Impact of retro-reflective materials as urban coating: a theoretical study through simulations

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Abstract

The use of retro-reflective materials has been recently proposed as a strategy to mitigate the urban overwarming by increasing the solar irradiation reflected out of the urban environment. The hereby study focuses on the definition of a methodology to estimate the impact of retro-reflective coatings through a comparison with other surface treatments such as traditional and high-reflective materials. The case study is an urban canyon located in Milan (Italy). Firstly, the impact given by the geometry and the canyon's orientation was investigated. Secondly, traditional, diffuse high-reflective and retro-reflective materials were applied to the façade and to the street. The outcomes demonstrated how the retro-reflective layer could perform better than the high-reflective when applied to the street in wide canyons, increasing by four times the solar irradiation reflected towards the sky dome. Conversely, the retro-reflective façade turns out to be more performant in narrow urban canyon models.

Introduction

Urban densification can be seen as one strategy to achieve sustainable objectives from an economic, social and environmental point of view (Lima, Scalco and Lamberts, 2019). However, densification also presents some drawbacks when it comes to energy use for building climatization. Both cooling and heating energy use are demonstrated to be influenced by the urban context because of mutual solar inter-building reflections, and by the so-called urban heat island (UHI) effect (Hassid et al., 2000; Santamouris, Paraponiaris and Mihalakakou, 2007; Santamouris et al., 2015; Allegrini, Dorer and Carmeliet, 2012; Santamouris, 2014; Xu et al., 2018). Several studies have revealed that the energy use in standing-alone buildings is lower than the amount calculated for the same building if included in a built context (Hassid et al., 2000; Santamouris, 2014; Santamouris et al., 2015). It was demonstrated that the average increase in cooling demand is around 23%, whereas the corresponding average reduction of heating demand is around 19%. In total, the average energy demand of building appears to increase by more than 10% by including UHI-related thermal loads (Santamouris et al., 2015). Other related consequences to the urban overwarming are represented by the reduction of natural ventilation, as well as the worsening of the air quality (lower pollutant dispersion) and people's health (Stathopoulou et al., 2008; Santamouris and Kolokotsa, 2015).

Cool materials have been recently proposed (i.e. high-reflective façades, cool paving, etc.) to lower the fraction absorbed by buildings and reduce UHI effects (e.g. increment of outdoor temperature, high energy demand for cooling), although they increase the amount of solar irradiation reflected within the canyon boundaries. On the one hand, evidence from different researches proved that outdoor air temperature values can be lowered by around 5°C in urbanized areas by applying high-albedo materials. On the other hand, these surface treatments contribute to increasing the number of solar inter-building reflections (Han, Taylor and Pisello, 2015) and the amount of solar irradiance that is trapped at the bottom of the urban canyon (UC).

In this scenario, retro-reflective (RR) materials have been introduced as a subgroup of high-reflective (HR) layers (Rossi et al., 2014), and proposed as a potential solution to lower the UHI effect while mitigating mutual shortwave radiative exchanges among buildings. RR materials are able (i) to decrease the mutual inter-building solar reflections, (ii) to reduce the solar energy loads in the UHI boundary, and (iii) to reflect incident solar irradiation back towards the sky dome.

This paper presents an original investigation to assess the potentials of RR materials. It is structured in a background section about the state-of-the-art of RR materials and the definition of research questions and goals. The methodology section describes the workflow developed and used for the analyses, the case study, and the involved parameters. In results and discussion sections the outcomes are presented and commented; finally, a conclusion section summarizes the main findings of the study.

Background

The application of RR layers in the building sector has been only recently explored. In their studies, Nilsen and Lu (Nilsen and Lu, 2004) firstly introduced the use of RR coatings in buildings as a valid and efficient alternative to the traditional materials. In the review article carried out by J. Yuan (Yuan, Emura and Farnham, 2016), RR materials were compared to the HR ones discussing the advantages guaranteed by their application to urban elements (i.e. building's façade, street ground). Nevertheless, the lack of performance standards represents the main barrier to the application of RR materials as urban coatings. During the last decade, several research activities (Sakai, Emura and Igawa,

2008; Rossi et al., 2014; Akbari and Touchaei, 2014; Rossi et al., 2015; Qin et al., 2016) have focused on the characterization of RR materials, ranging from the definition of an assessing protocol to the evaluation of their specific RR properties. Commercial films (prism-array structured), capsule-lens, and bead-embedded layers were analyzed and compared after they have been tested in miniature models of UCs or districts to demonstrate their effectiveness in mitigating UHI (Sakai et al., 2008; Rossi et al., 2014). The measurement facility employed in (Rossi et al., 2015) to test the efficiency of RR materials was equipped with 19 photodiodes (with a 10° wide step, from 0° to 180°), which estimate the reflected fractions in different directions. The outcomes from different samples demonstrated how a RR behaviour can be usually observed when the solar irradiation hits the material mainly perpendicularly, while an HR behaviour is shown in the case of mostly parallel sunrays' direction.

Despite the proven advantages of the different RR technologies, there are still some aspects, which need to be addressed to fully enable the potentialities of these systems. Indeed, the RR materials could present some side effects such as (i) the increment of heating energy requirements in winter, since less solar irradiation is absorbed by the façades; and (ii) the higher lighting pollution level due to the reduction of urban surfaces able to absorb the city lights. To overcome these issues, two materials, which could be classified as selective RR materials, have been proposed by Sakai and Iyota (Sakai and Iyota, 2017), while a new inverse approach has been recently proposed (Manni et al., 2018) to identify optimal selective angular properties of RR surfaces (both horizontal and vertical).

In this scenario, the study presented in this paper aims at giving an original contribution to the evaluation process of RR materials by proposing a methodology to preliminary assess their mitigation potential in different UC environments.

Methodology

The methodology is based on a cluster of solar analyses which separately assess the contributions from direct and diffuse solar irradiation. It is applied to carry out a comparison among traditional, HR, and RR materials. Because of the numerical modeling approach, based on *Radiance*, this paper also investigates the suitability of ray tracing simulation to predict the potentials of the application of RR materials to increase the amount of solar irradiation reflected beyond the canyon. Some representative UC configurations are considered, where RR coatings are applied to street and building's façade.

Workflow and parameters

As reported in Figure 1, the research is structured in two stages. Stage 1 aims at defining the UC models characterized by the highest and the lowest amounts of solar irradiation reflected towards the sky dome in order to provide two geometry configurations where different material patterns can be assessed in Stage 2. The main input parameters are the orientation of the UC, the aspect height-to-width ratio (H/W), and the geographical and

climate information. The output considered during the selection process of the UC geometry configurations is the amount of solar irradiation reflected beyond the canyon by all the surfaces (Irr_{out}).

The solar analyses for Milan latitude were carried out by changing the UC orientation (north-south, east-west, and northwest-southeast) and the H/W (from 0.5 to 1.0, and to 2.0) to explore low, medium, and high urban density patterns. In total, 9 different geometry configurations were investigated (Figure 2). The length of the building fabrics is set to avoid any uncontrolled boundary effects

Figure 1: Overview of the workflow. The main inputs and outputs are reported along with the investigated scenarios for each stage.

in the middle of the canyon during the calculation. This is obtained by multiplying the canyon's width by six. Therefore, the building blocks vary through the study according to the H/W aspect ratio. For an H/W equal to 1.0, the building blocks are 6 m of height (H) x 6 m of width (W) x 36 m of length (L). In case of H/W equal to 2.0, the building fabrics' height is doubled up to 12 m, whereas in the last geometry configuration – H/W of 0.5 – the streets' width is increased from 6 m to 12 m while the height of the building is kept constant up to 6 m (Figure 3).

Figure 2: Overview of the 9 geometry configurations of UC obtained by varying the canyon's orientation and the H/W aspect ratio.

Figure 3: From the left: UC geometry configurations and dimensions in case of H/W equal to (a) 1.0, (b) 0.5, and (c) 2.0.

In the second part of Stage 1, the influences of the solar reflectance parameter (ρ) on the outcomes carried out from the first cluster of analyses were assessed by varying the homogenous ρ value set for the canyon's surfaces from 0.2 to 0.4, and to 0.6. These analyses were conducted for the two extreme scenarios and an intermediate one.

The two case studies selected at the end of Stage 1 were used in Stage 2 to investigate three surface treatments (traditional diffuse, diffuse HR, and RR materials) to be applied to the street and to the façade. The scenario with traditional diffuse materials (named as 'base case') was compared to the ones exploiting HR and RR materials (named as 'cool scenarios'). The output parameter evaluated in this part of the study is the percent variation ($\Delta \text{Irr}\%$) between the Irr_{out} estimated for the cool scenario and the one calculated for the base case.

Material properties and simulated scenarios

A generic Lambertian diffuse coating with a solar reflectance value of 0.2 was used in the selection process

of the UC models in Stage 1. Then, the ρ value was increased from 0.2 to 0.4, and to 0.6 to assess the dependency of the results from the chosen solar reflectance number.

The base case defined during Stage 2 shows traditional diffuse materials from standard *Radiance* library applied to the street (asphalt, $\rho = 0.2$) and to the building's façades (brown painting, $\rho = 0.35$).

As far as the cool treatments are concerned, the wording 'high-reflective materials' identifies a cluster of materials characterized by a solar reflectance higher than 0.90, while the wording 'retro-reflective materials' is referred to a group of coatings able to totally reflect back towards the skydome the solar irradiation impinging on the surface.

Two scenarios were assessed for HR and RR materials depending on their field of application (street or façade). Therefore, the investigated materials patterns are the ones reported in Table 1. In cool scenarios, conventional materials are always applied to those surfaces where HR or RR treatments are not exploited (i.e. to street surface in HR-F scenario).

Table 1: Overview of the material patterns investigated during Stage 2.

Scenario	Applied Material		
	Façade facing south (or east)	Street	Façade facing north (or west)
base case	brown painting	asphalt	brown painting
HR-P	brown painting	HR	brown painting
HR-F	HR	asphalt	brown painting
RR-P	brown painting	RR	brown painting
RR-F	RR	asphalt	brown painting

Simulation tool and data processing

The UC investigated in this study was parametrically modelled in *Grasshopper* environment and it was visualized in *Rhinoceros* to generate different geometry configurations by modifying the algorithm's input values (i.e. H/W ratio, orientation).

The *Diva for Rhino* plug-in, based on *Radiance* engine, was chosen to conduct solar analyses using the .epw weather data climate of Milan (Italy). A grid of test points facing the street was generated by offsetting the ground surface by a distance equal to the building's height. A cells' size of one meter by one meter was also considered (Figure 4).

Figure 4: Grid of test points set for the solar analyses.

Table 2: Set of 'rtrace' parameters employed for conducting solar radiation analyses with Diva-for-Rhino.

Ambient bounces	Ambient divisions	Ambient super samples	Ambient resolution	Ambient accuracy
0/1/5	1,000	20	300	0.1

The *Radiance* simulation parameters were set as shown in Table 2. The outputs are referred to the solar irradiation incident on the test points throughout the year, which has been evaluated both yearly and seasonally. The Irr_{out} is estimated as the specific solar irradiation per square meter impinging the one-meter-wide strip surface located at the middle of the canyon (it permits to avoid boundary effects). The extension of the strip ranges from 6 m² (H/W of 1.0 and 2.0) to 12 m² (H/W of 0.5).

The ambient bounces (ab) value, that counts the number of the solar reflections before the sunray hits the analyzed surface, was set equal to 5 to estimate global solar irradiance composed by diffuse, direct and up to fifth-reflection contribution (Irr_{tot}). This last setting guarantees the ideal compromise between computational time and accuracy of the results when it comes to multiple reflections (Pesenti, Masera and Fiorito, 2018). The values of 0 and 1 for ab were used to calculate the solar incident irradiation component due to direct ($Irr_{dir,inc}$) and diffuse solar irradiation ($Irr_{dif,inc}$). In particular, a weather file customized in *Elements* environment has been generated with null values for the direct sunlight. It has been used in the assessment of the diffuse fraction.

The analyses were conducted with an hourly time-step throughout the whole year. The yearly duration was organized according to the four seasons: spring (March, April, May), summer (June, July, August), fall, (September, October, November) and winter (December, January, February).

Custom *Radiance* materials properties were set considering the parameters of colour (RGB values), specularity (fraction of incident light that is reflected; varying from 0.0 for a perfectly diffusive surface to 1.0 for a perfect mirror), and roughness (surface irregularities quantified by the deviation from its ideal direction of the normal vector of a surface; the value varies from 0.0, which corresponds to a perfectly smooth surface, to 1.0 that corresponds to a perfectly irregular surface).

Since models of RR materials are not available, the proposed approach is based on the manipulation of weather data file and materials' properties. Three independent simulations were carried out to define the three retro-reflected contributions – direct (Figure 5 a) and diffuse (Figure 5 b) solar irradiation retro-reflected from the RR surface, and global solar irradiation reflected out of the UC from the non-RR surfaces (Figure 5 c) – and arithmetically add them. In particular, a material able to completely absorb the solar radiation impinging on the surface (null ρ value) was used instead of the RR materials to calculate the solar irradiation reflected beyond the UC by non-RR surfaces.

Figure 5: Schematic representation of the approach followed to estimate the three components of Irr_{out} (a, b, and c) when RR are applied to the façade ($F_{1,RR}$).

This simplification leads to underestimating the Irr_{out} since a minimum fraction of the solar irradiance absorbed by the surface with null ρ value would be actually retro-reflected towards the street or the façade, and then eventually further reflected beyond the canyon.

Results

Definition of the UC configurations

The estimated solar irradiation reflected by the UC underline how the orientation input parameter provides a negligible variation (lower than 3%) in canyon's configurations with the same H/W (Figure 6). Conversely, the H/W influences the Irr_{out} : its least, 85 kWh/m², is shown in the narrowest geometry configuration (H/W equal to 2.0), while the maximum, 160 kWh/m², corresponds to the widest (H/W equal to 0.5). These two extremes were chosen as the H/W values proper of the best and the worst UC configurations.

When it comes to the orientation, the west-east was coupled to the 0.5 H/W value (the resulting model was named as 'W-E_0.5') and the north-south to the 2.0 H/W (the resulting model was named as 'N-S_2.0'). They were considered as the most and the least advantageous orientations, respectively, since they are characterized by the greatest and the lowest difference in terms of collected solar irradiation among the façades (Vallati, Mauri and Colucci, 2018).

Figure 6: Comparison of Irr_{out} values estimated for each geometry configuration considering a homogeneous solar reflectance of 0.2 for the whole UC.

In the second part of Stage 1, the solar reflectance parameter was investigated. The W-E_0.5 and the N-S_2.0 models were considered as case studies along with an intermediate one (named as 'NW-SE_1.0') that is oriented northwest-southeast and whose H/W is equal to 1.0. Increasing the ρ value, the Irr_{out} raises similarly in all the models. In particular, varying the solar reflectance from 0.2 to 0.4 doubles the estimated Irr_{out} , while the variation is lower when incrementing from 0.4 to 0.6 (Figure 7).

The chosen homogeneous solar reflectance ($\rho = 0.2$) does not influence the relationship among the different geometry configurations in terms of solar irradiation leaving the UC (i.e. varying the ρ value, the Irr_{out} estimated for the N-S_2.0 is always lower than the amount calculated for the W-E_0.5).

Figure 7: Outcomes from the solar analyses conducted on three representative geometry configurations varying the homogenous ρ value of all the canyon's elements.

Impact of cool materials on the best-configuration

The scenario with traditional diffuse materials applied to the street and to the façade of the W-E_0.5 model shows an amount of annual Irr_{out} equal to 200 kWh/m² (Figure 8). The seasonal contributions amount to 85 kWh/m² and 20 kWh/m² in summer and in winter, respectively.

When HR are considered as street's surface treatment, the irradiation reflected out of the UC is increased by more than 240% (690 kWh/m²), while the seasonal $\Delta Irr_{\%}$ is more than 280% in summer and around 160% in winter (Figure 8). The exploitation of HR on building's façade (HR-F) causes a lower variation in the estimated Irr_{out} , that achieves 320 kWh/m² ($\Delta Irr_{\%}$ of 55%). The seasonal amounts of solar energy leaving the canyon are 120 kWh/m² for the summer and 35 kWh/m² for the winter (Figure 8).

Figure 8: Amount of solar irradiation leaving the UC and percentage variation from the base case estimated for each material pattern of the best configuration.

Applying RR materials instead of HR allows reducing the amount of solar irradiation that remains trapped within the UC by improving the Irr_{out} . The model with the RR street (RR-P) presents the greatest Irr_{out} . The yearly, summer, and winter values equal to 995 kWh/m², 475 kWh/m², and 70 kWh/m², while the $\Delta Irr_{\%}$ ranges from 390% to 455%, and to 255% (Figure 8). As far as the scenario with the RR façade (RR-F) is concerned, the UC reflects towards the sky dome 460 kWh/m² per year ($\Delta Irr_{\%}$ of 130%), while the Irr_{out} equals 140 kWh/m² in summer and 75 kWh/m² in winter (Figure 8).

Impact of cool materials on the worst-configuration

When traditional materials are applied to the N-S_2.0 canyon model, the yearly amount of solar irradiation reflected beyond the UC is 150 kWh/m² (Figure 9). The summer and winter seasons contribute for 65 kWh/m² and 15 kWh/m², respectively.

Figure 9: Amount of solar irradiation leaving the UC and percentage variation from the base case estimated for each material pattern of the worst configuration.

Enhancing the solar reflectance of the street through HR materials (HR-P) increases the Irr_{out} up to 240 kWh/m² – 100 kWh/m² in summer and 25 kWh/m² in winter ($\Delta Irr_{\%}$ constantly equals 60%). Conversely, the HR layer applied to the façade is able to increment the Irr_{out} by more than 90% annually (285 kWh/m²), while the seasonal contributions amount to 120 kWh/m² in the summer and 30 kWh/m² in the winter.

The scenario with RR applied to the street (RR-P) shows 490 kWh/m² per year of specific solar irradiation leaving the UC ($\Delta Irr_{\%}$ of 225%). The seasonal amounts are 210 kWh/m² in summer ($\Delta Irr_{\%}$ of around 230%) and 50 kWh/m² in winter ($\Delta Irr_{\%}$ of 220%). In the case study with the RR façade (RR-F), the greatest amounts of Irr_{out} for the N-S_2.0 model is observed: the annual Irr_{out} equals 575 kWh/m² ($\Delta Irr_{\%}$ is 285%), and it ranges from

275 kWh/m² to 60 kWh/m², in summer and winter, respectively ($\Delta\text{Irr}\%$ varies from 330% to 310%).

Discussion

Potentials for the street application of RR materials

The yearly solar analyses conducted in Milan demonstrate that applying RR to the street instead of HR is always advantageous to lower the solar energy trapped within the UC. Indeed, the RR coating significantly reduces the shortwave radiative exchanges among the street and the two façades by reflecting the solar irradiation incident on the street towards the sky dome. The efficiency of the RR technology strongly depends on the amount of specific solar irradiation impinging the treated surface: when applied to wide canyon environments, they usually perform better than when exploited in narrow configurations characterized by a shadowed street surface (Figure 8 and Figure 9). The same behaviour can be observed in HR surface treatments.

When it comes to the seasonal assessment of the RR materials' efficiency in N-S_2.0 model, it can be observed how the $\Delta\text{Irr}\%$ in summer is almost the same as in winter. Conversely, in the W-E_0.5, it is greater in the warm than in the cold season (Figure 10). Furthermore, the Irr_{out} values for winter are negatively affected by RR materials (and HR as well) which are responsible for the reduction of solar energy gains in buildings and the consequent raising of the heating energy demand.

Figure 10: Amount of seasonal values of Irr_{out} and $\Delta\text{Irr}\%$ estimated for each material pattern of the (a) best- and the (b) worst configuration.

The following practical guidelines about the application of RR layer to the street surface have been carried out from the results:

- Exploiting RR materials in wide UCs (low H/W) is more advantageous than in narrow ones (high H/W) where the street is shadowed for most of the time;

- RR materials applied to the street are more effective than HR during summer when they completely reflect the incident solar irradiation out of the UC;
- In winter, the RR materials are responsible for the low solar energy gains within the UC.

Potentials for façade application of RR materials

The analyses conducted on the models enhanced with a RR façade defined the narrow canyon as the best façade application of RR materials. In the N-S_2.0 model, both the scenarios exploiting cool materials on the façade (HR-F and RR-F) turn out to be more advantageous than the configurations with HR or RR paving. Indeed, the yearly $\Delta\text{Irr}\%$ increases from 60% (HR-P) to more than 90% (HR-F) and from 225% (RR-P) to 285% (RR-F) (Figure 8 and Figure 9).

The seasonal evaluation of the solar irradiation in W-E_0.5 model shows RR materials increasing the Irr_{out} more in winter (when it is not necessary) than during summer (Figure 10). This trend is less evident in the HR configuration than in the RR, which can be considered, for this reason, as the worst among the investigated RR applications. When it comes to the N-S_2.0 model, the $\Delta\text{Irr}\%$ does not vary passing from the summer to the winter and it equals 315% (RR-F) (Figure 10). Similarly, the $\Delta\text{Irr}\%$ is constantly equal to 90% in the HR scenario.

The hereby practical guidelines about the exploitation of RR materials in the most irradiated façade summarize the outcomes from this study:

- RR materials applied to the façade are less performant in wide UCs (low H/W) than in narrow ones where façade surface is longer exposed to direct solar irradiation;
- RR materials are as advantageous as HR in terms of reduction of the solar energy trapped within wide UCs during summer;
- As demonstrated for the street application, RR materials are responsible for the reduction of winter's solar energy gains.

Conclusions and future developments

This study describes an approach for evaluating the impact of RR materials in relation to the increment of solar irradiation reflected out of the UC. The main findings can be summarized as follows:

- The UC configuration having traditional coatings on the surfaces with the greatest Irr_{out} value (200 kWh/m²) is the W-E_0.5 model (main axis oriented eastwards and H/W equal to 0.5);
- The amount of solar direct irradiation impinging on the treated surface influences the performance of the RR materials;
- The façade application of the RR technology should be considered only for narrow canyons;
- RR materials applied to the street always perform better than HR during summer;
- All the investigated configurations can increase the Irr_{out} during summer while reducing solar gains during winter.

The outcomes highlighted how the investigated RR materials cannot be considered advantageous throughout the year when exploited in the building sector. Although they increase the Irr_{out} more than HR in summer, they also contribute to reducing solar gains in winter. Thus, it is necessary to implement a selective behaviour – based on the angle of incidence of the sun rays – in the RR technology to activate its RR features only during the warm season.

The enhancement of the numerical model can represent an important step in the future developments of the present workflow allowing a better evaluation of the RR materials' performances and permitting handling parameters which cannot be fully replicated in the present modelling approach (i.e. angular dependency of the coating's reflectance value, directionality of the solar beam). Furthermore, its application to the assessment of angular-selective RR materials in different climatic contexts and scenarios would be fundamental as well.

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