Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 48 (2014) 1244 – 1253

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and IndustrySeptember 23-25, 2013, Freiburg, Germany

On the solar reflectance angular dependence of opaque construction materials and impact on the energy balance of building components

Emiliano Carnielo[a,*], Michele Zinzi[b], Aldo Fanchiotti[a]

[a]*Università degli Studi Roma Tre, Engineering Department, Via della Vasca Navale 79/81, Rome 00146, Italy*
[b]*ENEA - Italian National agency for new technologies, Energy and sustainable economic development, Via Anguillarese 301, 00123, Roma, Italy*

Abstract

The solar reflectance of the surfaces is a property that varies according to spectral and angular distribution of the incident solar radiation which in turn depends on orientation and latitude. In this paper, an optical characterization was conducted on some typical opaque building materials, generally used as roof covers: shingles, membranes, bricks and tiles. The measurements were carried out through an experimental factory equipped with a large integrating sphere which allows to measure the spectral reflectance at different incidence angles of the light beam on the sample. Thus it was possible to create a function that linked reflectance values with the incidence angle. The results obtained were included within a dynamic software in order to optimize the calculation of solar gains in the energy balance of a building.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: Solar reflectance; Solar gains; Integrating sphere; Incidence angle.

---

* Corresponding author. Tel.: +39-06-5733-3289; fax: +39-06-559-3732.
*E-mail address:*emiliano.carnielo@uniroma3.it

1876-6102 © 2014 The Authors. Published by Elsevier Ltd.
Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.141

Nomenclature

I	Irradiance	[W/m^2]
Q	Heat power	[W/m^2]
θ	Incidence angle	[°]
ρ	Solar reflectance	[-]

Subscript

SG	Solar gain
g	Global
b	Beam
d	Diffuse

1. Introduction

The reflectance is a property of construction materials well investigated in literature in order to assess their selective capability to reflect radiation at different wavelengths [1]. This study is aimed at investigating how reflectance is angular dependent. Solar reflectance of surfaces varies between a minimum value corresponding to a normal incidence angle of a light beam to a maximum value corresponding to a 90° incidence angle with a trend depending on the roughness of surface. Typically smooth surfaces present a high regular reflectance component strictly dependent on incidence angle while very rough materials are less affected by the change in incidence angle even though they also present changes in reflectance as a function of that parameter.

Solar radiation changes in intensity during the day and can be divided into two components, a diffuse and a direct one, in percentages that vary with the time of day and with latitude. While the diffuse component always strikes a surface from every direction during daylight, the direct component changes its angle of incidence. Most of thermo-physical models take into account the aforementioned geometric and energetic distribution of solar radiation, while they may consider constant the solar reflectance of surfaces during the daylight at every incidence angle of direct beam solar radiation assuming that each surface is lambertian (constant distribution of hemispherical radiance and independent by the incidence angle). This assumption may not be valid for some real materials not perfectly diffusive, which increase their reflection power if struck with a high incidence angle of light beam. This issue induces an overestimation of solar gains.

In recent years the construction materials manufacturers are introducing in the market an increasing number of innovative components to be used as external coatings of roofs and facades, such as the *cool material.* These materials have high solar reflectance values, which reduce the solar radiation absorbed by conventional building materials and limit the surface temperature rise in the presence of high solar loads. These characteristics allow to keep buildings cooler during the hot season improving thermal comfort and energy savings due to a reduced cooling demand. Moreover a massive use of this passive technology in urban scale induces a mitigation of the urban heat island effect. Several studies were carried out during the past years showing potentialities and limits of the technology by means of numerical analyses [2, 3, 4] and monitoring in real buildings [5, 6, 7, 8, 9]. The *cool materials* technology is now well-established especially with regard of coatings for roof applications. The latter generally have smooth surfaces with a reflection mode that presents a not negligible regular component. In this perspective the reflectance solar dependence on incidence angle plays an important role on the estimation of solar gains on building components.

The paper introduces a method to compute the reflectance values in order to calculate more accurately the energetic flows involved in the energy balances of buildings.

2. Methodology

Solar gains that affected an orientated surface are obtained by multiplying the value of solar irradiance for the absorptance. The latter is determined by subtracting solar reflectance from unity. Typically the equation which governs solar gains in the most of thermo-physical models is the following:

$$Q_{SG} = I_b \cdot (1-\rho) + I_d \cdot (1-\rho) = (I_b + I_d) \cdot (1-\rho) = I_g \cdot (1-\rho) \tag{1}$$

It implicitly considers the surface hit by the solar radiation as lambertian, perfectly diffusive, with a constant reflectance independent from the angle of incidence of beam solar irradiance. The method proposed in this study enables to consider solar gains not only dependent on the change in intensity of global solar irradiance during the daylight but also dependent on the variation of the reflectivity power of the interested surfaces as a function of the incidence angle. Two different reflectance types were considered. The first one, $\rho(\theta)$ is the angular dependent one, obtained from the interpolation of experimental values performed at several incidence angles. It is correlated to the beam solar irradiance which is the component of the global irradiance that varies the angular incidence on surfaces. The second one, ρ_d, is a constant value, obtained as an integral average of the previous function from 0 to 90 degrees of incidence, see equation 3. It is correlated to the diffuse solar irradiance that strikes a surface uniformly. The solar gains equation turns in:

$$Q_{SG}(\theta) = I_b \cdot [1-\rho(\theta)] + I_d \cdot (1-\rho_d) \tag{2}$$

with

$$\rho_d = \int_0^{90} \rho(\theta) \cdot d\theta \tag{3}$$

Optical measurements were performed on typical opaque building materials at different incidence angles. The results were used to find the correlation between incidence angles and reflectance in the form of equation 2. The latter was inputted in a building energetic tool, the TRNSYS. The results allowed to compare several energetic parameters of the surfaces obtained applying the method exposed in this study, with the default calculation preset in the software. Henceforth the former will be called the $\rho(\theta)$ method, the latter the ρ constant method.

3. Description of tested materials

The tested materials are generally used as roof covers. They have different surface finishing, both smooth and rough. Furthermore there are also two materials classified as "*cool*":

- Smooth polyvinylic *cool* membrane – light gray (number 1 in Fig. 1);
- Rough polyvinylic *cool* membrane – gray (number 2 in Fig. 1);
- Bituminous shingle – dark gray (number 3 in Fig. 1);
- Smooth ceramic tile – beige (number 4 in Fig. 1).

Fig. 1: Surfaces of the tested materials.

4. Experimental

4.1. Optical bench description

Spectral measures were performed by means of an experimental facility [10]. The four coatings samples were tested at five different incidence angles of the light beam: near normal, 30°, 45°, 60°, 75°. For issues related to the shape of the measure instrument it was not possible to perform measures with an incidence angle greater than 75°. The incidence angle is typically considered 0° when a light beam hits a surface normally, while is 90° when the light beam is parallel to it. An optical characterization which involves a variation of the angle of incidence of the beam on the sample is typically not feasible with commercial spectrophotometers. Large integrating sphere equipments needed to perform angular measurements on such materials. The used optical bench consisting of the following parts:

- A tungsten halogen lamp with adjustable power, ranging from 250 up to 1000 Watt, see number 1 in Fig. 2. The collimated beam diameter can be modulated through a diaphragm according to the measurement requirements. Usual diameters range from 4 to 10 cm;
- An integrating sphere with a 75 cm diameter composed by an external aluminum shell, while the internal surface is made of spectralon, a white material with a reflectivity greater than 95% in the whole solar range (300-2500 nm). The sphere is equipped with several ports; the layout of the facility can be adjusted in order to perform transmittance, reflectance and absorptance measurements;
- The sample is mounted on a holder sited in the centre of the sphere, which arm can rotate in order to vary the beam angle of incidence, see number 2 in Fig. 2.
- Detection system consisting of three array spectrometers and three detectors: NMOS for the 250-1000 nm range (dispersion 1.4 nm/pixel); InGaAs for the 900-1700 nm range (dispersion 3.125 nm/pixel); ExtInGaAs for the 1600-2500 nm range (dispersion 3.52 nm/pixel).

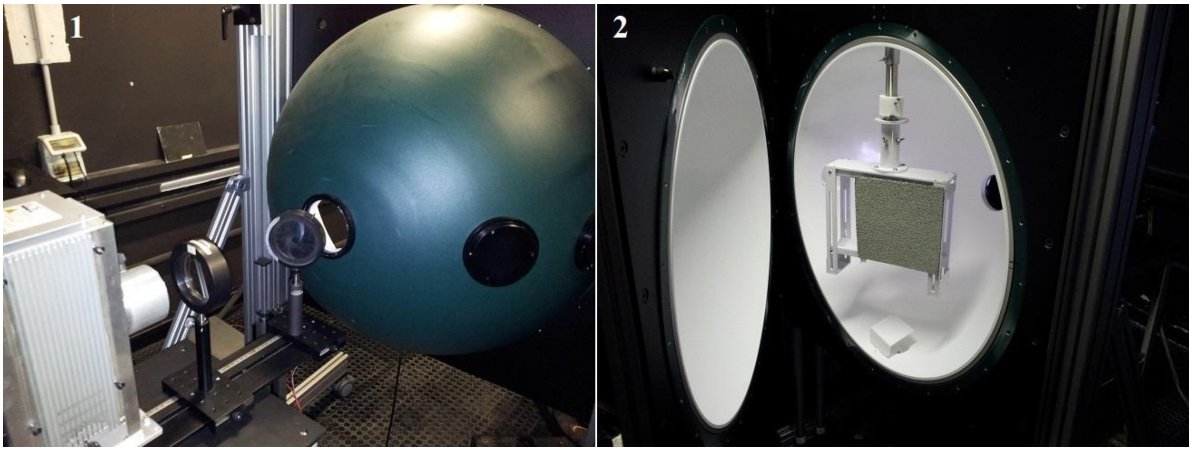

Fig. 2: Integrating sphere. Lamp and entering port (1), Central sample holder (2).

Spectral angular reflectance measurements were performed as described in the following procedure: Light beam port is 7.5 cm in diameter and the beam diameter is about 6 cm. The radiation enters the sphere through the port facing the sample holder and hits the sample at the chosen incidence angles. The reflectance is the ratio between the reflected energy by the sample and the energy reflected by a spectralon reference whose calibration curve is known and certified. The measures obtained were corrected multiplying the spectral values for the corresponding values at equal wavelength obtained from the calibration curve of the reference. Measurements were performed between 380 and 1700 nm, covering the 92.7% of the whole solar spectrum energy.

4.2. Experimental result

Fig. 3 shows the spectral measured reflectance of one selected sample, the smooth polyvinylic *cool* membrane, in order to put in evidence the spectral variation at the five incidence angles.

The spectral response of reflectance is sensibly affected by the incidence angle. It is important to notice how the trends are parallel translating upward only as a function of the angle. For 8° (near normal) and 30° the trends are very close, almost superimposed. Increasing the angle the reflectance becomes progressively higher. The spectral curve at 75° is much more irregular than the others due to a design limit of the optical bench. At 75° of incidence the spot of the light beam is very elongated going beyond the edges of the sample. To overcome this problem the dimension of the spot was sensibly decreased penalizing the amount of incoming energy in the sphere and the accuracy of detectors.

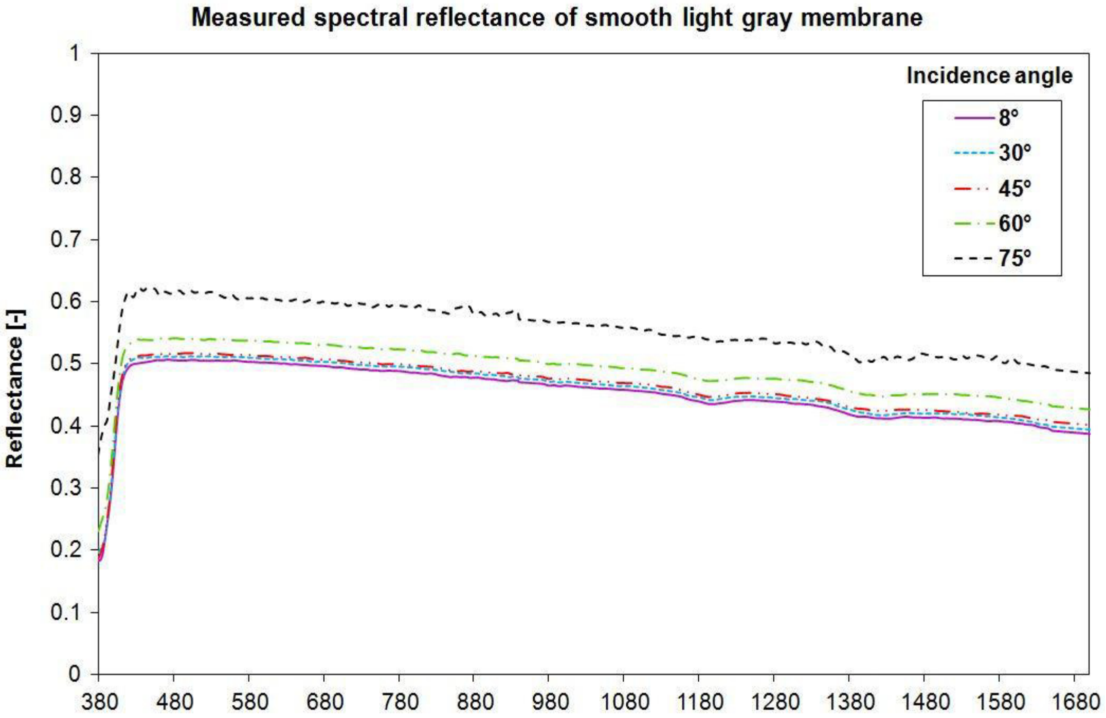

Fig. 3: Spectral reflectance at the five considered incidence angles.

The integrated solar reflectance of the samples was calculated starting from the spectral data using the standard reference of the solar spectrum defined in ISO 9050:2003 [11]. In Figs. 4, 5, 6 and 7, the evolution of integrated reflectance, increasing incidence angle, is shown. The previously described function $\rho(\Theta)$ that links reflectance to angle was obtained by means of a mathematical fitting of the integrated values using the cubic spline method. At a light beam incidence angle of 90° the reflectance was set to 1 as a geometric condition. The increasing of reflectance with angle in the smooth samples (Fig. 4 and Fig. 5) seems to be more progressive if compared to the one of rough samples. This factor is due to the higher regular component of reflectance in the smooth samples. This component is the main factor that makes the reflectance value dependent on the incidence angle. The rough samples present generally a low regular reflectance and a high diffusive reflectance that is less sensible to an angle variation as shown in Fig. 6 and Fig. 7. For these samples, as a matter of fact the trend is almost horizontal even at 75° of incidence.

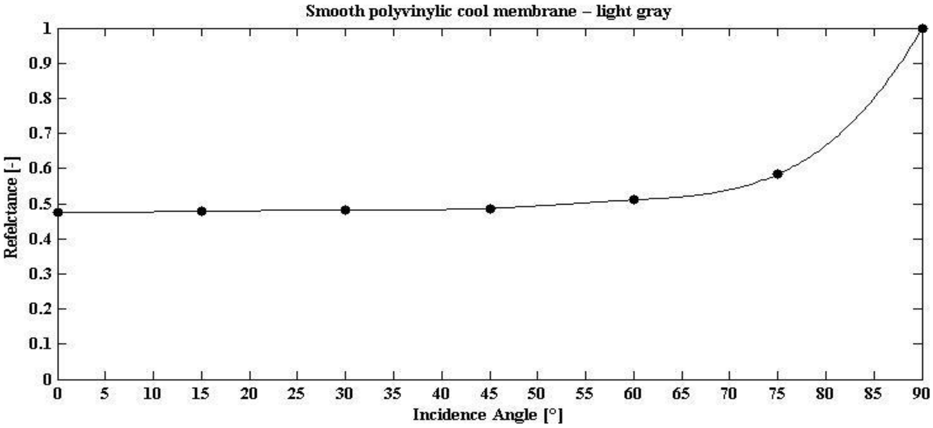

Fig. 4: Spline method applied on integrated reflectance values (black dots) of smooth membrane.

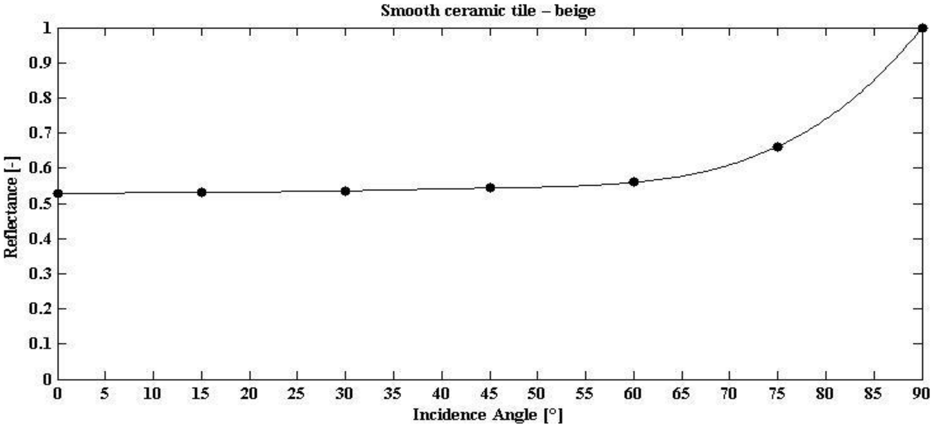

Fig. 5: Spline method applied on integrated reflectance values (black dots) of beige tile.

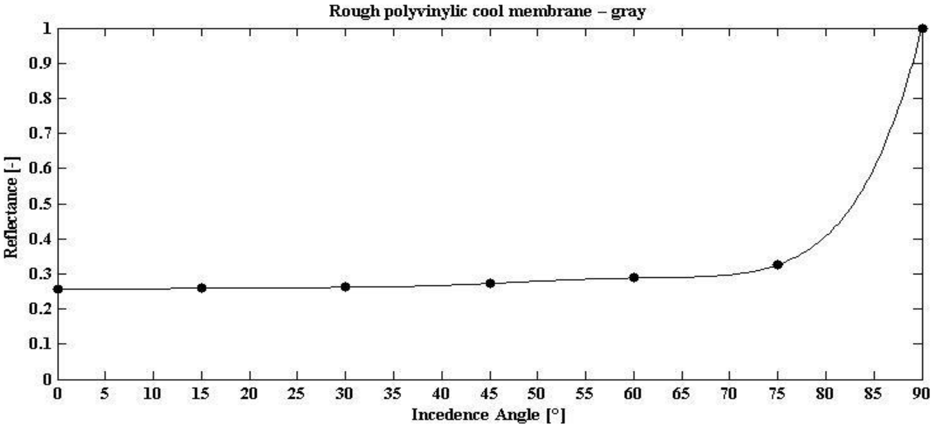

Fig. 6: Spline method applied on integrated reflectance values (black dots) of the rough membrane.

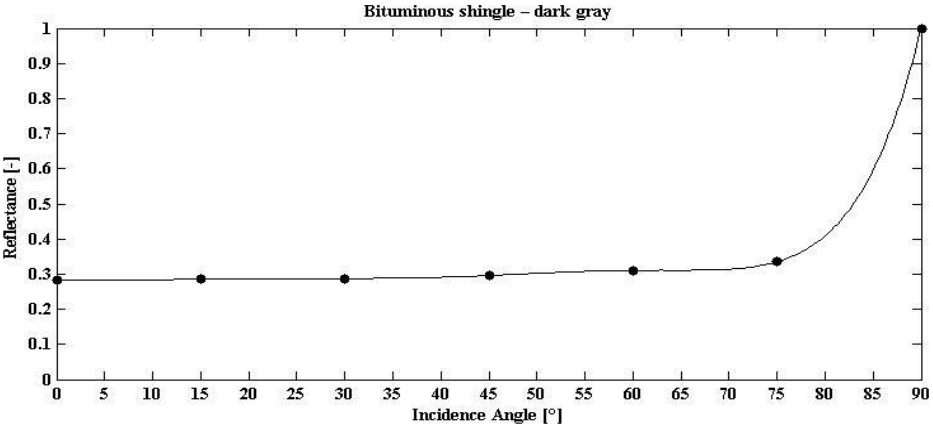

Fig. 7: Spline method applied on integrated reflectance values (black dots) of shingle.

5. Calculation

5.1. Model description

The energetic analysis software used in this study is the TRNSYS. It is a well known and calibrated calculation model based on a series of components linked each other making easier the modeling of the problem. The functional blocks are called "types" and are written in Fortran language. They consist of mathematical elements that model the performance of one part of the system. "Types" can be linked together to compose the main structure of the project.Ultimately TRNSYS is a collection of energetic components models grouped around a simulation engine. A section called TRNBuild allows to design the building envelope with its thermo-physical properties. By linking it at weather data "*types*", TRNSYS is able to calculate the heat fluxes which affect the structure.

The examined structure is a simple unique thermal zone box with a plant area of 100 m^2. The height of the vertical walls is 4 m. In this way all the main expositions were covered (North, South, East, West, Horizontal). Two insulation levels of the structure were considered: the vertical and horizontal walls thermal transmittance was 1 Wm^2K in the first case, obtained considering two layers of hollow bricks separated by an air layer and 0.56 Wm^2K in the second case, replacing the air layer with an insulating material. No windows or other openings were modeled in order to emphasize only the contribution of solar gains for the opaque surfaces in the energetic analysis. The internal temperature was set to 20 °C during winter and 26 °C during summer. The climatic data were extracted from WMO (World Meteorological Organization) database. Three Italian cities were chosen at three different latitudes: Rome, Palermo and Milano.

Simulations were performed for the whole year, but only two seasons were taken into account: winter, from November to the end of February and summer from May the 15th to September the 15th. The outputs of the simulations are the solar gains and the thermal fluxes.

5.2. Results

Table 1 presents the solar gains in kWh/m^2, calculated by means of TRNSYS with the $\rho(\Theta)$ method versus the ρ constant method, for the three cities. The percentage variation between the two methods was also reported in table. Solar gains obtained with the reflectance angular dependent method are lower than constant reflectance method for each orientation and latitude. Relevant percentage variation were founded for each case. The maximum value is 17% obtained for Palermo during summer, orientation South.

Table 2 shows instead the absolute values of thermal fluxes calculated for both insulation levels in kWh/m^2. A positive thermal flux goes from wall into the thermal zone while the minus sign during winter indicates that the flux is going from the thermal zone into the wall [12]. As a matter of fact thermal flux obtained with ρ(Θ) method is lower during summer while is higher during winter due to a lower value of solar gains.

Table 1: Solar gains calculated with ρ(Θ) method versus ρ constant method.

		Summer Solar Gains [kWh/m^2]			Winter Solar Gains [kWh/m^2]		
		ρ(Θ) method	ρ constant method	% Variation	ρ(Θ) method	ρ constant method	% Variation
Milan	N	87.4	103.1	15.2	22.5	26.1	13.7
	S	167.7	195.6	14.2	91.9	99.5	7.6
	E	174.2	194.6	10.5	40.4	46.2	12.5
	W	175.5	196.1	10.5	39.7	45.5	12.7
	Hor	307.4	339.7	9.5	60.1	70.4	14.8
Rome	N	90.2	107.2	15.9	29.0	33.6	13.7
	S	177.4	210.2	15.6	172.2	184.3	6.6
	E	201.7	224.8	10.3	66.9	76.2	12.1
	W	204.0	227.4	10.3	67.6	76.9	12.1
	Hor	369.6	402.8	8.2	99.9	115.9	13.8
Palermo	N	92.1	110.0	16.3	33.2	38.4	13.7
	S	163.4	197.0	17.0	167.7	180.7	7.2
	E	203.2	226.9	10.4	71.2	81.1	12.2
	W	208.6	232.6	10.3	72.0	82.0	12.2
	Hor	385.8	419.1	7.9	113.6	130.0	12.6

Table 2: Thermal flux for the not insulated and insulated configuration calculated with ρ(Θ) method versus ρ constant method.

		Not Insulated				Insulated			
		Summer Thermal Flux [kWh/m^2]		Winter Thermal Flux [kWh/m^2]		Summer Thermal Flux [kWh/m^2]		Winter Thermal Flux [kWh/m^2]	
		ρ(Θ) method	ρ constant method	ρ(Θ) method	TRNSYS method	ρ(Θ) method	ρ constant method	ρ(Θ) method	TRNSYS method
Milan	N	3.44	3.50	-45.51	-45.41	1.57	1.61	-25.60	-25.54
	S	5.43	5.88	-42.91	-42.67	2.54	2.76	-24.25	-24.11
	E	5.50	5.74	-44.83	-44.65	2.62	2.75	-25.24	-25.14
	W	5.83	6.09	-44.88	-44.70	2.72	2.85	-25.27	-25.17
	Hor	8.25	8.89	-45.84	-45.49	3.92	4.25	-25.72	-25.53
Rome	N	4.86	4.93	-28.74	-28.62	2.20	2.25	-16.24	-16.17
	S	7.59	8.23	-23.44	-23.07	3.56	3.90	-13.45	-13.24
	E	8.25	8.58	-27.30	-27.01	3.93	4.12	-15.49	-15.32
	W	8.62	8.95	-27.29	-27.01	4.07	4.26	-15.48	-15.32
	Hor	12.26	12.94	-28.40	-27.86	5.94	6.32	-16.03	-15.73
Palermo	N	7.21	7.26	-16.18	-16.05	3.26	3.31	-9.24	-9.15
	S	9.76	10.39	-11.74	-11.39	4.59	4.92	-6.86	-6.66
	E	11.17	11.46	-14.83	-14.55	5.33	5.49	-8.53	-8.36
	W	11.39	11.67	-14.86	-14.58	5.43	5.59	-8.53	-8.37
	Hor	15.76	16.39	-15.34	-14.82	7.69	8.03	-8.77	-8.48

Fig. 8 and Fig. 9 represent the percentage change in flux respectively for the not insulated and insulated configurations. As it graphically shown with histograms the results are very similar. During summer, changes in heat flow are represented with negative values to emphasize the decrease of the entering flux obtained with the reflectance angular dependent method of calculation. Conversely, during winter, the percentage change of the thermal flux is represented with positive values indicating the increase of heat loss towards the outside.

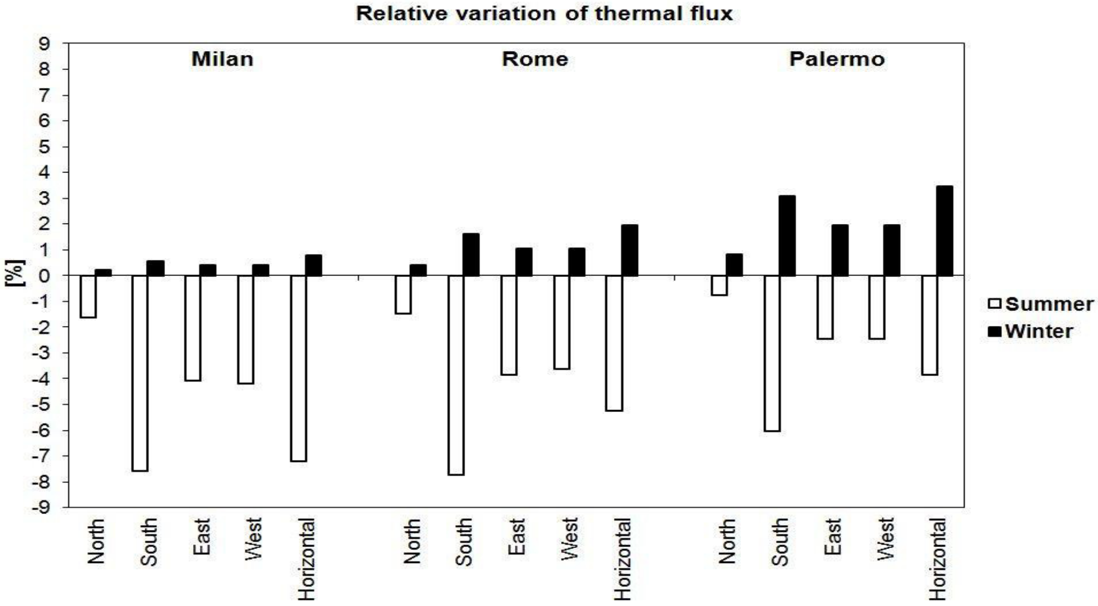

Fig.8: Percentage variation of thermal flux for not insulated configuration

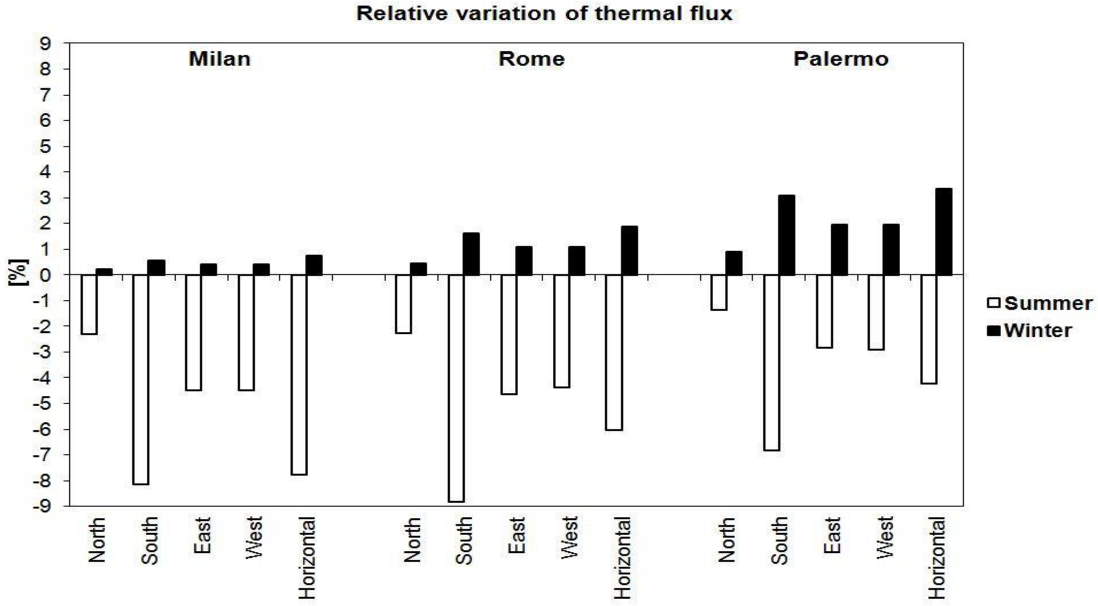

Fig.9: Percentage variation of thermal flux for insulated configuration

The amount of percentage variations of thermal fluxes is sensibly higher during summer compared to the winter ones, except for Palermo where the values are more similar. The higher variations were registered for south and horizontal orientations with values higher than 7%.

6. Discussions and conclusions

Solar reflectance is angular dependent. An optical characterization able to quantify the change in reflectance at different incidence angles demonstrates the extent of this dependence. Four samples of building components used as roof covers were tested with different surface finishing: two smooth and two rough. The reflectance of smooth samples showed a high sensibility to an increasing of incidence angle.

The function that links the reflectance to angles was used to find an accurate method of calculation of solar gains. This method was compared to the constant reflectance method typically used in the thermo-physic models. The TRNSYS tool allowed to perform an energetic simulation of a simplified building in order to assess the differences between the two methods by calculating the energy balance of a wall and in particular the thermal flux.

The results showed an underestimation of reflective power of materials for the constant reflectance method leading to an overestimation of solar absorptance and thus of solar gains. Thermal fluxes calculated with the constant method compared with ones obtained with reflectance angular dependent method are higher during summer and lower during winter. The percentage difference between the two thermal fluxes calculation method reaches not negligible values for south and horizontal orientations for the three considered cities and for both insulation levels.

The calculation method for reflectance proposed in this paper demonstrated the limits of the thermo-physic models generally used to perform energetic analyzes. The concept expressed can also be extended to transparent components for the optimization of g-value calculation. Further developments will concern a more detailed thermal analysis on building scale in order to assess the importance of this different approach in the evaluation of reflectance on energy demands of buildings.

References

[1] Zinzi M. Cool materials and cool roofs: Potentialities in Mediterranean buildings. *Advances in Building Energy Research* 2010; 4: 201-266.

[2] Rapporto Energia e Ambiente, ENEA; 2012.

[3] Synnefa A, Santamouris M, Akbari H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings* 2007; 39(11): 1167-1174.

[4] Akbari H, Bretz S, Kurn D, Hartford H. Peak power and cooling energy savings of high albedo roofs. *Energy and Buildings* 1997; 25: 117-126.

[5] Suehrcke H, Peterson E L, Selby N. Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Buildings* 2008; 40: 2224-2235.

[6] Bozonnet E, Doya M, Allard F. Cool roofs impact on building thermal response: A French case study. *Energy and Buildings* 2011; 43(11): 3006-3012.

[7] Kolokotroni M, Gowreesunker B L, Giridharan R. Cool roof technology in London: An experimental and modelling study. *Energy and Buildings* 2011.

[8] Romeo C, Zinzi M. Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy and Buildings* 2011.

[9] Kolokotsa D, Diakaki C, Papantoniou S, Vlissidis A. Numerical and experimental analysis of cool roofs application on a laboratory building in Iraklion. *Energy and Buildings* 2011.

[10] Maccari A., Zinzi M. Simplified algorithms for the Italian energy rating scheme for fenestration in residential buildings. *Solar Energy* 2000; (69 Suppl.) Nos. 1-6: 75-92.

[11] ISO 9050. Glass in building-Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors; 2003.

[12] TRNSYS 16 Manual. Multizone building modeling with type 56 and TRNBuild; 6: 101-105.