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Modeling and labeling heterogeneous directional reflective roofing materials

Hashem Akbari *, Ali Gholizadeh Touchaei

Heat Island Group, Concordia University, Montreal, Canada H3G 1M6

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ABSTRACT

Solar reflectance (R) of roofing materials is a function of irradiance magnitude and direction, and surface properties. Current methods of labeling the surface reflectance are applicable to homogeneous materials. However, reflectivity of recently developed directional reflective materials (DRM) has a strong dependence on the heterogeneity of the surface.

We have developed a model to calculate the hourly reflectance of DRMs as a function of zenith and azimuth angles. We investigate options to represent the reflectance of DRMs. Two main options are proposed for labeling; (1) Option 1: using one reflectance for the whole year, and (2) Option 2: using seasonal reflectance (a number representing summer reflectance, a number representing winter reflectance, and the mean of the winter and summer reflectances for other months of a year). We propose a simple method based on Option 2 to label the solar reflectance of DRMs. The proposed option assigns the average reflectance of DRMs as the winter reflectance and the reflectance of the DRM according to a 20° zenith toward the reflective side as the summer reflectance. In summer, the selected metric estimates the mean hourly heat absorption and energy saving for building energy models accurately, and peak heat absorption of the surface by 8% ($<40\ W/m^2$) error. In winter, the potential energy savings of buildings is overestimated by an error of less than 20%, and mean hourly and peak heat absorptions are estimated by an error of 22 kJ/m^2 and 9 W/m^2, respectively.

1. Introduction

Homeowners can save money by installing reflective roofs that reduce cooling costs with a possible small increase of heating cost [1]. Recognizing the energy saving potentials of cool roofs, many states and municipalities have developed codes and standards to promote installation of cool roofs [2]. White roofs offer the highest solar reflectance, but some consumers may desire other colors than white because of architectural aesthetic. Levinson et al. [3,4] have investigated the optical properties of most available pigments that are used in cool roofing materials. Recently, some directional reflective materials (DRMs) are introduced to the roofing market. DRMs (Fig. 1) are innovative products that reflect sunlight (by reflective side) during summer (when the sun is high in sky) and absorb sunlight (by absorptive side) during the winter (when the sun is low). By design, DRMs look dark from the street and light from the sky.

The Cool Roof Rating Council (CRRC) currently measures the solar reflectance of roofing materials using ASTM Standards C1549, E903, and E1918 [5–7]. Standards C1549 and E903 are for measuring solar reflectance of homogeneous surfaces with diffused and isotropic reflected radiation. Applying these standards in their current forms to heterogeneous DRM surfaces (designed to reflect most incoming radiation to sky but appear dark from streets) is impractical.

In collaboration with the Technical Committee of the CRRC, we developed a technique for rating and labeling the solar reflectance of DRMs. Our method uses global solar spherical reflectance (R_g) to estimate the seasonal and annual performance of DRMs. There are two challenges for labeling DRMs; (1) measuring the directional solar reflectance as a function of solar position with respect to the surface, and (2) given the directional solar reflectance, labeling DRMs products. Here, we only address the labeling of DRMs and assume that the measured angular solar reflectance of DRMs are available. Since we did not have measured data for directional reflectivity of DRMs, we developed a model to calculate the reflectance for corrugated samples. The reflectance is calculated as a function of corrugation angle and reflectivity of the light and dark colors (reflective and absorptive sides).

2. Methodology

Reflectance of a homogeneous roofing material is a function of the material's properties and position of the Sun. Reflectance of

* Corresponding author. Tel.: +1 514 8482 424x3201.
E-mail address: Hashem.Akbari@Concordia.ca (H. Akbari).

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Nomenclature

English letters

A	Maximum cross section area of corrugations (m^2)
E_{cool}	Error in cooling energy saving
E_{heat}	Error in heating energy saving
E_{year}	Error in annual energy saving
$F_{b\to w}$	View factor of reflective side to absorptive side
$F_{w\to b}$	View factor of absorptive side to reflective side
$F_{s\to b}$	View factor of absorptive side to sky
$F_{s\to w}$	View factor of reflective side to sky
H	Calculated mean hourly heat absorption of DRM (kJ/m^2)
$\overline{H}$	Estimated mean hourly heat absorption of DRM using metrics (kJ/m^2)
H^*	Calculated peak heat absorption of DRM (W/m^2)
$\overline{H}^*$	Estimated peak heat absorption of DRM using metrics (W/m^2)
I_b	Solar irradiance on the absorptive side (W/m^2)
I_{beam}	Beam solar irradiance (W/m^2)
I_{diff}	Diffused solar irradiance (W/m^2)
I_g	Global solar irradiance (W/m^2)
$I_{n,b}$	Normal solar irradiance on the absorptive side (W/m^2)
$I_{n,w}$	Normal solar irradiance on the reflective side (W/m^2)
I_w	Solar irradiance on the reflective side (W/m^2)
M	Angle between maximum cross section area of corrugations and reflective side (degree)
N	Angle between maximum cross section area of corrugations and absorptive side (degree)
$n_{I,surface}$	Unit vector of irradiance on the surface's coordinate system
$n_{I,earth}$	Unit vector of irradiance on the earth's coordinate system
O	Incident angle of radiation normal to corrugations (degree)
Q_b	Absorbed energy of the absorptive side (W/m^2)
Q_w	Absorbed energy of the reflective side (W/m^2)
R_{ave}	Average global solar reflectance
δR_{cal}	Difference between characteristic reflectance of regular roof and calculated reflectance of DRM roof
R_g	Global solar reflectance
δR_m	Difference between characteristic reflectance of regular roof and DRM roof
R_s	Summertime global solar reflectance
$\overline{R}_s$	Metric reflectance for summer
R_t	Rotation matrix
R_w	Wintertime global solar reflectance
$\overline{R}_w$	Metric reflectance for winter
R_y	Annual global solar reflectance
$\overline{R}_y$	Metric reflectance for annual
R_{20}	Global solar reflectance of DRM when zenith is 20° toward reflective side
z	Zenith angle (degree)

Greek letters

α_g	Global solar absorptance
β	Solar altitude (degree)
δ	Declination of sun (degree)
θ	Rotation angles of the surface about y (degree)
ξ	Solar azimuth (degree)
φ	Rotation angles of the surface about z (degree)
ψ	Rotation angles of the surface about x (degree)

DRMs (heterogeneous), in addition, is a function of the surface orientation. First, we calculate the solar position based on an algorithm proposed by Duffie et al. [8] (see also Appendix A). To calculate the amount of energy strike on the surface, ASHRAE [9] suggests a method to estimate the global, beam and diffused solar irradiances (the detailed procedure is discussed in Appendix B). [Other more accurate algorithms and models for estimating available solar irradiance [10–12] have not been used in our analysis.]

We use a simple model to estimate the reflectance of DRMs for all zenith angles with a constant beam to diffused ratio (Appendix C). As a result, we have the reflectance distribution of DRMs (for azimuth angles of [−180°, 180°] and zenith angles of [0°, 90°]). We consider heterogeneous DRMs that the reflection of sunlight follows spectral properties of matte surfaces and it's not a function of incident solar angle [13].

There are two independent requirements for measuring and labeling the solar reflectance of DRMs: (1) the hemispherical solar reflectance of the roofing DRMs, which is only a function of the material properties, and (2) the solar irradiance and instantaneous reflectance of a DRM as a function of the sun position. In this analysis, we assume that the given hemispherical solar reflectance (hence solar absorptance) of the DRM surface is independently measured. Figs. 2 and 3 are examples of solar reflectance (absorptance) of a DRM with different reflectance of absorptive and reflective sides, and corrugation angles, respectively. We utilize some surface properties such as average reflectance (R_{ave}) and reflectance of the surface at 20° (toward reflective side of DRM; azimuth of 180°) zenith angle (R_{20}). We define the average reflectance of the surface as the mean of all axisymmetric measured reflectances (e.g. the maximum and minimum reflectances).

We used the reflectivity model to evaluate the performance of a DRM roof located on 37° latitude (37° N). The model can estimate the reflectance of different DRMs. For further simplification, we calculate an average tilt angle (ATA) to represent all other considered tilt angles [10°–60°]. To determine ATA, for each DRM we calculate the summer, winter, and annual reflectances from all considered tilt angles (11 tilt angles from 10° to 60° changing in 5° interval). Then we select the tilt angle ATA as one closest to the average seasonal reflectance of all tilted roofs. We calculated ATA for all selected DRMs and we found that ATA does not change significantly with the choice of DRM. ATA for all DRMS was about 30° and this was used as a representative tilt angle for all subsequent calculations.

Simulations are for 21st day of each month (representing the whole month) on hourly basis. We define three DRM reflectances: summer reflectance R_s, winter reflectance R_w and annual reflectance R_y. Summer period includes May, June, and July. Winter is November, December, and January. We develop several methods to relate R_s, R_w, and R_y to measured (here simulated) properties of DRMs. The appropriate choice of metric is the simple one with the least error in prediction of mean hourly and peak absorbed heat (H and H^*). Finally, analyzing the performance of DRM for other locations (latitudes), tilt angles, and the reflectance of absorptive and reflective sides evaluates the applicability of the selected options.

We consider two options to propose a simple and accurate metric. Since standards for current roofing materials assign only one value to the initial reflectance of a material [14], in the first approach, we follow the same method and find a single value that can represent the reflectance of a DRM. The advantage of this method is simplicity and ease of labeling. The second option is assigning one reflectance for summer ($\overline{R}_s$) and another reflectance for winter ($\overline{R}_w$). These two