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System multilayered applied to the radiative cooling

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In applied optics, the multilayered structures (MLS) take an important place in many instrumental and industrial devices. The aim of this work is to study the MLS in order to optimize the inverse greenhouse effect ; its is made by a survey on theoretical formalism of the energy exchange phenomena. This optimization requires that the window materials (MLS) are good reflectors in the visible range and assuring a total transmission in the infrared zone (8-13 µm). One of the support elements, of the window, answering to these criterions is germanium, for which we have studied the thickness influence and have found that the equilibrium temperature reached by the absorber has a minimal value between 0.01 µm and 0.06 µm. However, only with germanium, the window can not products the inverse greenhouse effect. Indeed, the germanium must include other layers in order to increase the visible reflectance and the infrared transmittance (8-13µm) ; what forms a multilayered structure. Several system have been used, only 7 of them have been kept for this work: S1, S2, …, S7 systems
Only the following systems : S2/S1, S3/S2/S1 and MgO/S3/S2/S1 give a radiative cooling effect, with a very good result of 15 °C below ambient temperature in the case of the S6 system. To approach of the real conditions of this system realization (S6), we simulated the effects of such imperfections, as presence of air, that would be due to the quality of the layers deposition. This study is made in the case of the S7 system. As results, we found that, for zenithal angles ≤ 60°, the layers of air, for which the thickness is lower than 0.5 µm, don't present any influence on the absorber's equilibrium temperature.

I. INTRODUCTION

In this work, we are interested to study the inverse greenhouse effect, again called radiative cooling. This phenomenon represents an exchange of energy between the bodies and the atmospheres, with a leak of energy due to the existence of transparency region in the emission spectrum of the atmosphere (8-13µm)[1,2]. Therefore, the terrestrial radiation in this range of wavelength is not counterbalanced by atmospheric flux. The consequence that ensues from, is a temperature drop in comparison with the ambient environment.

Several works have been done in order to produce the inverse greenhouse effect[3-9]. This work examines the relation between the radiative properties of the bodies and the distribution of the system equilibrium temperatures, in the case where the exchanges are dominated by the radiation transfers. Our simulation interest numerous convenient questions about exploitation problems and solar energy controls. The optimization of the greenhouse effects and the inverse greenhouse effects is part of these questions.

To succeed the radiative cooling optimization, the multilayered structures must then satisfy the two followings conditions : (i) a total reflection outside of the atmospheric window and (ii) a good infrared transmission. The resolution of these two problems will give the essential tool of a competitive industrial exploitation in comparison with the other means of cooling, notably electric. In this work, we do a survey on the theoretical formalism of the energy exchange phenomena ; what permits us to show how the temperature of a system given can depend mainly on the followings parameters : (i) optic utilized material properties as well as their qualities, (ii) the optimization of the window emittance, (iii) thickness of the different elements of a multilayered, (iv) the sequence of the layers and (v) climatological conditions (atmospheric constituents). Thus, we can simulate the realistic system permitting to optimize the good materials which can product radiative cooling.

In our computation, we use a solar panel model, intended to the heating of the dwellings or to the production of hot water sanitary, easier to put in industrial production. The optimization of the emittance and the spectral properties of the window requires a good study of the optical properties, that we wish to develop in the following paragraph.

II. THEORETICAL MODEL FOR THE RADIATIVE HEAT TRANSFER

In this section, we use the solar panel model constituted mainly of the following elements (cf. figure.1):

- a black "panel" called absorber (selective surface),
- a window generally formed by simple or multilayered system, supposed parallel to the absorber surfaces.

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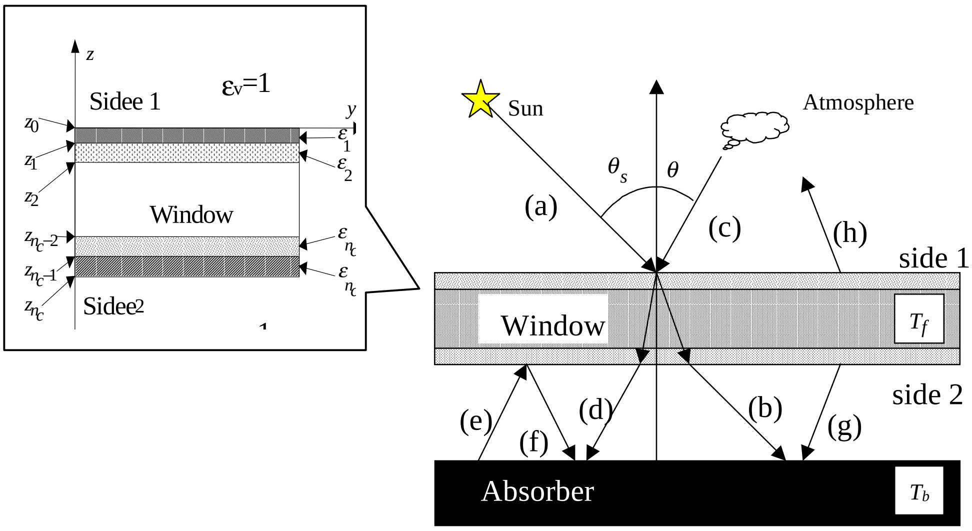

FIG. 1. Equilibrium temperatures reached by an absorber covered by a transparent window (stratified structure)

On all surfaces treated in this problem, we suppose that the radiation emitted is in conformity with the Lambert's law. The equilibrium temperatures reached by an absorber covered by a transparent window results from energy flows described here. The sources of energy are the sun, providing energy under an well-defined incidence θ_s, and the atmosphere, which radiates at all incidences. The incident beam from the sun (a) is attenuated into emerging ray (b) before reaching the absorber. A given ray from specified atmospheric element (c) is also attenuated (d) before being absorbed. Due to the temperature reached, the absorber emits (e) in all directions, but a fraction of this radiation (f) is reflected back by the window. The window itself stabilizing itself, after stabilizing its temperature, emits radiation back to the atmosphere (h) and to the absorber (g).

II. 1. ENERGY EQUILIBRIUM

II. 1. 1. HYPOTHESES OF WORK

In our model, the sun is approximated to a hot sphere with $R_S = 7.10^8\, m$ as radius, this sphere is located at a distance $h = 1.5\ 10^{11}\, m$ from the surface of the earth. As a light emitter, the sun behaves like a black body being at the temperature $T_S = 5870\ K$. The atmosphere is considered to be an absorbing environment, receiving a part of the sun power and supposed to remain at the same temperature $T_a = 300\, K$. The window and the absorber are, otherwise, supposed to receive the energy of two distinct sources that is the sun and the atmosphere constantly.

We consider in more the following hypotheses :

- We only account for radiative exchanges, neglecting all forms of conductive or convective energy transfer, the effect of the distance between the absorber and the window is also neglected.

II. 1. 2. WINDOW EQUILIBRIUM

From the sun, the atmosphere and the emitter, the window receives light in a large interval of wavelength. The reflected wavelength of the incident light doesn't participate to the window thermal radiation ; only the absorbed energy participates there. At thermal equilibrium, the temperature of the window will be adjust so that the thermal radiation balances the absorbed energy.

The window is characterized by three coefficients measuring the fraction of the incidental spectral power being able to be subjected to the reflection, transmission and absorption. For each wavelength and incident angle, there are two transmission coefficients $T_1(\lambda,\theta)$ and $T_2(\lambda,\theta)$; the first term corresponds to the waves travelling from the sun side (side 1 on figure 1) toward the absorber (through side 2), the second term corresponds to the waves travelling, in the opposite direction, from the absorber toward the atmosphere. In the same way, we consider the two reflection coefficients of the side1 and 2 of the window: $R_1(\lambda,\theta)$ and $R_2(\lambda,\theta)$. The absorption coefficient of the window can be calculated as follows :

for the sun side: $$A_1(\lambda,\theta) = 1 - T_1(\lambda,\theta) - R_1(\lambda,\theta) \quad (1)$$

for the absorber side: $$A_2(\lambda,\theta) = 1 - T_2(\lambda,\theta) - R_2(\lambda,\theta) \quad (2)$$

The power absorbed from the direct Sun exposition by the window is then given by :

$$P_S = \int_0^\infty A_1(\lambda,\theta_s)\frac{R_S^2}{h^2} b(\lambda,T_S)\cos\theta_s\, d\lambda \quad (3)$$

where $b(\lambda,T) = \dfrac{2\pi\,(2\,\pi\,\eta)\,c^2}{\lambda^5}\dfrac{1}{e^{\frac{2\pi\,\eta\, c}{k_B\, T\, \lambda}} - 1}$ is the

wavelength distribution of the sun radiation considered as a black body (Planck's radiation formula).

The power received from the atmosphere and absorbed by the window is given by the following equation :

$$P_a = 2\int_0^{\pi/2} d\theta \sin\theta \cos\theta \int_0^\infty A_1(\lambda,\theta)\varepsilon_a(\lambda)b(\lambda,T_a)d\lambda \qquad (4)$$

where $\varepsilon_a(\lambda)$ is the atmospheric emissivity supposed equal to 1 in all spectrum except in the 8-13 µm range where it takes the value zero (Box Model)[10].

The power of the thermal radiation emitted by the absorber being at the temperature T_e and absorbed by the window is given by :

$$P_e = 2\int_0^{\pi/2} d\theta \sin\theta \cos\theta \int_0^\infty A_2(\lambda,\theta)b(\lambda,T_e)d\lambda \qquad (5)$$

At thermal equilibrium, the window, being at the T_f temperature, emits a thermal radiation by these two sides 1 and 2. While supposing that the thermal radiation obeys to the Lambert's law, this power is given by:

$$P_{th} = \int_0^\infty [\varepsilon_1(\lambda)+\varepsilon_2(\lambda)]b(\lambda,T_f)d\lambda \qquad (6)$$

This window thermal equilibrium requires that the absorbed energy is compensated by the emitted one. This is given by :

$$\begin{aligned}\int_0^\infty [\varepsilon_1(\lambda)+\varepsilon_2(\lambda)]b(\lambda,T_f)d\lambda &= \int_0^\infty A_1(\lambda,\theta_s)S(\lambda,\theta_s)d\lambda \\ &+ \int_0^\infty \overline{A}_1(\lambda)\varepsilon_a(\lambda)b(\lambda,T_a)d\lambda + \int_0^\infty \overline{A}_2(\lambda)b(\lambda,T_e)d\lambda\end{aligned} \qquad (7)$$

where $\overline{A}_i(\lambda) = 2\int_0^{\pi/2} A_i(\lambda,\theta)\sin\theta\cos\theta d\theta,\ i=1,2$: is the hemispherical absorption coefficient, for side 1 or side 2 entrances.

The equation number 7 associates the temperature of the window T_f to the absorber's one (T_e). According to the Kirchhoff's law, the spectral emissivities of the two sides of the window can be identified with the hemispherical absorption coefficients, which is expressed by the following equality :

$$\varepsilon_i(\lambda) = \overline{A}_i(\lambda), \quad i=1,2 \qquad (8)$$

On the other hand, the emissivity of the blackbody used in this work is equal to the unity.

II. 1. 3. ABSORBER EQUILIBRIUM

The power received by the absorber has three source of energy : the sun, the atmosphere and the window side (side 2). These powers are given by the equations 9, 10 and 11 respectively. It is necessary to notice that the radiation received from the sun and the atmosphere are filtered by the window.

$$Q_S = \int_0^\infty T_1(\lambda,\theta_s)\frac{R_S^2}{h^2}b(\lambda,T_S)\cos\theta_s\, d\lambda \qquad (9)$$

$$Q_a = 2\int_0^{\pi/2} d\theta \sin\theta\cos\theta \int_0^\infty T_1(\lambda,\theta)\varepsilon_a(\lambda)b(\lambda,T_a)\, d\lambda \qquad (10)$$

$$Q_f = 2\pi\int_0^{\pi/2} d\theta \sin\theta\cos\theta \int_0^\infty \frac{1}{\pi}\varepsilon_2(\lambda)b(\lambda,T_f)\, d\lambda \qquad (11)$$

Heated with this energy, the absorber reaches the temperature T_b, that controls its thermal emission, according to :

$$Q_{th} = 2\pi\int_0^{\pi/2} d\theta \sin\theta\cos\theta \int_0^\infty \frac{1}{\pi}b(\lambda,T_b)d\lambda = \int_0^\infty b(\lambda,T_b)d\lambda \qquad (12)$$

It is important to notice that this energy is partially reflected back by the window side (side 2) to the absorber, where it is again thermalized. The energy so reflected is given by :

$$Q_r = 2\pi\int_0^{\pi/2} d\theta \sin\theta\cos\theta \int_0^\infty \frac{1}{\pi}R_2(\lambda,\theta)b(\lambda,T_b)d\lambda \qquad (13)$$

The absorber's equilibrium can be expressed as:

$$\begin{aligned}&\int_0^\infty T_1(\lambda,\theta_s)S(\lambda,\theta_s)d\lambda + \int_0^\infty \overline{T}_1(\lambda)\varepsilon_a(\lambda)b(\lambda,T_a)d\lambda \\ &+ \int_0^\infty \varepsilon_2(\lambda)b(\lambda,T_w)d\lambda + \int_0^\infty [\overline{R}_2(\lambda)-1]b(\lambda,T_b)d\lambda = 0\end{aligned} \qquad (14)$$

where: $\overline{T}_1(\lambda) = 2\int_0^{\pi/2} T_1(\lambda,\theta)\sin\theta\cos\theta d\theta$ (15)

and $\overline{R}_2(\lambda) = 2\int_0^{\pi/2} R_2(\lambda,\theta)\sin\theta\cos\theta\, d\theta$ (16)

Equations (7) and (14) form a system of two equations with two unknown parameters, the window temperatures T_f and the absorber temperatures T_b. The numerical computation solving of these equations allows to these two equilibrium temperatures, which are function of the sun position and the optical structure of the window. Keeping in mind that in our model, the distance between the window and the absorber plays no significant role.

II. 2. WINDOW TRANSMISSION (T), REFLECTION (R) AND ABSORPTION (A) COEFFICIENTS

The computation of the reflectivity for a multilayered window, has been largely discussed in the literature[11-14]. This calculation presents no conceptual difficulty, but care should be taken to implement the formulas in order to get a maximum of precision.

In the case of multilayered window, such as those considered here (cf. figure 1), the dielectric function is a succession of constant values $\varepsilon_\lambda,\ \lambda = 1, 2 ... n_c$, where n_c is the layer number of the window.

For the s-waves (transverse-electric waves), we find that the electromagnetic layer impedance on successive interfaces can be calculated by applying the following recurrence :

$$\zeta_s\left(z_{n_c}\right) = -i\sqrt{\varepsilon_s - \varepsilon_v \sin^2\theta} \tag{17}$$

For two successive interfaces Z_{l-1} and Z_l, the impedance obey to the following relations:

$$\zeta_s\left(z_{\lambda-1}\right) = \frac{\zeta_s(z_\lambda)\cos k_\lambda d_\lambda - g_\lambda \sin k_\lambda d_\lambda}{\cos k_\lambda d_\lambda + \zeta_s(z_\lambda)\dfrac{\sin k_\lambda d_\lambda}{g_\lambda}} \tag{18}$$

where $$g_\lambda = \sqrt{\varepsilon_\lambda - \varepsilon_v \sin^2\theta} \tag{19}$$

and $$k_\lambda = \frac{\omega}{c}\sqrt{\varepsilon_\lambda - \varepsilon_v \sin^2\theta} \tag{20}$$

with $$d_\lambda = z_{\lambda-1} - z_\lambda \tag{21}$$

This should be iterated until $\zeta_s(z_0)$ is known. Then, the reflectance $R_{s1}(\lambda,\theta)$ can be writing as :

$$R_{s1}(\lambda,\theta) = \left|\frac{\zeta_s(z_0) + i\sqrt{\varepsilon_v}\cos\theta}{\zeta_s(z_0) - i\sqrt{\varepsilon_v}\cos\theta}\right|^2 \tag{22}$$

The transmission coefficient $T_{s1}(\lambda,\theta)$ is given by :

$$T_{s1}(\lambda,\theta) = \frac{4}{\sqrt{\varepsilon_v}\cos\theta}\frac{\Re e\left[\sqrt{\varepsilon_s - \varepsilon_v \sin^2\theta}\right]}{\left|\prod_{\lambda=1}^{n_c} r_\lambda\right|^2 \left|1 + i\dfrac{\zeta_s(z_0)}{\sqrt{\varepsilon_v}\cos\theta}\right|^2} \tag{23}$$

with $r_\lambda = \cos k_\lambda d_\lambda + \zeta_s(z_\lambda)\dfrac{\sin k_\lambda d_\lambda}{g_\lambda}$

For the window side 2, the computation of reflectance $R_{s2}(\lambda,\theta)$ and transmittance $T_{s2}(\lambda,\theta)$ only requires to reverse the sequence of dielectric constant values and thicknesses.

For the p-waves (transverse-magnetic waves), the solution takes a slightly different form : the recurrence is developed as :

$$\zeta_p\left(z_{n_c}\right) = -i\frac{\sqrt{\varepsilon_s - \varepsilon_v \sin^2\theta}}{\varepsilon_s} \tag{24}$$

$$\zeta_p\left(z_{\lambda-1}\right) = \frac{\zeta_p(z_\lambda)\cos k_\lambda d_\lambda - g_\lambda \sin k_\lambda d_\lambda}{\cos k_\lambda d_\lambda + \zeta_p(z_\lambda)\dfrac{\sin k_\lambda d_\lambda}{g_\lambda}} \tag{25}$$

with $g_\lambda = \dfrac{\sqrt{\varepsilon_\lambda - \varepsilon_v \sin^2\theta}}{\varepsilon_\lambda}$ and

$k_\lambda = \dfrac{\omega}{c}\sqrt{\varepsilon_\lambda - \varepsilon_v \sin^2\theta}$ What gives the reflectance

$$R_{p1}(\lambda,\theta)\quad R_{p1}(\lambda,\theta) = \left|\frac{\zeta_s(z_0) + i\dfrac{\cos\theta}{\sqrt{\varepsilon_v}}}{\zeta_s(z_0) - i\dfrac{\cos\theta}{\sqrt{\varepsilon_v}}}\right|^2 \tag{26}$$

The transmission coefficient $T_{p1}(\lambda,\theta)$ is given by :

$$T_{p1}(\lambda,\theta) = \frac{4\sqrt{\varepsilon_v}}{\cos\theta}\frac{\Re e\left[\dfrac{\sqrt{\varepsilon_s - \varepsilon_v \sin^2\theta}}{\varepsilon_s}\right]}{\left|\prod_{\lambda=1}^{n_c} r_\lambda\right|^2 \left|1 + i\dfrac{\zeta_p(z_0)\sqrt{\varepsilon_v}}{\cos\theta}\right|^2} \tag{27}$$

The reflection $R_{p2}(\lambda,\theta)$ and transmission $T_{p2}(\lambda,\theta)$ coefficients only require to reverse the sequence of dielectric constant values and thicknesses.

For the non polarized light, the reflectance and transmittance are given by an average on the values of to the s and p waves as :

$$R = \frac{R_{Si} + R_{Pi}}{2}\ ;\ T = \frac{T_{Si} + T_{Pi}}{2}\ ;\ \text{where } i = 1{,}2 \tag{28}$$

III. VALIDATION OF OUR MODEL WITH EXPERIMENTAL RESULTS OF THE LITERATURE

In order to validate the results of our simulations, we did a set of comparison with experimental results of the literature[15-18] ; it concerns the following materials : Al, Au, Cu, Ag, MgO and NaCl. This comparison is summarized by figures presented below (figure 2, 3, 4 and 5).

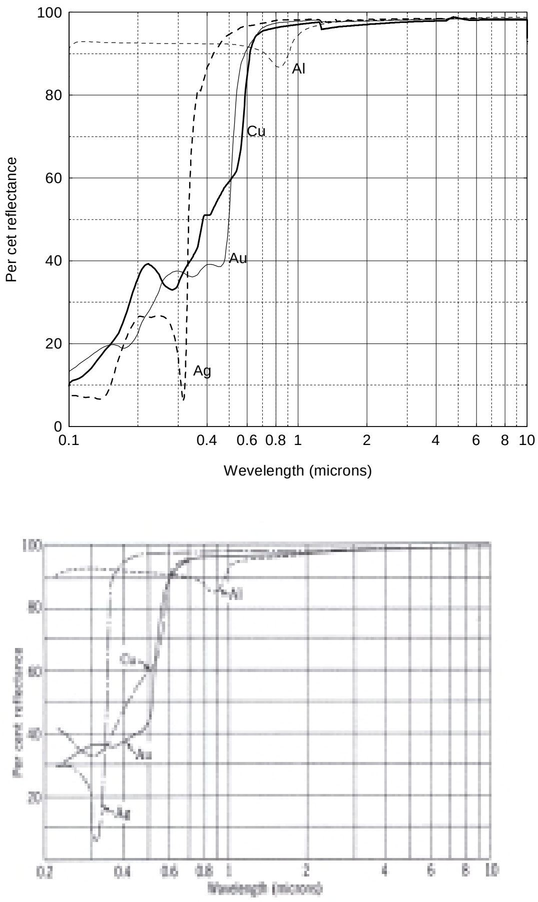

FIG. 2. Spectral reflectance of metal films (a) ,simulated values (b) after G. Hass[15].

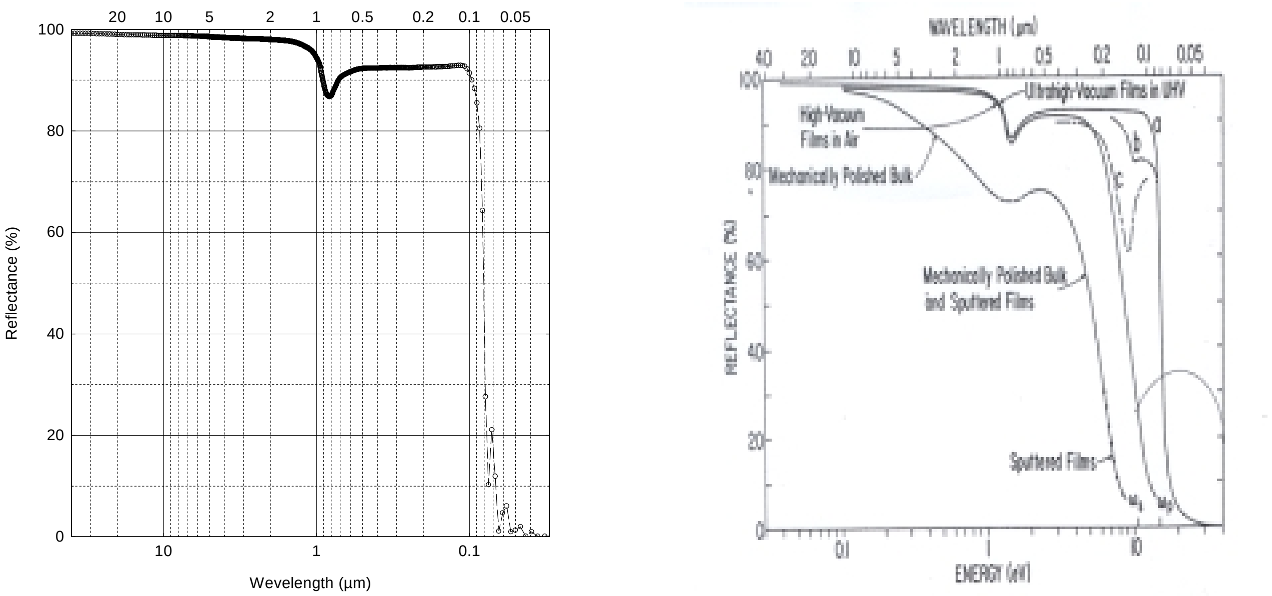

FIG. 3. Spectral reflectance of Aluminium (a), simulated values (b) after J. G. Endriz[16].

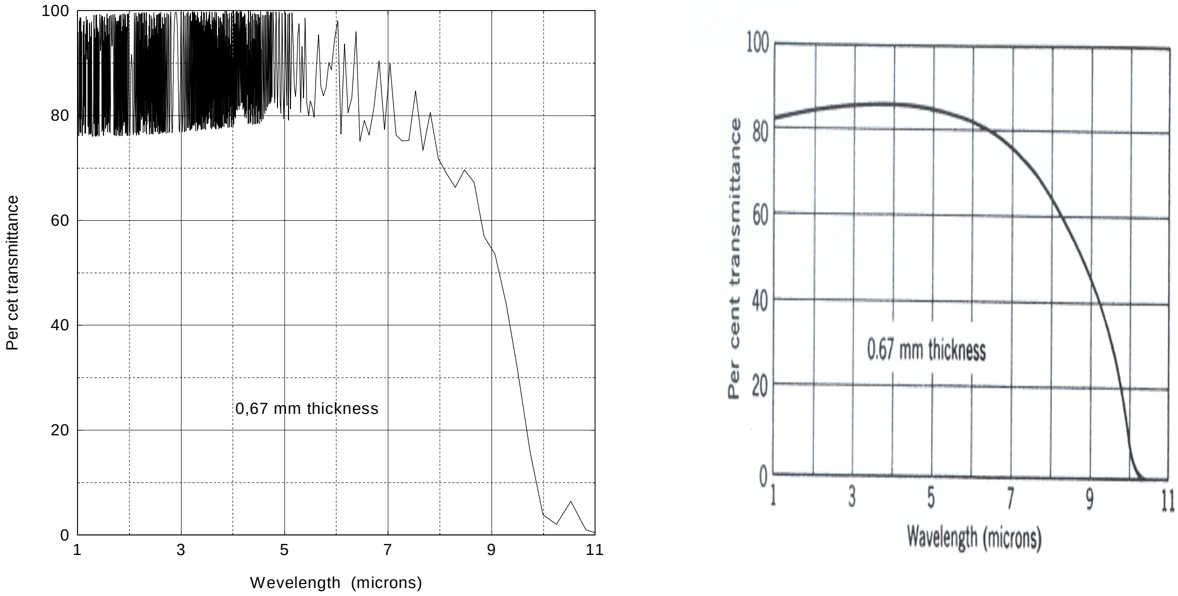

FIG. 4. Spectral transmittance of MgO (a), simulated values (b) after Courtesy of Norton Company[17].

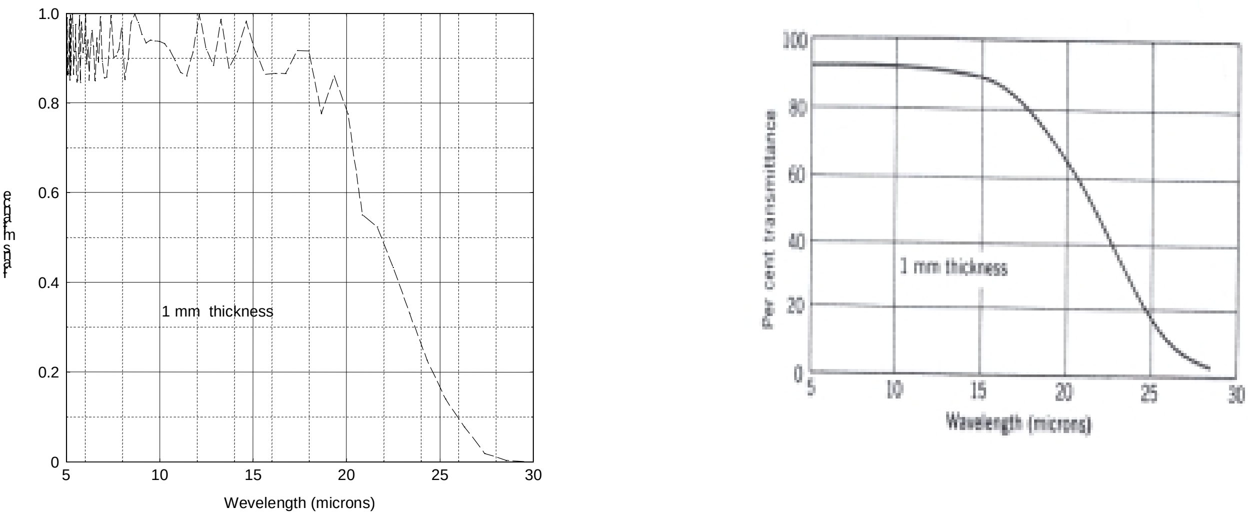

FIG..5. Spectral transmittance of NaCl (a), simulated values (b) after Courtesy of Harshaw Chemical Company[18].

We notice that these results agree perfectly with those of the literature found by G. Hass[15] in the case of aluminum, Gold, Copper and Silver (cf. figure 2), by Endriz[16] in the case of Aluminum (cf. figure 3), by Courtesy of Norton Company[17] for the MgO (cf. figure 4) and by Courtesy of Harshaw Chemical Company[18] for the NaCl (cf. figure 5). After this validation and in order to produce the inverse greenhouse effect, our model is applied to optimize the optical parameters of some materials which can be used in the window.

IV. APPLICATIONS

As application and in order to find the adequate structure permitting to produce the cooling appropriate radiative, we treat several materials (simple or multilayered structure) in the goal to achieve the window giving place to the higher temperature drop in relation to the ambient. Let's recall that the studied system includes an absorber (black body) protected by this window side sun (cf. face 1).
One elements answering to these criterions is germanium, for which we have studied the thickness influence and have found that the equilibrium temperature reached by the absorber has a minimal value between 0.01 µm and 0.06 µm. However, only with germanium, the window can not products the inverse greenhouse effect. Indeed, the germanium must include other layers in order to increase the visible reflectance and the infrared transmittance (8-13µm)

A. THERMAL EQUILIBRIUM WITH A GERMANIUM WINDOW

In this part, we are going to study the influence of the thickness of the germanium layer on the absorber's temperature. The obtained results are carried on the following figure:

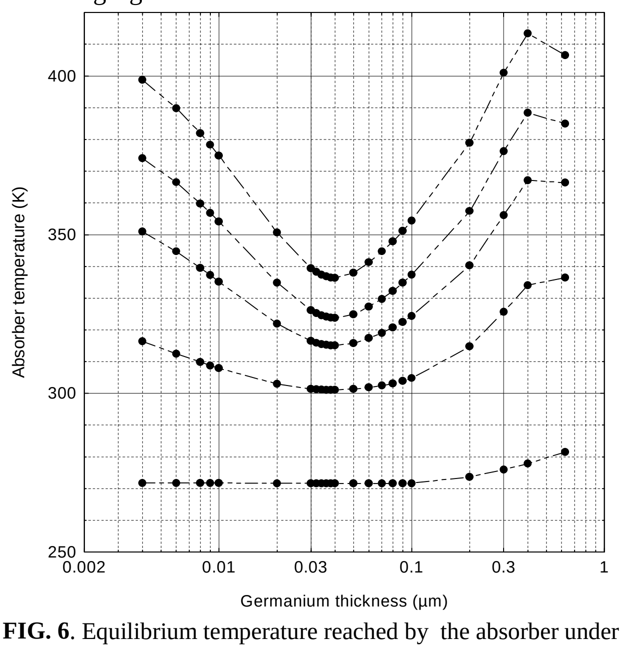

FIG. 6. Equilibrium temperature reached by the absorber under Solar illumination through a window composed of a germanium layer. The temperature is calculated according to the thickness of germanium.

The variation of the absorber's temperature according to the thickness of germanium permits us to select the thickness optimizing the best of the inverse greenhouse effect, it appears between 0.01 µm and 0.06 µm. This result is related to a system formed by only one «layer» of germanium, it will be used like support for the multilayered system realization and this in order to decrease the window-absorber's temperature in regard to the ambient.

B. COMPARISON OF THERMAL EQUILIBRIUM OF THREE WINDOWS, FOR WHICH THE GERMANIUM IS USED AS THE SAME SUPPORT

The three systems used separately (for the three windows) are summarized like follows :

- System 1 (S1) :
  [Ge(0.06µm)/NaCl(400µm)/Ge(0.03µm)].

The choice of this system depends in the fact that it assures a good reflection of the visible (between 60 and 80 %), and a good transmission of the infrared (more than 80%).

- *System 2 (S2) :*
  [PbS(0.06µm)/CaF_2(2µm)/Ge(0.03µm)/PbS(0.06mµ)/CaF_2(2µm)]
- System 3 (S3) :
  [PbS(0.06µm)/CaF_2(2.36µm)/Ge(0.01µm)/PbS(0.06µm)/CaF_2(2.36µm)]

The S2 and S3 systems differ only by the thickness of some layers (CaF_2 and Ge). They permit us to eliminate, by absorption, a good part of the visible.
Let's notice that the layers being at the above of the right extremity of the three systems, given before, are exposed to the sun.

From these structures, we simulated the absorber's temperature. This computation is achieved for different zenithal angles. The figure 7 gives a comparison of the different temperatures of the absorber of the three systems taken separately.

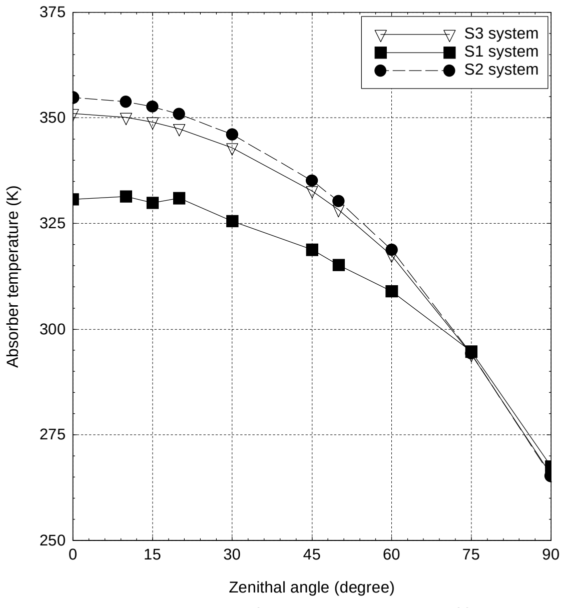

FIG. 7. Temperatures of the absorber at different zinithal angles.

According to these results, we notice that the lowest temperature is given by the system 1. The one of the two other systems is very neighboring and distinctly overhead to the case of the system 1, except for zenithal angles superior to 75°, where the three curves coincident ; they correspond to the prone of the sun.

C THERMAL EQUILIBRIUM WITH A WINDOW CONSTITUTED BY SEVERAL SYSTEM COMBINATIONS

Let's recall that the main goal of the optimization of a window is a matter for its good reflectance in the visible and its important transmittance in the infrared. The material, answering at 100 % to these criteria, doesn't exist, it becomes important to combine several materials in order to approach the most possible to the ideal conditions (two system can be combined to give place to a new system taking advantages of each of them). This paragraph treats some combinations based on the system following:

a) System 2 deposited on the system 1 : S2/S1 (S1 is the side sun),
b) System 3 deposited on [system 2/système 1] : S3/S2/S1 (S1 is the side sun),

To reinforce the transmission of the remaining infrared trapped between the window and the absorber one can add, side absorber, a wave quarter layer of MgO. This material is often used in the transparent component manufacture in the infrared; it plays, indeed, the role of antireflection coating. This layer deposited on S3/S2/S1 gives place to the combination (c) following :

c) MgO deposited on the structure of the b case : MgO/S3/S2/S1 (S1 is the side sun).

The temperature obtained for the absorber concerning the three cases above are reported below on the figure 8:

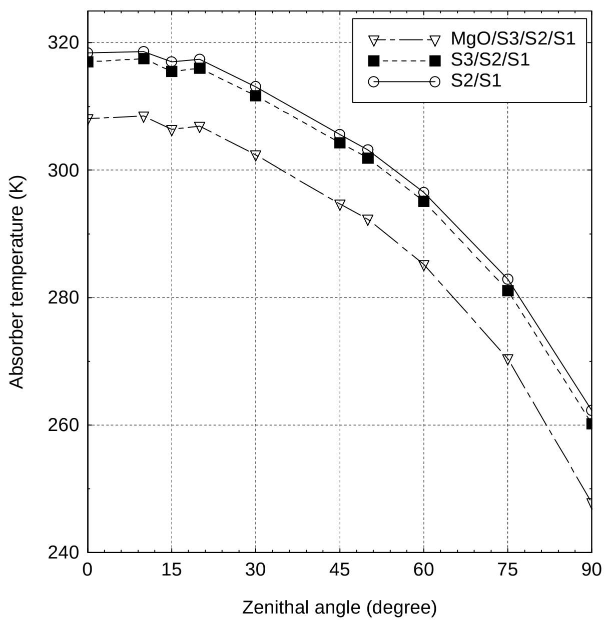

FIG. 8. Temperatures of the absorber at different zinithal angles.

The introduction of the MgO layer provoked the decrease of the absorber's temperature. This temperature decrease is about of 10°C at 60° as zenithal angle. It essentially comes from the strong transmission of this layer of which the thickness, $\lambda/4$, has been adapted maximally to the absorber infrared emission.

In the next section, we study the effect of the air presence between the different layers or system. It is, indeed, one of the technical problems often encounter in the realization of the multilayered structures.

d) Effect of air layers introduced in the c) case

To study the influence of the air layers on the thermal behavior of a multilayered system, we simulated them in the case of a structure presenting 14 layers (MgO/S3/S2/S1 system). We introduced two layers of air between the different S1, S2 and S3 systems ; what give place to a new system of 16 layers (MgO/S3/air/S2/air/S1). In a first time, the thickness of the air layers have been fixed at 0.1 µm. The results of this study are carried below on the figure 9 below:

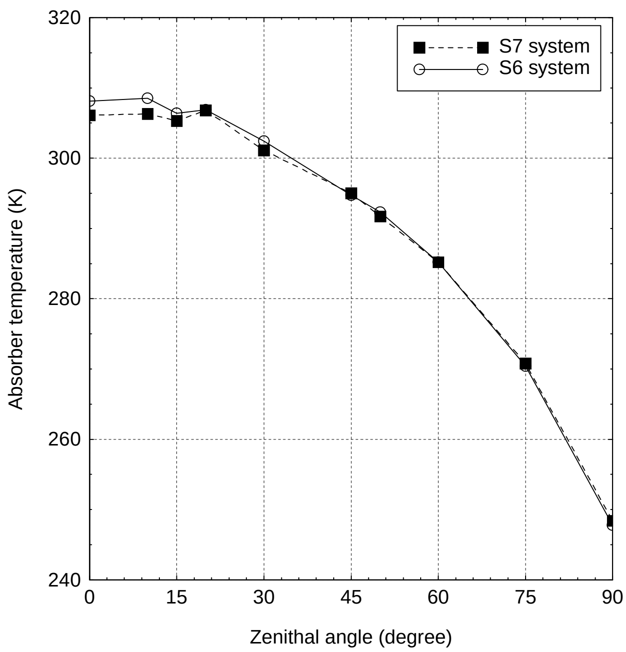

FIG. 9. Temperatures of the absorber at different zinithal angles.

This figure shows that air, with a thickness of 0.1 µm, can only influence very little the absorber's thermal equilibrium. To have a lucid idea, we studied the effect of the thickness of the air layers on the absorber's temperature. This study is presented under shape of two curves ; the first one (cf. figure 10) gives the relative variation of the temperature($\Delta T/T$) for different zenithal angles ; where $\Delta T/T$=[T(with air layer)-T(without air layer)] /T(without air layer).

For lower zenithal angles or equal to 60 degrees, the layers of air, of which the thickness takes a value below

0,5 µm, present a beneficial effect for the radiative cooling. At the opposite, for thickness from 1 to 100 µm, the air layer decreases the inverse greenhouse effect while increasing the ΔT/T of 1 %, with a maximum of 2 % for 2.5 µm as air layer thickness. One can notice however that this maximum toward 2.5 µm (of air layer) corresponds to the quarter of wave of the maximum of the absorber emission (10µm/4).

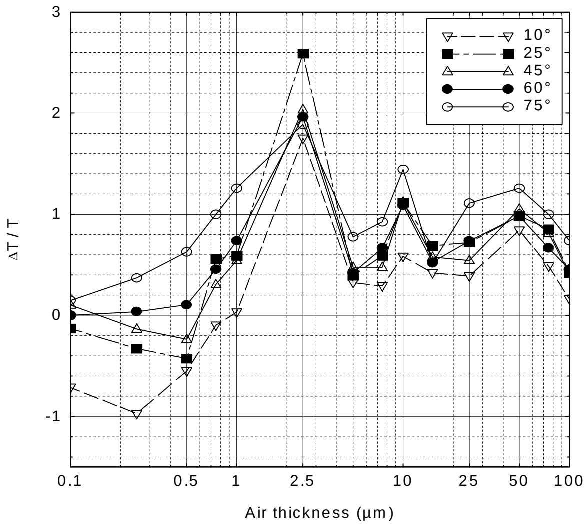

FIG. 10. Relative variation of the absorber's temperature according to the thickness of the air layer (the zenithal angle is taken as a parameter).

Figure 11 represents the relative variation for 60° as zenithal angle. This situation corresponds to the geographical position of Morocco.

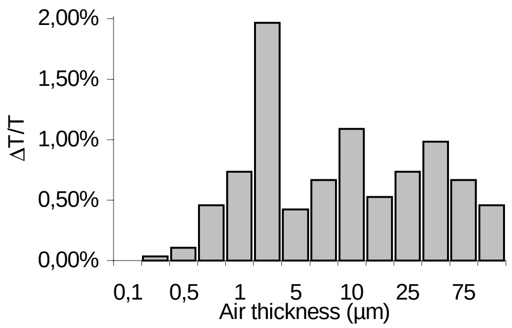

FIG. 11. Relative variation of the absorber's according to the thickness temperature of the air layer at 60° as zenithal angle.

According to these results, the ΔT/T is of a manner general lower to 2 %; what shows that in Morocco, the presence of the air layers between the laminated layers can be tolerated until a thickness of 10 µm.

V. CONCLUSION

Figure 1 In this work, we have interested to modeling the inverse greenhouse effect in order to control the absorber temperature, and so to save the use of the active system of air-conditioning. This economy is obtained, by exploitation of the natural radiative cooling, with the help of window corresponding to an opening of transparency in the 8-13 µm zone. This last permits the exchange radiative with the zones of low atmospheric temperatures. In a first time we described a model constituted of an absorber and of a partially transparent window. The physical information described in this model permitted to determine the temperatures of the emitter and the window, according to the optic properties of the materials constituting the window. The optimization of the window can summarized as follow : the inverse greenhouse effect needs an important reflection of the specter, except in the infrared range (8-13 µm called atmospheric window) for which a high transmittance is required. Some multilayered structures probably permit to approach of these ideal criteria. Without taking into account the exchanges non radiative and while considering the ambient temperature a bout 300 K, the temperature variation observed for the emitter is about 15°C below ambient temperature, in the case of the system of 14 layers (S6). Our result is to be compared to the one of Eriksson et al.19 who got a variation of 20°C below ambient temperature. In their system, Eriksson et al. have used the following system : glass/Al/SiO0.6N0.2/gas/Al (the used gas is the C2H4,C2H4O and NH3). We notice that in this reference19, the energy balance doesn't take into account the absorber-window coupling. The contributions and the character realistic of the described results affirm the hope that it is possible, by a choice discriminating of material, which we can easily elaborate to produce a radiative cooling. Our next challenge consists to find new materials permitting at alltimes and at all climates to produce important temperature drops below ambient temperature.

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