THE USE OF CERAMIC FILLED WHITE ELASTOMERIC ACRYLIC COATINGS TO REDUCE THE THERMAL LOAD OF BUILDINGS WITH LOW SLOPE ROOFS

João Pereira de Brito Filho
jbrito@ufpe.br.
Department of Electronic and Systems, Federal University of Pernambuco.

Abstract: Commercial and industrial buildings such as shopping centers, supermarkets, airports and sheds are in general some of the construction types characterized as having large roof surfaces compared to external wall surfaces. When climatized artificially, these buildings become great consumers of electrical energy. In order to reduce this energy consumption, insulation materials such as polyurethane and fiberglass wool are added to it. This is the mass insulation approach. Notwithstanding the effectiveness of such procedure, cost and environmental issues has been considered as limited factors to his widespread utilization. In this paper, it is analyzed the effect of the application of a selective ceramic filled white elastomeric acrylic coating with very high solar reflectance and thermal emittance for thermal radiation (5 to 30 μm) on the surface temperature of the roof and heat flux that crosses a mass insulated roof of a artificially climatized building. The study was carried out from a mathematical model that took into account the following parameters: time varying solar radiation and outside air temperature and additionally the properties of the construction materials of the roof. The results obtained demonstrate the good performance of selective coatings concerning the temperature of the roof and the heat flux reduction.
Keywords: Roofs, Insulation materials, Selective coating, Passive cooling, Energy.

1. INTRODUCTION

Cooling and heating are important methods to improve well-being conditions both in residential and commercial activities. In non-residential buildings, it is well-known that better employee's productivity can be reached when a thermal comfort standard is provided. As the most commonly used indicators of thermal discomfort in an indoors ambient are air and radiant temperature, one has to deal with effective procedures to minimize these phenomena.

In many workplaces, passive cooling methods alone are normally insufficient to guarantee acceptable temperature levels. Therefore, active methods such as the use of air conditioning systems are the alternative to reduce thermal discomfort on employees.

Heat transfer in walls, windows, roofs and floors of residential and non-residential buildings has been investigated intensively since the first oil crisis that occured in 1973. Some investigations deal with the different external walls conceptions (Lindberg *et al*, 2004 and Dombayci *et al*, 2006), double glass in windows (Smail & Henríquez, 2004 and Yang & Hu, 2006), ground heat exchangers (Kyriakis *et al*, 2006), building orientation (Mingfang, 2002), green roofs (Del Barrio, 1998 and Lazzarin *et al*, 2005) and so on. However, heat transfer in roofs in both conditioned and non-conditioned buildings has not been steadily studied (Abkari *et al*, 1999 and Bretz & Akbari, 1997).

Metallic roofs have been used in non-residential buildings such as in industry sheds, supermarkets and shopping centers because they are light and have low cost installation. In these buildings, the roof is certainly more exposed to the solar radiation than the external walls, having high internal temperature during the sunlight hours because they absorb fast 100% of the incoming solar radiation. They are responsible to great thermal loads, huge air-conditioning costs and the occurrence of elevated peak electricity load.

The classical approach to reduce thermal load in such cases consists of applying mass insulation layers such as polyurethane foam to the exterior surface of the roof and fiberglass wool underneath the metallic surface, in order to reduce heat transfer by conduction. Although a thicker mass insulation layer yields a higher resistance to heat transfer and consequently a lower thermal load, the cost of increasing the thickness of the mass insulation play an important role and should be considered. Mass insulations can reduce peak temperature during the day, but they release it during the night, producing important environmental concerns, such as the increase of urban temperature. Studies carried out worldwide have demonstrated that the reduction of the material surface temperature used in the buildings envelope (external walls and roofs) can give a significant contribution to mitigate the negative consequences of the so-called heat island phenomenon to the environment.

An alternative to increasing the thickness of the mass insulation is to combine heat transfer by conduction with heat transfer by thermal radiation. This means, the use of selective coatings applied on the external surface of a metallic roof with high solar reflectance or albedo and emittance in infrared regions (the infrared radiation corresponds to approximately 43% of the solar radiation spectrum).

The use of acrylic coatings to reduce air conditioning demand has been also investigated in the last two decades (Berdhal & Bretz, 1997). Experimental results have demonstrated that white elastomeric acrylic coatings could reduce the thermal load of poorly insulated roofs significantly. Furthermore, the coating can also protect the surface against degradation by thermal shock and water, thus minimizing roof maintenance and corrosion problems and therefore increasing its cost effectiveness.

In this work, a theoretical study was carried out in order to evaluate the effect of a selective coating with high solar reflectance and thermal emittance on the surface temperature of the roof as well as on the heat flux through it. The model allows a comparison of the thermal behavior of any kind of flat and smooth roof composition of an artificially climatized building. In the solution of the model equations, the unknowns are: the temperature profile on both external and internal horizontally positioned surface of the roof and the heat flux that reaches the internal ambient as a function of time. On the order hand, the main data used in the simulations are: thermophysical properties and geometry of the materials, solar radiation and outside air temperature values.

2. PHYSICAL MODEL

There are many geometries of roofs and materials commercially available (metal, sandwich, built-up, EPDM membrane, PVC, sprayed polyurethane, concrete deck etc.). In this study, it was considered a flat, smooth and horizontally positioned one made of multiples layers.

Figure 1 shows a composite roof consisting of M layers each of them of thickness L and thermal conductivity k. The external surface of layer 1 is assumed to be in contact with the outside air, having time varying temperature $T_a(t)$, and exposed to solar radiation $q_s(t)$ on the plan of the roof. In this surface, heat transfer occurs by natural convection and thermal radiation.

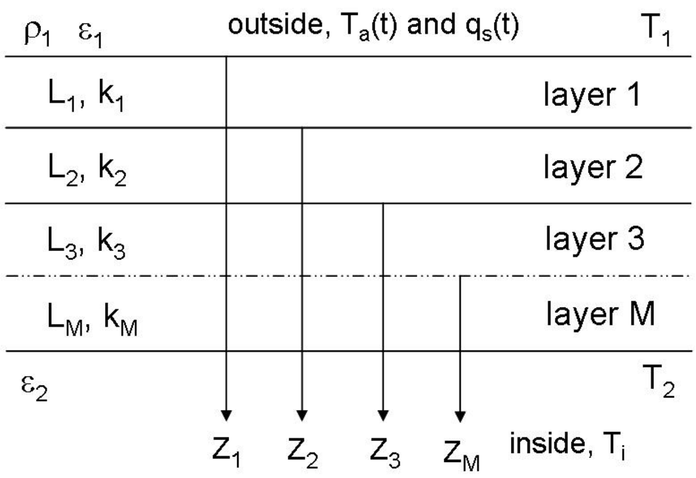


Figure 1 – Composite roof.

Otherwise, the external surface of layer M is assumed to be exposed to the inside air, having temperature T_i, held constant. In this surface, heat transfer occurs by natural convection and thermal radiation.

The heat transfer equations to study the influence of the thermal radiation properties of selective coatings on the temperature of the roof and heat flux that reaches the internal ambient were obtained applying the energy conservation principles on one unit section of the roof and assuming radiation and convection boundary conditions. In the model, the following assumptions were made:

- one-dimensional heat conduction;
- steady-state regime;
- temperature-independent thermophysical properties and
- constant convection heat transfer coefficients.

The temporal and periodic conditions are given by the outside air temperature and by the horizontal solar radiation. The differential equations obtained were:

$$\nabla T^2 = 0 \quad (1 \le m \le M) \tag{1}$$

$$-k_1 \left.\frac{dT_1}{dz_1}\right|_{z_1=0} = (1-\rho_1)q_s + h_1(T_a - T_1) \quad \text{(m=1)} \tag{2}$$

$$-k_{m-1}\left.\frac{dT_{m-1}}{dz_{m-1}}\right|_{z_{m-1}=L_{m-1}} = -k_m \left.\frac{dT_m}{dz_m}\right|_{z_m=0} \quad (2 \le m \le M) \tag{3}$$

$$-k_m \left.\frac{dT_m}{dz_m}\right|_{z_m=0} = h_2(T_2 - T_i) \quad (m=M) \tag{4}$$

In the present model, the thermal contact resistances between each layer were not considered. This assumption leads to the following condition:

$$T\Big|_{z_{m-1=L_{m-1}}} = T\Big|_{z_m=0} \tag{5}$$

The effective heat transfer coefficients h_1 and h_2 of both external and internal surfaces of the roof in Eq.(2) and (4) are given by:

$$h_1 = h_e + \varepsilon_1\sigma({T_a}^2 - {T_1}^2)(T_a + T_1) \tag{6}$$

$$h_2 = h_i + \varepsilon_2\sigma({T_2}^2 - Ti^2)(T_2 + T_i) \tag{7}$$

In Eq.(2), ρ_1 is the solar reflectance, (ε_1, ε_2) and σ in Eqs.(6-7) are the thermal emittance for the thermal radiation and the Stefan-Boltzmann constant, respectively. Both coefficients of natural convection heat transfer h_e e h_i were assumed to be equal to 6 W/m²K (very low wind velocity condition).

3. NUMERICAL STUDY

The numerical study was carried out using the Mathcad software and performed according to the following main steps:

1. Calculation of the solar radiation $q_s(t)$ on the plan of the roof;
2. Calculation of the outside air temperature $T_a(t)$;
3. Calculation of the outside surfaces temperature T_1 and T_2 and
4. Calculation of the heat flux that crosses the roof.

To calculate $q_s(t)$ and $T_a(t)$, climatic data from Rio de Janeiro (30°South) was used. This city was chosen because it has very hot summer days as well as great fluctuations in the air temperature in a 24h period.

In order to evaluate the benefit of use a selective coating on the external surface of the roof, four alternative concepts were considered, as follows:

- Aluminum;
- Aluminum with a selective coating layer;
- Polyurethane layer between two aluminum foils and
- Polyurethane layer between two aluminum foils, one of them (the external) with a selective coating layer.

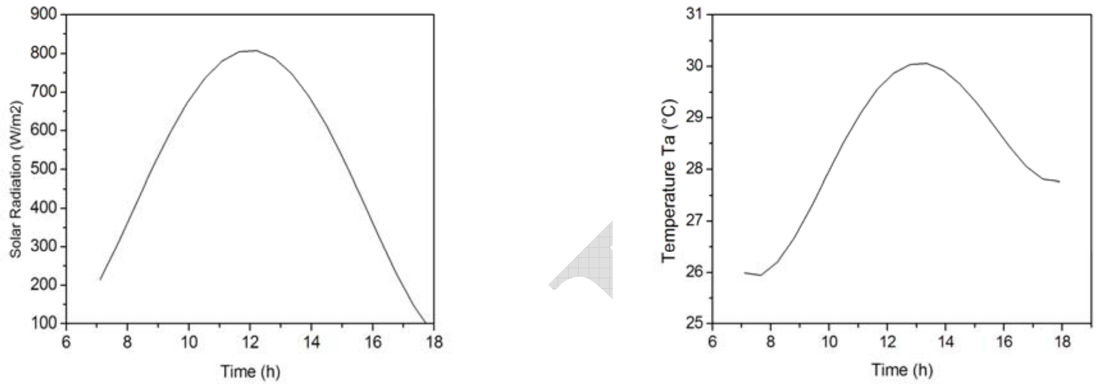
The calculation procedure used to evaluate $q_s(t)$ and $T_a(t)$ took into account both diffuse and direct monthly average daily solar radiation, monthly average daily temperature, monthly average daily minimum and maximum temperature of one typical day, in this case, February 16. Details of these calculations can be found in Brito Filho & Fraidenraich (2006).

The selective coating used was Maxtherm (www.emcdobrasil.com.br), a Brazilian product that uses an American technology. Table 1 presents the thermophysical properties of the materials of the roof and the selective coating used in the simulations.

Table 1. Thermophysical properties of the materials of the roof and of the selective coating.

Material	ρ_1(-)	ε(-)	k(W/m.K)	L(m)
Coating	0,8	0,9	0,00345	0,00003
Aluminum	0,35	0,216	206	0,0005
Polyurethane	x	x	0,0186	0,025

Figure 2 (a) shows the solar radiation on the plan of the roof and (b) the air temperature in Rio de Janeiro during sunrise and sunset in February 16.

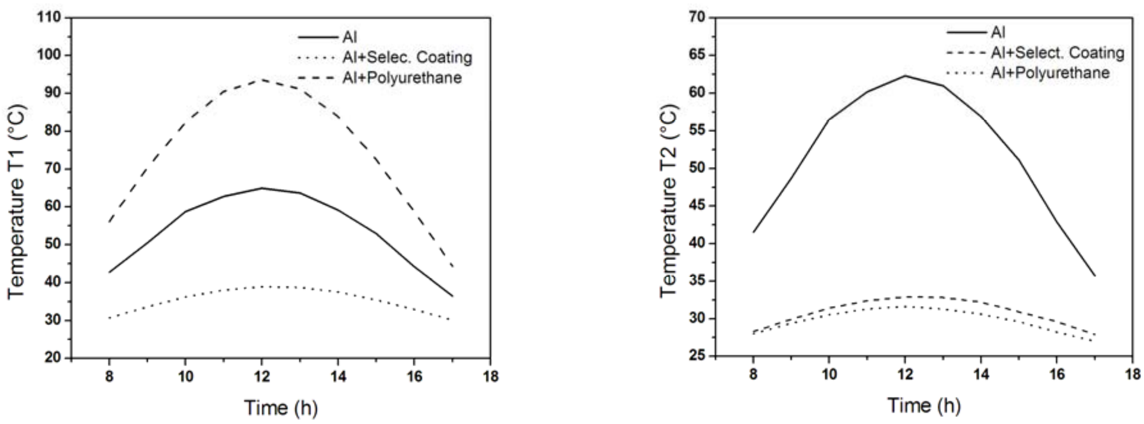


(a) (b)

Figure 2 – (a) solar radiation on the plan of the roof and (b) ambient air temperature in Rio de Janeiro (average daily temperature 26.5°C).

4. RESULTS AND DISCUSSIONS

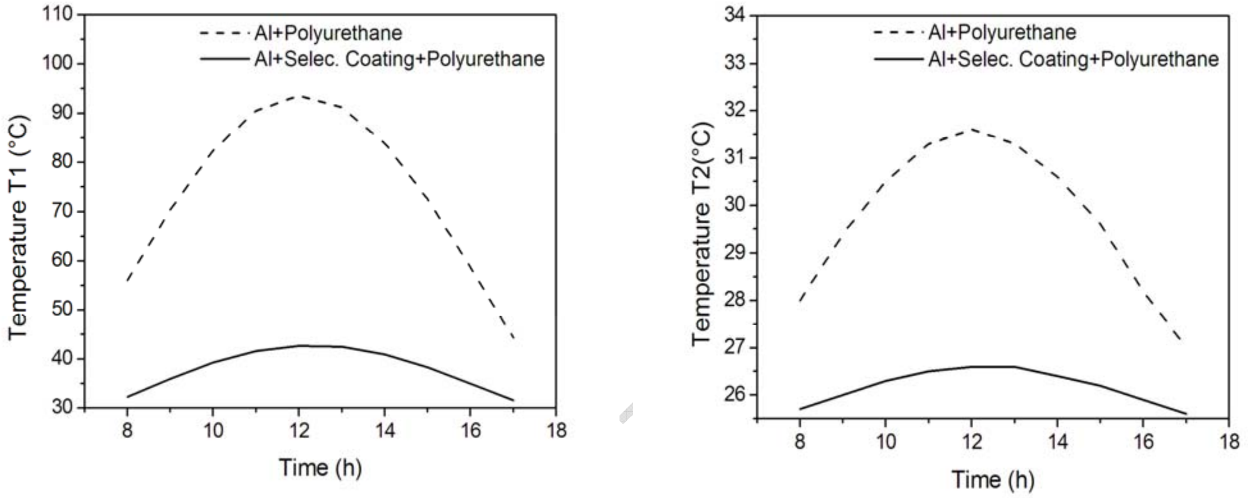
Figures 3a and b show the outside (T_1) and the inside (T_2) surface temperature profile of the roof during daytime for three of the four types of roofs mentioned above: (i) aluminum, (ii) aluminum with selective coating and (iii) polyurethane layer between two aluminum foils. In these three cases, the maximum outside surface temperature occurs at 12h approximately. The roof with polyurethane (dashed line in Fig.3a) has a maximum outside temperature of 94°C, while the aluminum roof with a selective coating layer (doted line in Fig.3a), this temperature is 39°C. It is evident that the mass insulation method contributes significantly to increase the heat island phenomenon. On the other hand, no important difference is observed between the maximum internal surface temperatures in those cases, as it is showed in Fig.3b.



(a) (b)

Figure 3 - (a) outside (T_1) and (b) inside (T_2) surface temperatures of the roof for three roofs types (aluminum, aluminum with selective coating and polyurethane layer in between two aluminum foils).

Figures 4a and b show the outside (T_1) and the inside (T_2) surface temperature profile during daytime for the roof composed of a polyurethane layer between two aluminum foils.



(a) (b)

Figure 4 – (a) outside (T_1) and (b) inside (T_2) surfaces temperatures of the roof for the polyurethane layer between two aluminum foils.

As expected, the use of a selective coating reduces drastically the surface temperature T_1 in about 50K at 12:20h. On the other hand, the reduction of the temperature T_2 is lower, approximately 5K at the same daytime. It should be pointed out that even with the use of selective coating, the outside surface temperature stays above the external air temperature, as one can verify comparing the results presented in Figs.2b and 4a.

Figure 5 shows the heat flux through the roof composed of a polyurethane layer between two aluminum foils during daytime.

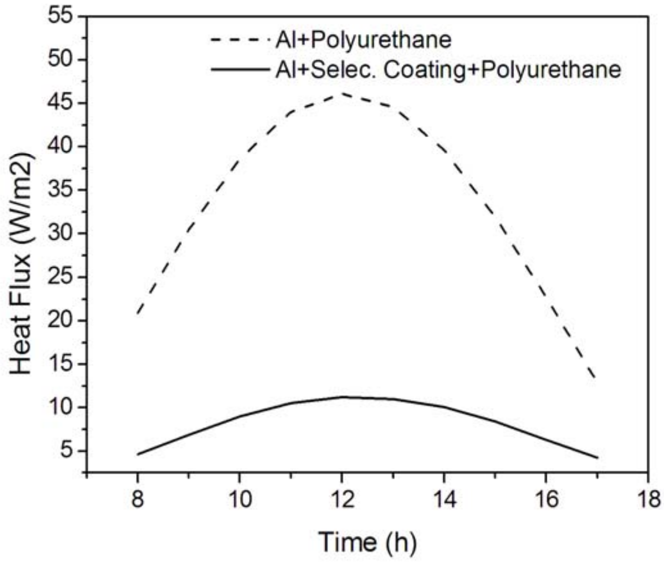


Figure 5 – Heat flux across the roof.

It indicates that the application of a selective coating on the external surface of the roof can reduce drastically the heat flux that reaches the indoor environment. Thereby, the building cooling loads decrease and consequently the electricity consumption by air conditioning during the day, where the outside climatic conditions in summer are very severe, especially in tropical countries.

5. CONCLUSIONS

Non-residential buildings have usually large roof surfaces compared to their external walls. These roofs are certainly the building component more exposed to the solar radiation. Therefore they are responsible for the great electricity consumption due the necessity of installing air conditioning systems to attend thermal comfort requirements. The use of mass insulations can reduce the building thermal load during daytime, but cost and insurance issues and environmental concerns (the contribution to wide spreading heat island effect) represents important restrictions factors that one has to take into account.

The use of selective coatings on the external surface of the roof can reduce significantly the average temperature of the roof and heat flux, reducing consequently buildings air conditioning needs.

Thermal insulation based on selective coatings has also the advantage of protecting the surface against degradation by thermal shock and water, minimizing roof maintenance and reducing the incidence of corrosion. Mass insulation together with the application of a selective coating represents a powerful combination of heat reliability and cost effectiveness.

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