

# Cooling of a dwelling by nocturnal radiation

Othmane Fahim<sup>1</sup>, Naoual Belouaggadia<sup>1</sup>, Mohamed Taqi<sup>1</sup> and Chérifa Abid<sup>2</sup>

<sup>1</sup>: Laboratory of Engineering and Materials (LIMAT), Ben M'Sik Faculty of Sciences, Hassan II University of Casablanca, B.P. 7955 Sidi Othmane, Casablanca, Morocco.

<sup>2</sup>: University Polytechnic School of Marseille, Department of Energy Mechanics, University of Provence.

E-mail: othmanefahim@gmail.com

**Abstract** - Atmospheric transparency in the infrared, responsible for night cooling, is exploited to obtain a cooling effect. Radiative cooling to the night sky is based on the principle of infrared radiation heat loss from a surface to a body at a lower temperature. The use of the emissivity equation allowed us to evaluate its variation as a function of wavelength and temperature. A comparison of the temperature variation was made between granite and the materials most often used in the manufacture of radiant panels of hybrid systems. The results show that the temperature of Tedlar-based plates or plastics considerably decreases, and, therefore are rather promising.

## 1. Introduction

Today, because of the expected shortage of energy supply and air pollution problems, energy conservation is really taken into account not only in the industrial sector, but also at the residential level. The energy required for heating and cooling buildings accounts for about 6.7% of total global energy and most of the cooling systems used are huge energy consumers. The use of passive cooling systems can contribute to a saving of 2.35% of global energy needs [1]. Night-sky cooling to the sky is based on the principle of radiation heat loss from one surface to another at a lower temperature. The roofs of buildings radiate heat, day and night, at an average rate of 75 W / m<sup>2</sup> during the day [2]. The use of the window of transparency of the atmosphere, in the wavelength range of the average infrared (8-14 μm), allows on a clear day, to selective materials whose surface is strongly emitting in the infrared to strongly cool. In this work, we propose to show that we can intensify this effect by a good choice of materials. We perform a comparative study between the performance of the proposed material and the materials most often used in the manufacture of this type of surfaces.

## 2. Determination of the cooling power

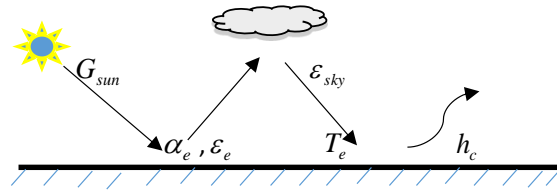
To determine the power of radiative cooling, we must establish the energy balance on a surface. From Fig. 1, we note that if a surface is in equilibrium with its environment, the energy balance of this surface can be expressed by:

$$\phi_{in} = \phi_{sun}(T_{sun}) + \phi_{atm}(T_{amb}) = G_{sun}(T_{sun})\alpha_e T_e + \varepsilon_{sky}(T_e)\alpha_e T_e^4 \quad (1)$$

$$\phi_{out} = \phi_{emittre}(T_e) + \phi_{cv} = \varepsilon_e(T_e)\sigma T_e^4 + h_c(T_{amb} - T_e) \quad (2)$$

$$\phi_{cooling} = \phi_{out} + \phi_{in} \quad (3)$$





**Figure 1.** Diagram explaining the energy balance of a surface

Here,  $\phi$  is the heat flux transferred to or from the surface of the emitter, and  $G$  is the irradiation of the sun. The thermal flux transferred by natural or forced convection (wind) is taken into account in the formulation, with  $h_c$  the coefficient of heat transfer by convection. The emission and absorption coefficients are respectively defined by  $\epsilon$  and  $\alpha$ , which are given here as the total and the average for all the surfaces of the transmitter. In order to correctly model the radiative cooling, we have to express the absorption emission coefficients as a function of the wavelength  $\lambda$ .

One of the situations required for night cooling is a clear sky and a dry air. In a clear sky, without dust or humidity, we could have a nocturnal radiative cooling, i.e.  $\phi_{in} \approx \phi_{out}$ . However, if there is dust and high humidity during the night, we have:  $\phi_{in} \approx \phi_{out}$  and we cannot have radiative cooling. We must emphasize that the most important consideration here is the spectral radiative transfer to and from the transmitter at different wavelengths. With the net spectral change of the radiative flux, we can have the radiation necessary for cooling. Therefore, the equations governing radiative cooling must be written considering monochromatic quantities. For this purpose, we consider an emitting surface (Fig. 1) at temperature  $T_e$ , with emissivity  $\epsilon_e(\lambda, \theta)$  and spectral absorptivity  $\alpha(\lambda, \theta)$ . In this formulation, we assume that a surface is exposed to a clear sky, is the case effectively at 0 K. Of course, the surface may receive the solar radiation and the atmospheric irradiating corresponding to an ambient temperature  $T_{amb}$ . The cooling per unit area of a surface is then expressed by the following relation:  $P_{cooling} = P_{in} - P_{out}$  and  $P_{out} = P_{rad}(T_e) + P_{cv}$  With:

$$P_{cv} = \phi_{cv} = h_c (T_{amb} - T_e) \quad (4)$$

$$P_{rad} = \phi_e(T_e) = 2\pi \int d\Omega \times \cos\theta \int_0^\infty d\lambda \times I_{BB}(T, \lambda) \times \epsilon(\lambda, \Omega) \quad (5)$$

$P_{cv}$  is the resulting power of the exchange by convection with the atmosphere.  $P_{rad}$  The radiation from the surface area per unit of surface, and integrated on the solid angle encompassing the Hemisphere

$$d\Omega = \int_0^{\pi/2} d\theta \times \sin\theta \int_0^{2\pi} d\phi \quad (6)$$

The radiative intensity of the spectral blackbody is expressed by:

$$I(T, \lambda) = \left( \frac{C_1}{\lambda^5} \right) / \left[ e^{\frac{C_2}{\lambda T}} - 1 \right] \quad (7)$$

The expression of the coefficients  $C_1$  and  $C_2$  is  $C_1 = 2hc^2$  with  $C_2 = h \frac{c}{k}$

$$P_{in} = P_{atm} + P_{sun} = \int d\Omega \cos\theta \times \int_0^\infty \epsilon(\lambda, \theta) \times \epsilon_{sky}(\lambda, \theta) \times I(\lambda, T_{sky}) d\lambda + \int_0^\infty \epsilon(\lambda, \theta) \times I(\lambda) d\lambda \quad (8)$$

$P_{ent}$  is the incident solar power absorbed by the surface per unit area. To obtain  $P_{soliel}$  and  $P_{atm}$ , we use Kirchhoff's law  $\alpha_\lambda = \epsilon_\lambda$  to replace the absorptivity of surface by the emissivity. Particularly, there are many correlations to calculate the emissivity of the sky which depend on the state of the sky clear or cloudy, we will remember them in Table.1

Clear sky		Cloudy sky	
Reference	Correlation	Reference	correlation
[2]	$\varepsilon_{cc} = 1 - 0.261 \exp[-7.77 \times 10^{-4} \times (273 - T_{amb})]$	[6]	$\varepsilon_{ciel} = (1 + 0.0496c^{2.45})\varepsilon_{cc}$
[3]	$\varepsilon_{cc} = 0.7 + 5.95 \times 10^{-5} e_{amb} \exp(1500/T_{amb})$	[7]	$\varepsilon_{ciel} = (1.03 + 0.34c)\varepsilon_{cc}$
[4]	$\varepsilon_{cc} = 1.24 \times (e_{amb}/T_{amb})^{1/7}$	[6]	$\varepsilon_{ciel} = (1 + 0.22c^{2.75})\varepsilon_{cc}$
[5]	$\varepsilon_{cc} = 0.770 + 0.0038T_{dp}$	[9]	$\varepsilon_{cc} = \varepsilon_{cc} + (1 + 0.0024n + 0.0035n^2 + 0.00028n^3)$

**Table 1.** Formulas for calculating emissivity in a clear and cloudy sky

### 3. Choice of materials

The emissivity of natural substances depends, in a general way, on their physical-chemical nature, their state of geometrical surfaces (flatness defects, roughness) and varies with the wavelength, the direction of emission and the surface temperature. The monochromatic expression is as follows:

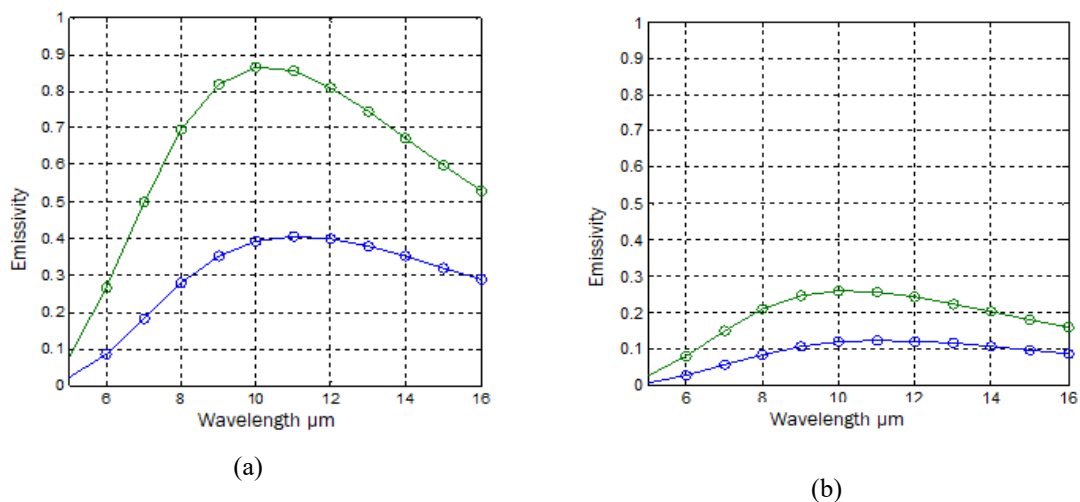
$$\varepsilon_{\lambda}(T) = \frac{\int_0^{\infty} \varepsilon(\lambda, T) M_{\lambda, T}^0 d\lambda}{\int_0^{\infty} M_{\lambda, T}^0 d\lambda} \quad (9)$$

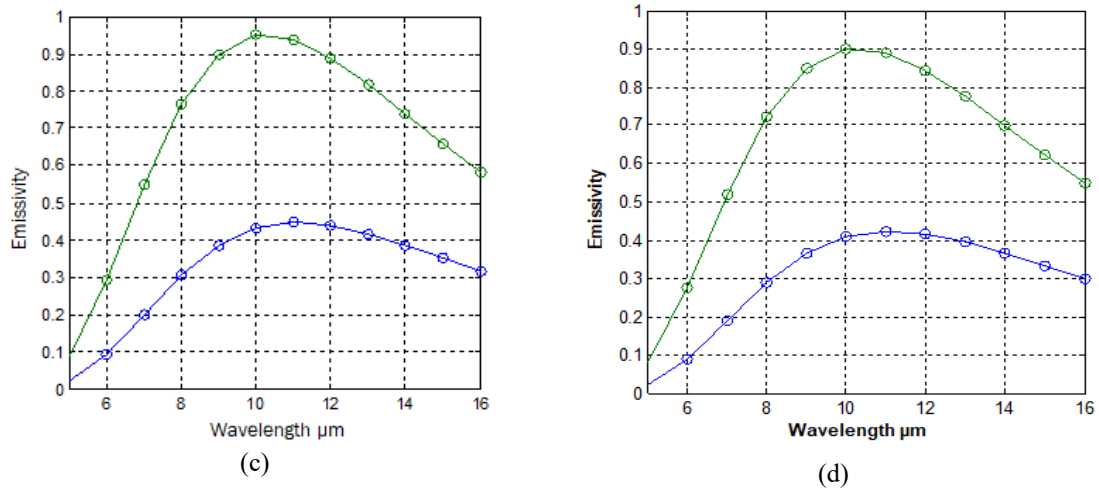
The systematic study of the properties of the few materials used in the manufacture of radiative panels led us to select four materials: Tedlar, already used by Silvestrini [9], white plastic, copper and granite. The study of the thermal radiation of the materials made it possible to highlight two great classes of radiative behavior: that of electrically conductive materials (Copper), and that of dielectrics (granite and white plastic). The properties of the selected materials are presented in Table 2.

**Table 2.** A few properties of thermo-physical of selected materials

	mass density kg/m <sup>3</sup>	thermal conductivity W/(m.K)	specific heat J/(Kg)
Granite	2650	3,0~3,4	834
Copper	8920	401	385
White plastic	1 190	0.7~1,4	1050
Tedlar	1390	0.033	1400

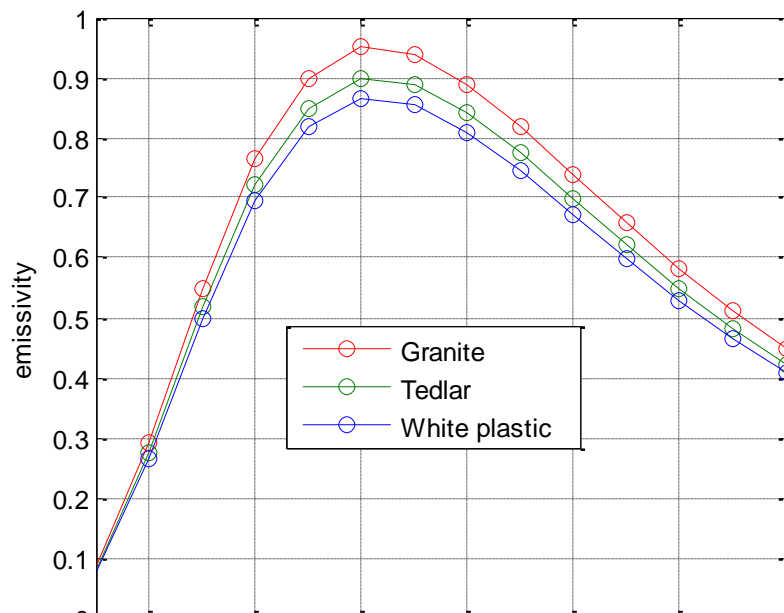
In Fig. 2, we plotted the variation of the emissivity of the selected materials as a function of the wavelength (5-15  $\mu\text{m}$ ) for two different temperatures of the emitter; in blue  $T_e = 286$  K and in green  $T_e = 310$  K.





**Figure 2.** (a), (b), (c) and (d) are respectively the variation of the emissivity as a function of the wavelength of white, copper, granite and Tedlar plastics. In a clear sky and an atmospheric temperature equal to 285 K

The Graphs tell us, with a flat surface its temperature is equal to the atmospheric temperature, the emissivity does not exceed its initial value even if in a field where the rays can easily switch to the atmosphere and it is seen in all the curves in blue. This is correct, because the cooling by night radiation based on the principle of heat loss by radiation to the atmosphere until reaching a thermal equilibrium ( $T_{at} = T_e$ ). In general, the monochromatic emissivity increases with the growth of  $T$  and  $\lambda$  in the atmospheric window and helpless when the atmospheric window when  $\lambda$  exceeds 13 μm. In order to compare the total monochromatic emissivity of these materials in the atmospheric window (8-14 μm), we have considered the following limiting case:  $\tau = 1$  and  $E_{at}(\lambda) = 0$  between 8-13 μm. where  $E_{at}$  is the atmospheric illumination and  $\tau$  is the transmission coefficient.



**Figure 3.** Comparison of the emissivity variation of selected materials between 8-14 μ.

From the results of Figure 2, we will choose the materials that have a great performance in the atmospheric window "Granite, Tedlar and White Plastic" in order. So to compare the variation of the monochromatic emissivity of these materials in the range of 5-18  $\mu\text{m}$  with a transmitter temperature equal to 310K while the temperature of the sky is 285K. When the temperature of the emitter is very high compared to that of the atmosphere, the emissivity of the materials can reach its maximum values of 9 to 10  $\mu\text{m}$ . However, it considerably decreases when this value is exceeded (Tab.2). The emissivity of granite is then slightly higher than that of Tedlar and white plastic. (Fig.3).

Wave length ( $\mu\text{m}$ )	Emissivity			
	Granite	Cuivre	White Plastic	Tedlar
8	0.76	0.20	0.69	0.72
10	0.95	0.24	0.86	0.89
12	0.88	0.20	0.80	0.84

**Table 2.** Emissivity values of materials in certain wavelengths

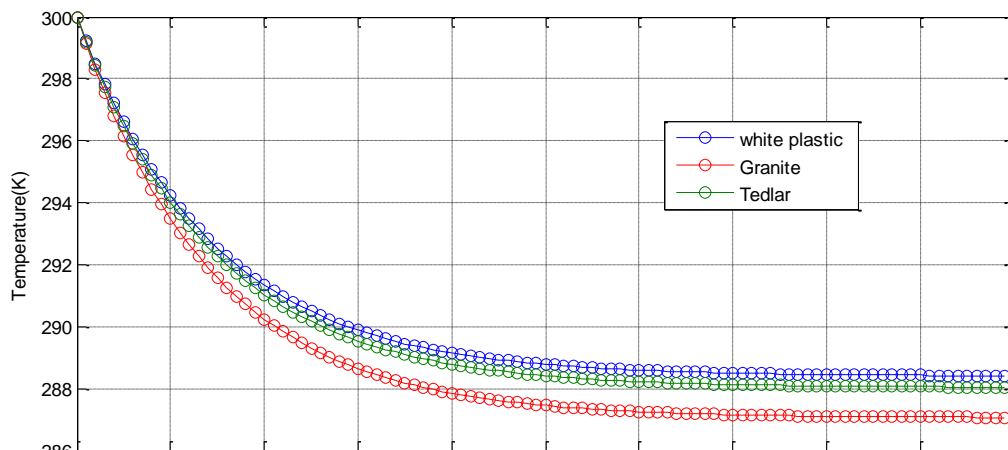
#### 4. The temperature evaluation

In this section we assess the temperature of the selected materials as a function of time in the interval of 8-14  $\mu$  (Fig.3) and to simplify the calculation we have neglected the heat transfer by conduction as well the Effects panel. In the application of the variation of the internal energy of a plate characterize by; 0.06 m in thickness and 1m<sup>2</sup> surface area, we obtained the differential equation:

$$\frac{dT}{dt} + AT^4 + BT = C \quad (10)$$

Where :

$$A = \frac{\sigma(\varepsilon_{sky} + \varepsilon_e)}{e \times \rho \times C_p} ; \quad B = \frac{h}{e \times \rho \times C_p} ; \quad C = \frac{hT_{amb} + \sigma(\varepsilon_{sky} + \varepsilon_e)}{e \times \rho \times C_p}$$



**Figure 4.** Temperature variation of selected materials at night

In figure. 4, we have shown the evolution of the temperature as a function of time for plates formed respectively by copper, white plastic, granite and Tedlar. The temperature of the different plates decreases with time. Granite is the most efficient since the temperature of the corresponding plate decreases by 13 ° C, this is due to its emissivity coefficient which can reach 0.95 in the atmospheric window. The temperatures of the Tedlar and white plastic plates decreased by 12 ° C and 11.7 ° C, respectively, for two minutes before stagnating. The temperature drop of the copper plate is 3.9 ° C. It

is obvious then that the heat loss due to the considerable temperature difference in the night, will be able to provide cooling power in certain climatic zones in Morocco. This power will be optimized by a suitable choice of materials depending on the surrounding conditions.

### 5. Evaluation of the power of nocturnal cooling

We used the energy balance (Eq.3) to establish the expression of the net cooling power and to simplify the calculations we assumed that:

- The radiator is placed so that the conduction due to the ground is actually a convection ;
- The flow is zero because of the absence of solar rays ;

So the net cooling expression becomes on the following form:

$$\phi_{refr,nette} = \varepsilon_e(T_e)\sigma T_e^4 - \varepsilon_{ciel}\alpha_e(T_e)\sigma T_{ciel}^4 + h_c(T_{amb} - T_e) \quad (11)$$

The emission and absorption coefficients are given taken here as the average for all surfaces of the transmitter. In the choice of correlations to calculate the emissivity of the sky we considered that the state of the sky is clear, so we can calculate its value by:

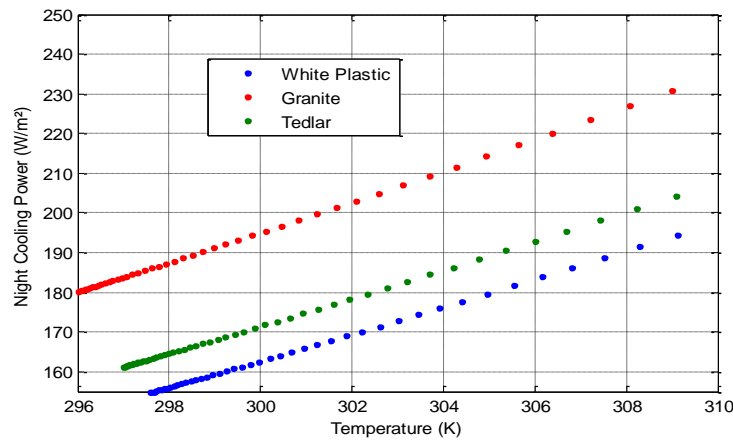
$$\varepsilon_{sky} = 0.77 + 0.0038T_{dp} \quad (12)$$

Where  $T_{dp}$  and  $T_{sky}$  are respectively the dew-point temperature and the temperature of the sky. We can express this last by the following correlation:

$$T_{skyl} = 0.0522T_{amb}^{1.5} \quad (13)$$

And  $h_c$  is the coefficient of exchange we can express it by the following correlation [10] :

$$h_c = 2,8 + 3,3 V \quad (14)$$



**Figure 5.** The variation in power as a function of transmitter temperature, in  $T_{amb} = 285K$ .

The decrease of temperature  $T_e$  is accompanied by a decrease in the cooling power, i.e. a drop of 13°C for granite, 12 °C and 11.7 °C for white plastic and Teldar respectively. As a result, the powers vary in a decreasing way up to a well-defined value of 180 W / m², 161.2 W / m² and 160 W / m², respectively presented by granite, Teldar and white plastic with an average difference of 19.4W / m² produced by the granite vis-à-vis compared to the other materials. These values reflect the equilibrium reached between the temperature  $T_e$  and  $T_{amb}$ .

### References

- [1] Energy Savings Potential of Radiative Cooling Technologies. (2015), (November).
- [2] Sloant, R., Shaw, J. H., & Williams, D. (1956). Rxx-DsxlKnx,(1), 46(7), 2–6.

- [3] Skies, F. C. (1981). A Set of Equations for Full Spectrum and a oTon above studies, 17(2), 295–304.
- [4] Resources, W. (1975). On a Derivable Formula for Long-Wave Radiation From Clear Skies FLD ), 11(5), 742–744.
- [5] Begger, X., & Burriot, D. (1984). About the Equivalent Radiative Temperature, 32(6), 725–733.
- [6] Sugita, M., & Surface, L. (1993). Cloud Effect in the Estimation of Instantaneous Downward Longwave Radiation, 29(3)
- [7] Lhomme, J. P., Vacher, J. J., & Rocheteau, A. (2007). Estimating downward long-wave radiation on the Andean Altiplano, 145, 139–148. <https://doi.org/10.1016/j.agrformet.2007.04.007>
- [8] Maykut, 1973. Report of the Joint U.S. POLEX Panel to the U.S. Committee for the Global Atmosphere [i.e. Atmospheric] Research Program (GARP), Committee on Polar Research (CPR), Committee on Atmospheric Sciences (CAS), Ocean Science Committee (OSC). USA
- [9] Cuomo, V., & Silvestrini, V. (1975). The Radiative Cooling of Selective Surfaces, 17.
- [10] Maamar Hamdani, Sidi Mohammed El Amine Bekkouche, Tayeb Benouaz, Rafik Belarbi, Mohamed Kamel cherier, 'Minimization of indoor temperature and total solar insolation by Optimizing the building orientation in hot climate', Engineering structures and Technologies, N°6, pp 131-149,2014