Simulated Energy Savings of a Cool Roofs applied to Industrial Premises in the Mediterranean Area

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ABSTRACT

Cooling energy savings and improved thermal comfort in hot climates can be achieved using cool roofing materials. High solar reflectance and infrared emittance values reduce the amount of absorbed solar radiation and the surface temperature of a material exposed to sun radiation, consequently the heat transfer into the building is lowered. A reduction of the urban heat island effect, caused by the presence of high absorption surfaces and the lack of vegetation, may be obtained using cool roofing materials.
Computer energy simulations have been used to assess the energy savings and temperature profiles consequent to the application of a cool roofing material when applied to industrial premises in three Mediterranean cities: Genoa, Madrid and Cairo. In particular, the related influence on cooling energy demand and maximum temperature at the outside face of the roof are analyzed, varying the roofing material and the insulation thickness.
The results of this study showed that using a cool roofing material in the Mediterranean area for industrial premises leads to significant sensible cooling energy savings, up to 42%. Moreover, it was obtained that the maximum roof outside surface temperatures decrease of 40÷50°C when cool roofing materials are applied.

1. INTRODUCTION

1.1 Cool roofing materials

Cool roofing materials are characterized by high solar reflectance and infrared emittance values. The solar reflectance is the total reflectance of a surface, considering the hemispherical reflectance of radiation, integrated over the solar spectrum, including both specular and diffuse reflections (Synnefa *et al*. 2006). High reflectance materials, such as white painted metal roofing, have values of around 0.8. It means that the roof retains the 20% of the heat coming from the sun. The infrared emittance is the ratio of the radiant heat flux emitted by a sample to that emitted by a black body radiator at the same temperature. The wavelength range for this radiant energy is roughly from 5 to 40 micrometers. Most building materials are opaque in this part of the spectrum, glass included, and their emittance is roughly 0.9. These two properties mainly affect the surface temperature of a material exposed to sun radiation (Berdahl and Bretz, 1997).

1.2 Advantages

Lower radiation absorption and surface temperature lead to lower heat transfers into the building, therefore they reduce the cooling energy consumption and peak electricity demand during cooling season in conditioned buildings and increase thermal comfort in summertime in unconditioned buildings.

Field studies reported reduction in cooling energy consumptions (Akbari *et al*. 1997, Parker *et al*. 1998, Konopacki and Akbari 2001 and 2002, Akbari *et al*. 2005). Konopacki and Akbari (2001) measured in a retail store in Austin (Texas, US) a reduction of the average summertime daily maximum roof surface temperature from 76°C to 52°C by applying reflective roof membrane. The air-conditioned energy consumption decreased by 11%. The peak air-conditioning demand was reduced of 14%.

Akbari *et al*. (2005) monitored the effect of six buildings in California (US) at three different sites. A retail store, an elementary school and a four-building cold storage facility. Results showed that installing a cool roof reduced the daily peak roof surface temperature of each building by 33-42°C. For the retail store (U-value of the roof equal to 0.81 $WK^{-1}m^{-2}$), when the outside temperature was above 38°C, the measured savings in average peak demand (from noon to 5 p.m.) was about 10 W m^{-2}. For the elementary school (U-value of the roof equal to 0.19 $WK^{-1}m^{-2}$), when the outside temperature was above 32°C, the measured savings in average peak demand (10 a.m.-4 p.m.) was about 5 W m^{-2}. The consequent drawbacks in the heating demand are not relevant, since the influence of solar reflectivity is low in wintertime, because of short day length, low sun angles, cloudy weather and snow on the roof.

"Urban Heat Island effect" is the name given to describe a higher temperature (3-5°C) in urban area than in its surroundings. It is caused by the presence of high absorption surfaces, as building and road materials, and the lack of vegetation. The urban heat island effect causes thermal discomfort, health problems, increases the demand of cooling energy and speeds up the generation of smog. A reduction in the urban heat island effect can be achieved using cool materials (Santamouris 2001, Akbari *et al*. 2001).

1.3 Disadvantages

Insolation, moisture, temperature, and natural and anthropogenic pollutants are the major elements that degrade roof coatings (Anderson *et al*. 1990). The high initial solar reflectance of a white roof (circa 0.8) can be lowered to about 0.6 (Levinson *et al*. 2005).

Bretz and Akbari (1997) concluded that most of the degradation of coatings occurred within the first year (average decrement: 0.15) of application, in particular within the first two months of exposure. After such period the degradation slowed. They estimated a 20% reduction from the first year energy savings for all subsequent years. The variation in albedo over time depends on the coatings, the texture of the surface, the slope of the roof and the nearby sources of dirt and debris.

Byerly and Christian (1994) monitored solar reflectance of a white roof coating in Tennessee over a 3.5 year period. Solar reflectance dropped from 0.80 to 0.59, with most of the decrease in the first year. Most of the above presented results were obtained for white or light colour coatings. However, recent developments of non-white products have been studied because darker colours are preferred from an aesthetic point of view.

The solar reflectance can be restored with increasing effectiveness by wiping, rinsing, washing and bleaching (Levinson *et al*. 2005). Washing the roof with soap returned the solar reflectance to 90÷100% of the original value, but since dirt accumulation can already occur in the first couple of months, the benefits from washing are short lived and not cost-effective according to Brets and Akbari (1997).

The purpose of this study is to quantify the cooling energy savings due to a cool roofing material by means of computer energy simulations, in the Mediterranean area.

2. METHODS

2.1 Description of the building

The building is a one-storey industrial shed with a rectangular foot-print of 40 m by 60 m. The shed height is 6 m. The external walls are constructed with 20 mm of plaster, 70 mm of glasswool and 10 mm of internal plaster.
The windows have a U-value equal to 2.7 $WK^{-1}m^{-2}$. They have a total area of 148 m^2 (6% of the floor area).
The analyzed roof structures are described in Table 1.

Table 1. Roof structures considered in the present simulations

Layer	Name	Layer characteristics	
External (Roofing Material)	Warm	s_r = 0.06	ε = 0.86
	Cool	s_r = 0.83	ε = 0.92
Inner (Thermal Insulation)	Low	λ = 0.04 $Wm^{-2}K^{-1}$	t = 0.06 m
	High	λ = 0.04 $Wm^{-2}K^{-1}$	t = 0.20 m
Internal (Plaster)		λ = 1.00 $Wm^{-2}K^{-1}$	t = 0.01 m

with:
s_r = solar reflectance
ε = infrared emittance
λ = thermal conductivity
t = thickness

As regards the external layer, the standard roofing material (here is referred as "Warm") consists in smooth bitumen (Parker D.S. *et al*. 1993), while the cool roofing material ("Cool") is "Sarnafil White" (LBNL, Unpublished results, Rose S. and Berdahl P., 1998). The floor consists in 0.09 m of glasswool and 0.3 m of concrete (density = 2200 kg/m^3). Internal walls and partitions are not considered.

2.2 Description of loads and HVAC system

Occupants contribute to both sensible and latent loads. 90 occupants are present (27 m^2 per person). They have an activity level of 1.5 met (1 met = 58.15 Wm^{-2}), therefore the total heat produced per occupant is 160 W. The balance between sensible and latent heats is calculated by the program. The occupants are present from Monday to Friday, 24 hours per day, because the working time is organized in three shifts. Saturday and Sunday are holidays. No other public holidays are assumed. All other internal heat gains, such as lighting, electrical equipments and working machines are summarized as a constant total heat gain equal to 15 Wm^{-2}.

The infiltration is considered to be constant and equal to 0.1 air changes per hour. The mechanical ventilation is also constant during working days and equal to 1.0 air change per hour. A heat recovery exchanger with an efficiency of 60% is applied.

The energy simulations were performed for the same building placed in three Mediterranean cities: Genoa (latitude: 44.41°) , Madrid (latitude: 40.41°) and Cairo (latitude: 31.4°). The cities were chosen in order to describe various climates in the Mediterranean area.

The simulated cases are summarized in Table 2.

Table 2. Simulated cases. Location of the building, type of the used roofing material and level of insulation

Site	Roof Insulation Level	Roofing Material	Identification Code
Genoa	Low	Warm	**G-WL**
		Cool	**G-CL**
	High	Warm	**G-WH**
		Cool	**G-CH**
Madrid	Low	Warm	**M-WL**
		Cool	**M-CL**
	High	Warm	**M-WH**
		Cool	**M-CH**
Cairo	Low	Warm	**C-WL**
		Cool	**C-CL**
	High	Warm	**C-WH**
		Cool	**C-CH**

2.3 Simulation software

In this research, a robust building energy simulation program was used. It is named EnergyPlus. It has been developed by DOE (Department of Energy, U.S.) and bases on the previous experiences gained by means of BLAST and DOE-2.1. This program performs simulations of the building and system as a whole. It calculates the thermal loads to be satisfied and defines the system strategy needed to fulfil the required comfort conditions. Such a program allows users to obtain a detailed description of the most common systems. This way, consistent predictions of design peak loads and yearly energy consumptions are obtained. In the present research, EnergyPlus is mainly used in order to predict the thermal behaviour of the building envelop. The modelled HVAC system is simple because the focus was on the effect of roofing materials on the cooling energy consumptions.

3. RESULTS

The results of the energy simulations for the 12 cases mentioned above (Table 2) are presented.
The yearly maximum external surface temperature of the roof are reported in Table 3.

Table 3. Yearly maximum external surface temperature of the roof

	Identification code			
Site	**WL (Reference)**	**WH**	**CL**	**CH**
Genoa	81.5°C	81.9°C	37.9°C	37.8°C
Madrid	82.8°C	83.2°C	39.1°C	39.1°C
Cairo	103.8°C	104.2°C	50.5°C	50.6°C

The maximum outside surface temperature does not depend on the roof insulation thickness, as shown in Table 3. The maximum roof external surface temperature depends on the roofing material and the site, as shown in Figure 1 and Figure 2. In fact, the outside surface temperature has the same profile in both cases, regardless to the roof insulation level.

The roof inside surface temperature shows important variations, instead. In the case of high insulation thickness, this temperature has a low rise and the peak temperature is shifted about three hours later than in the case of high U-value roof. This implies higher comfort levels too, since the mean radiant temperature perceived by the occupants is lower.

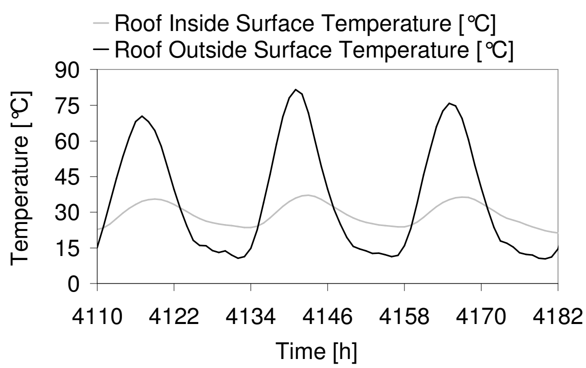

Figure 1 – Roof inside and outside surface temperature in simulation GWL, from the 20th of June to the 22nd of June

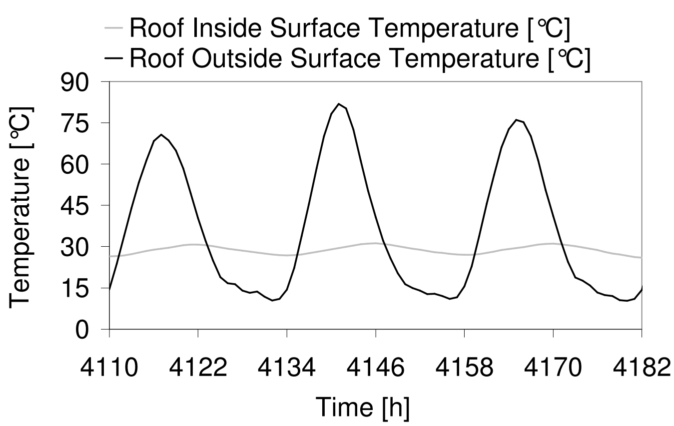

Figure 2 – Roof inside and outside surface temperature in simulation GWH, from the 20th of June to the 22nd of June

Then, the attention may be focussed on the difference in the external roof side maximum temperature due to the roofing material. When cool roofing material is used, the maximum roof outside surface temperatures are 40÷50°C lower than in the reference case. This implies lower thermal stresses for the roofing materials and lowers the heat island effect, hence the feasibility of using the roof even as a usable area.

Such a difference is clear comparing Figure 1 with Figure 3.

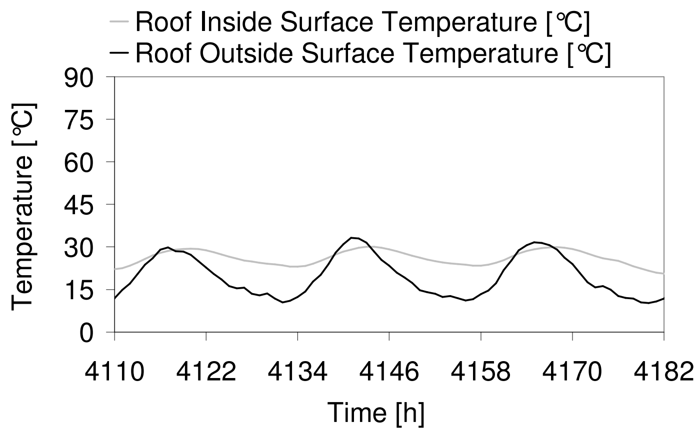

Figure 3 - Temperature at the external and internal sides of the roof in simulation GCL, from the 20th of June to the 22nd of June

During night time and cloudy days, the roof outside surface temperature profile is almost the same, as shown in Figure 1, Figure 2 and Figure 3, whatever the insulation level and the roofing materials. In fact, in such conditions, the thermal behaviour of the roof surface is mainly influenced by the infrared emittance of the roofing material. As introduced in the first part of the present paper, differences in the emittance of various building materials are low, so the behaviour of the external side of the roof is not relevantly modified by the choice of the roofing material, during low solar radiation periods.

As regards the energy aspect, the heating energy consumption is negligible in Genoa and Madrid, and it is null in Cairo. The heating system was working only at Monday mornings for few hours in wintertime, in order to reach set conditions since the very first occupation hours. During the weekends the internal heat gains generated by people and equipment is null.

The sensible cooling energy consumptions for the twelve simulated cases are summarized in Table 4. The latent load is not reported because the HVAC system does not control the humidity level. In the Table 4 the percentage of energy savings compared to the reference case is reported between brackets.

Table 4 Sensible energy consumptions as a function of the location (city), the thermal insulation level and the roofing material. The percentage of savings compared with the reverence case (WL) is reported between brackets

	Sensible Cooling Energy			
Site	WL (Reference)	WH	CL	CH
	Consumption [$kWhm^{-3}$]	Consumption [$kWhm^{-3}$]	Consumption [$kWhm^{-3}$]	Consumption [$kWhm^{-3}$]
Genoa	7.46	6.52 (13%)	4.39 (41%)	5.37 (28%)
Madrid	8.87	7.51 (15%)	5.11 (42%)	6.16 (31%)
Cairo	21.61	18.89 (13%)	15.29 (29%)	16.56 (23%)

The highest sensible cooling consumption is obtained for the reference case, where the traditional roofing material (solar reflectance = 0.06) and the low thermal insulation level (U = 0.6 $Wm^{-2}K^{-1}$) are used. When the "Warm" roofing material is used, the required energy is lowered if a higher level of thermal insulation is applied (0.2 m of glasswool against 0.06 m).

4. DISCUSSION

At first, it must be pointed out that the roofing solutions presented in this article affect many factors of the thermal balance of the enclosure. The emittance, solar reflectance and thermal insulation level influence the heat transfer phenomena.

The thermal insulation affects the sensible cooling savings in two opposite ways, depending on the roofing materials. In the case of "warm" roofing materials, the usage of a high thermal insulation reduces the sensible cooling energy consumption. In the case of "cool" roofing materials, the use of a high thermal insulation increases the sensible cooling energy consumption. The reason is explained below.

The roof thermal insulation hampers the heat conduction from the outside surface towards the inside one and vice versa. It means that it reduces the incoming heat flow from the sun radiation and at also the outgoing heat flux induced by the indoor heat gains. In the case of "warm" materials, heat flows due to solar radiation are prevailing, so an increase in thermal insulation implies the reduction of sensible cooling energy consumption. In the case of "cool" materials, the fraction of absorbed solar radiation is low (high s_r values), so internal gains constitute an important amount of the heat flows. In this case, the thermal insulation lowers the discharge of heat from indoor to outdoor.

The variations in sensible cooling energy consumptions, shown in Table 4, indicate the benefit of using the cool roofing materials. The percentage of the savings is not a good index of the effect of the cool roofing material, because it also depends on the contributions of internal heat gains and external heat flows coming from infiltration and conduction through the walls. Thus, the cooling saving percentage can not be extended to others cases. An example is the case of Cairo, compared to Madrid, when cool roofing materials are used. In Cairo the sensible cooling energy savings are equal to 30%, that is lower than in Madrid (about 41%). That is due the high outdoor environment temperatures in Cairo, compared with Madrid. In fact, that implies higher heat loads due to infiltration and heat conduction, thus the influence of the savings acted by the roof.

The sensible cooling energy savings obtained using a cool roofing material is high compared with the values found in the literature. This is due to the really high value of the solar reflectance. In the simulation the most different roofing material were used in order to stress the different behaviors and find which are the maximum sensible cooling energy savings. Weathering would soon reduce the performance of the cool roofing material. In this paper this aspect was not taken into account, but in practice it should be considered.

5. CONCLUSIONS

The main conclusions are listed below:

1. Using a cool roofing material in the Mediterranean area for industrial premises leads to significant sensible cooling energy savings, up to 42%. Those results were obtained using the best cool roofing material available on the market.
2. The maximum roof outside surface temperature does not depend on the roof insulation thickness.
3. The maximum roof outside surface temperatures decrease of 40÷50°C when the cool roofing materials are applied.

6. REFERENCES

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