and the cool membrane highlights the higher solar reflectance of the innovative cool membrane. Although the average albedo measured during the monitoring period for the proposed membrane is equal to 51%, the albedo increases by about 80% if compared to the bitumen membrane (11%). Such increased albedo results in an improved shield to the heat gains through the roof, as thoroughly expressed in the following analyses. Additionally, the in-field monitoring over time showed a slight reduction (4%) of the cool roofing membrane albedo due to weathering and aging effects. Further analyses of such phenomenon are still on going.

4.2. Thermal performance of the prototype case study building

Further analyses have been performed on the influence of the implemented cool solutions on the indoor/outdoor thermal properties of the test-room. The results show that with equivalent outdoor air temperature conditions the cool roofing membrane is able to decrease the indoor operative temperature of the prototype building by a maximum of 2.6°C (11%) in the hottest day. Whereas, the further application of the cool painting on the South-facing façade of the test-room generates a lower reduction in the indoor operative temperature, i.e. 0.5°C (2%). Consistent and slightly lower differences have been obtained in terms of mean radiant temperature decrease in the CR scenario and the CR+F scenario, compared to the S scenario. Therefore, the passive cooling potential of the cool roof membrane is significant. Whereas, the effect due to the cool façade painting is reduced, when applied together with an already effective solution, i.e. cool roof. The results are depicted in Fig. 2, which shows the distribution of indoor operative temperature with respect to the outdoor dry bulb temperature for the three scenarios. Finally, the combined effect of the cool painting and cool roofing membrane generates a maximum indoor passive cooling effect of 3.1°C (13%) in terms of indoor operative temperature. Additionally, the cool roofing membrane is able to cool the external roof surface up to 19.8°C (55%), and the internal ceiling up to 3.4°C. Non-negligible results are detected for the cool painting in terms of surface temperatures. It is, indeed, able to reduce both the external and internal surface temperature of the South-facing wall up to 9.9°C (25%) and 4.4°C, respectively.

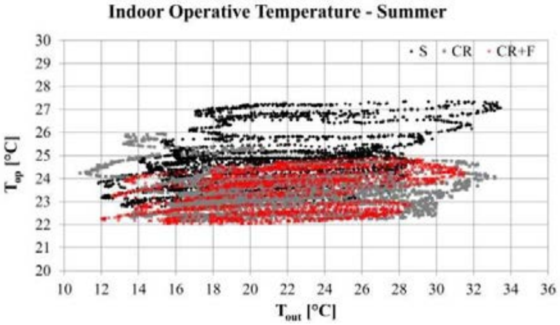

Fig. 2. Distribution of indoor operative temperature vs. outdoor dry bulb temperature for the three scenarios during the monitoring period.

4.3. Sensitivity analysis

The sensitivity analysis has been carried out to compare the effect of the two cool envelope solutions and of their coupling on the indoor thermal conditions of the case study building. To this aim, the equivalent reflectance of the building envelope has been assumed as the only IP. The S scenario corresponds to the lower solar reflectance value, the CR scenario to the medium one, while the CR+F scenario presents the higher reflectance. Fig. 3 reports the results in terms of maximum hourly value of indoor operative temperature, the OP, during the monitoring period.

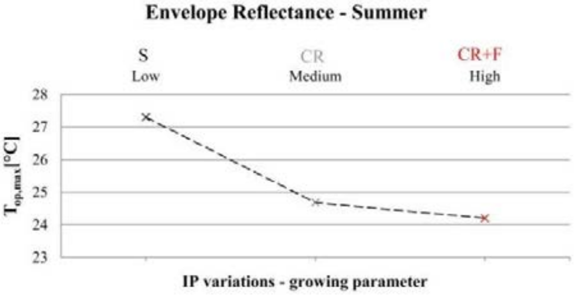

Fig. 3. Sensitivity analysis results for the maximum hourly value of indoor operative temperature during summer period.

Findings are consistent with the above mentioned results of indoor thermal behavior. The graph indicates the effectiveness of the cool roof membrane in reducing the maximum indoor operative temperature, stressed by the high slope of the line between the S and the CR scenario. Moreover, the lower line slope between the CR and the CR+F scenario confirms the minor contribution of the cool façade painting in the indoor passive cooling. In particular, the two coupled solutions optimize the thermal performance of the case study building. Nonetheless, the comparison among CR and CR+F results shows limited discrepancies in terms of indoor thermal comfort.

5. Conclusion

In this paper, the benefits deriving from the applications of two passive cooling strategies for building envelope, i.e. cool roof membrane and cool façade painting, were evaluated and compared. To this aim, a continuous monitoring of the thermal performance of a prototype building, i.e. test-room, was performed, after the application of both the proposed solutions on (i) the roof and (ii) the South-facing façade of the building. Finally, a sensitivity analysis was carried out in order to quantify the effectiveness of the two solutions in improving the indoor thermal conditions of the case study building by considering both the separate and combined contributions.

The results showed that the only cool roof membrane is able to decrease up to 2.6°C (11%) the indoor operative temperature. The combination of the two cool solutions leads to an overall temperature reduction of 3.1°C (13%). Additionally, the application of the only cool membrane is able to guarantee a 19.8°C (55%) decrease of the external roof surface temperature, while the further surface temperature reduction generated by the cool façade painting is equal to 9.9°C (25%). Therefore, this study demonstrates how the passive cooling contribution of the proposed façade painting to the enhancement of the indoor thermal performance of the test-room is relatively limited with respect to the cool roof effect in terms of operative temperature decrease. However, the contribution of the cool façade is not negligible in terms of surface temperature of the case study building. Moreover, findings of this study stress how this solution, i.e. the cool façade, deserves much more investigation as future developments of this research. The possible effect in reducing building façade temperatures in urban areas, and its role in mitigating urban heat island phenomenon should be assessed more in detail. The combination of the two innovative solutions, indeed, best optimizes the thermal behavior of the test-room.

Acknowledgements

The authors would like to thank the CVR s.r.l. company for providing the samples for the laboratory measurements and assisting the experimental set up. The first author acknowledgments are due to the “CIRIAF program for UNESCO” in the framework of the UNESCO Chair “Water Resources Management and Culture” for supporting her research.

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