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Modelization of helio-thermal converters : application to the greenhouse effect

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Résumé. — Ce travail fait suite à une étude exhaustive ayant pour but la détermination des performances de capteurs héliothermiques mettant en œuvre une surface de captage sélective. Cette étude, basée sur une modélisation, montrait que la notion de facteurs optothermiques totaux généralement utilisés, ne permettait pas une analyse suffisamment rigoureuse et qu'il fallait prendre en compte leurs variations spectrales.

Nous avons voulu démontrer ici qu'il était possible d'étendre cette étude à différents convertisseurs solaires. La méthode employée est basée sur la détermination de facteurs optothermiques traduisant le comportement de leurs faces insolées. On détermine alors, à partir de ces paramètres, la surface sélective équivalente. On obtient ainsi une description unitaire des dispositifs de captage de l'Energie Solaire. L'association effet de serre, surface sélective est étudiée à titre d'exemple.

Abstract. — In a previous work, based on modelling the total optothermal factors of an absorbing selective surface, we stated that these factors were not sufficient to give a strict analysis, and that their spectral variations had to be considered.

In the present paper, we tried to show that this study could be extended to various solar converters. Our method uses the optothermal factors determination that describes the irradiated converters surface behaviour. Using these parameters, an equivalent selective surface is determined. By this way, we obtain a unitary description for the solar converters behaviour.

The selective surface — greenhouse effect association is discussed as an example.

The conversion which allows transforming the solar flux into utilisable heat involves various types of devices covered by the generic term « helio-thermal converter ».

Generally, it can be considered that the radiative fluxes which act within the converter may be classified according to two spectral ranges $\Delta\lambda_s$ and $\Delta\lambda_{IR}$:

— range $\Delta\lambda_s$, matching the incident solar flux, is comprised between 0.25 and 3 μm and therefore, consists of ultra-violet, visible and close infra-red radiations ;

— range $\Delta\lambda_{IR}$ matches the fluxes emitted respectively by the absorption surface, the annex thermal losses reduction devices, and the environment. Those fluxes depending on the temperatures of these elements, range $\Delta\lambda_{IR}$ mostly spreads from close to remote infra-red.

Depending on the configuration, the incident solar

flux reaches the absorption surface directly (direct insolation) or through more or less complex dioptric or catadioptric devices ensuring an adaptation of the flux. When this adaptation is a concentration, it will be characterized by defining a « geometrical concentration factor » C equal to the ratio of the flux collected by the absorber to the one which would be collected under direct insolation. As the action of those elements on solar radiations has an optical finality, they will be termed « optical elements ».

On the contrary, thermal exchanges between the absorbing surface, the losses-reduction-devices, and the collector environment concern those elements opto-thermal factors and respective temperatures. So they will be termed « opto-thermal elements ».

Considering the converter (concentrator + selective absorbing surface) and, in a first phase, considering radiative exchanges only, useful flux per absorbing surface unit Φ_{ur} is expressed :

$$\Phi_{ur} = \alpha CH - \varepsilon M^0 + \alpha' M_E^0 \quad (1)$$

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in this formula :

- H is the incident solar flux per absorbing surface unit,
- ε is the total emissivity of the absorbing surface supposedly raised to a uniform temperature T ,
- α is the total absorptivity of the absorbing surface for solar spectrum,
- α' is the total absorptivity of the absorbing surface for environmental, radiation considered under a uniform temperature T_E ,
- M^0 and M_E^0 are given by the Stephan-Boltzman law ($M^0 = \sigma T^4$, $M_E^0 = \sigma T_E^4$).

As it can be noticed, the user is offered various possibilities of combining optical and opto-thermal elements to build a helio-thermal converter liable to meet solar energy collection requirements. For a proper selection between these possibilities, F. Papini *et al.* [1] conducted a complete study on a simplified converter model.

The model selected (which is intentionally very simple), is based on the assumption that the monochromatic absorptivity factor α_λ has two values, respectively constant in two spectral ranges I and II, the common limit of which is wavelength λ_c , termed « cut-off wavelength ». As shown in figure 1, this factor has a value A in range I, and E in range II, hence the name : *model* « A, E, λ_c ».

This model allows a more precise analysis compared to the analysis developped using classical opto-thermal parameters for absorbing surface : ε , α and α' .

This model allows a solution of the general problem arising by optimization of a solar converter designed to work in given conditions, especially to determine the relative part of selectivity and concentration to be used.

However, it is obvious that on one hand, not all selective surfaces meet that model, and that on the other hand the opto-thermal elements of a converter hardly ever confine to a selective surface. Therefore, it seems that the model proposed, though interesting from a theoretical point of view, will hardly yield exploitable practical results.

But as it has been demonstrated [1, 2] for certain

Fig. 1. — Modelization of selective surface optical properties.

heliothermal converters, and as we will show here, in another specific case, we have :

$$\Phi_{ur} = \alpha_e CH - \varepsilon_e M^0 + \alpha'_e M_E^0 \quad (2)$$

where α_e , ε_e and α'_e are the equivalent opto-thermal factors of the device involved. Obviously, these factors are dependent on the physical properties of the opto-thermal elements, and their expression may be rather complex. In [1], are to be found some examples of expressions concerning greenhouse effects (single or multiple), selective surfaces and honeycomb structures.

Here, knowing those factors, we propose to develop a method to define an equivalent modeled selective surface, the *equivalent monochromatic factors* which have values A_e and E_e in spectral ranges I and II and separated by an *equivalent cut-off wavelength* λ_{ce} . From this modelization, the result of the study quoted can be used.

In a second phase [1, 3], and still starting from the simplified heliothermal converter model, thermal transfer modes other than radiation were evidenced ; then, the radiative equation (1) becomes a thermal equation expressed :

$$\Phi_u = \alpha CH - \varepsilon M^0 + \alpha' M_E^0 + P_c \quad (3)$$

where P_c represents the flux of convection losses (natural or forced) and conduction losses in the adjacent materials.

Consequently, the last section of this article will analyse those losses in the example selected.

In the numerical applications reported here after, we will suppose that the equivalent environmental temperature T_E is 280 K, and that the sun radiates as a black body brought to 6 000 K.

1. Modelization of the opto-thermal elements of a heliothermal converter. — Consideration is given here to the modelization of heliothermal converters, the radiative equation of which is given by relation (2). It can be noted that the equation is similar to the one of the simplified converter (1), provided that factors α , α' and ε are replaced by equivalent factors α_e , α'_e and ε_e .

In model « A, E, λ_c », factors α , α' and ε are connected to parameters A , E and λ_c by a system of three equations [1, 2]. Let us pursue the analogy between (1) and (2) to determine equivalent parameters A_e , E_e and λ_{ce} , also by means of a system of three equations similar to that mentioned above :

$$\alpha_e = (A_e - E_e) k_{Se} + E_e, \quad (4)$$

$$\varepsilon_e = (A_e - E_e) k_e + E_e, \quad (5)$$

$$\alpha'_e = (A_e - E_e) k_{Ee} + E_e. \quad (6)$$

Equivalent cut-off wavelength λ_{ce} does not appear explicitly in these relations and we may recall that it

is the upper limit of the integrals which actually permits to calculate the factors k_{Se} , k_e , k_{Ee} ,

$$k_{Se} = \frac{\int_0^{\lambda_{ce}} M_\lambda^0(T_S) d\lambda}{\sigma T_S^4}; \quad k_e = \frac{\int_0^{\lambda_{ce}} M_\lambda^0(T) d\lambda}{\sigma T^4};$$

$$k_{Ee} = \frac{\int_0^{\lambda_{ce}} M_\lambda^0(T_E) d\lambda}{\sigma T_E^4}.$$

Combining equations (4), (5) and (6), we obtain very simple relations between equivalent factors α_e , ε_e , α'_e and the k_{ie} 's; i.e. relations between these factors and equivalent cut-off wavelength λ_{ce} .

$$\frac{\alpha_e - \varepsilon_e}{\alpha_e - \alpha'_e} = \frac{k_{Se} - k_e}{k_{Se} - k_{Ee}} = a(\lambda_{ce}, T) \quad (7)$$

$$\frac{\varepsilon_e - \alpha'_e}{\alpha_e - \alpha'_e} = \frac{k_e - k_{Ee}}{k_{Se} - k_{Ee}} = b(\lambda_{ce}, T), \quad (8)$$

and

$$\frac{\varepsilon_e - \alpha'_e}{\alpha_e - \varepsilon_e} = \frac{k_e - k_{Ee}}{k_{Se} - k_e} = c(\lambda_{ce}, T). \quad (9)$$

To evaluate $a(\lambda_{ce}, T)$, $b(\lambda_{ce}, T)$ and $c(\lambda_{ce}, T)$, we simply need to know the values of various factors k_{ie} . In this concern, we may either carry out numeric integrations of Planck law, or use tables such as Sargent's tables [4].

The curves in figure 2 indicate the variations of ratio $a(\lambda_{ce}, T)$ as a function of λ_{ce} for certain temperatures T of the absorption surface.

The graphs in figures 2 permit to demonstrate that

Fig. 2. — $a(\lambda_{ce}, T) = f(\lambda_{ce})$; $0 < \lambda_{ce} < 16 \mu m$.

one and only one equivalent cut-off wavelength corresponds to a value of $a(\lambda_{ce}, T)$ and T .

In other words, knowing the equivalent opto-thermal factors of a given system, in given temperature conditions, knowing the corresponding factor $a(\lambda_{ce}, T)$ (formula (7)), it is possible to evaluate directly, using these curves, the equivalent cut-off wavelength λ_{ce} . From this value of λ_{ce} and from temperatures T_S , T and T_E , we determine equivalent factors k_{Se} , k_e and k_{Ee} (using Sargent's tables, for example), and, consequently, equivalent monochromatic factors A_e and E_e , from equations (4), (5) and (6). The equivalent modeled selective surface is hence perfectly defined.

Example of application :

Let a heliothermal converter, with absorption surface temperature $T = 500 K$, involve a certain opto-thermal device so that the radiative flux Φ_{ur} can be expressed by :

$$\Phi_{ur} = 0.95 CH - 0.25 M^0 + 0.10 M_E^0. \quad (10)$$

Therefore, the value of the opto-thermal factors is :

$$\alpha_e = 0.95; \quad \varepsilon_e = 0.25; \quad \alpha'_e = 0.10.$$

The factor $a(\lambda_{ce}, T)$ defined by relation (7) is therefore equal to 0.941. On the curve in figure 2, we can see that to this value of $a(\lambda_{ce}, T)$ corresponds an equivalent cut-off wavelength $\lambda_{ce} = 3.90 \mu m$.

Starting from the above relations, it can immediately be seen that :

$$A_e = 0.957, \quad E_e = 0.099.$$

Remark :

Another method can be applied to infer cut-off wavelength λ_{ce} from relations (4), (5) and (6). By evaluating A_e and E_e in two of these relations, and using their expression as an input to the third, we set up an expression connecting the equivalent opto-thermal factors and the factors k_{ie} :

$$(\alpha'_e - \alpha_e) k_e + (\alpha_e - \varepsilon_e) k_{Ee} + (\varepsilon_e - \alpha'_e) k_{Se} = 0, \quad (11)$$

i.e., using the factors defined in (7) and (8) :

$$k_e = a(\lambda_{ce}, T) k_{Ee} + b(\lambda_{ce}, T) k_{Se}. \quad (12)$$

A numeric computer method (consisting in scanning the space of λ_{ce}) permits to evaluate the equivalent cut-off wavelength quite rapidly.

2. Application to the « selective absorbing surface/ greenhouse effet » association ($P_c = 0$). — As it was recalled in the introduction, we can evaluate the opto-thermal factors of various losses reduction devices (and more particularly those of a selective surface) of single or multiple greenhouse effects, and of honey-comb structures. Subsequently, following the method

described above, we can set up their equivalent modelization.

We propose here to deal with the case of the selective absorbing surface/single greenhouse effect association. For obvious clarity purposes, we will suppose that the monochromatic absorptivity of the selective surface are equal to A , below the cut-off wavelength (which will be referred to as λ_A here), and to E , above λ_A . As for the cover which permits the greenhouse effect : it is transparent below cut-off wavelength λ_V , and totally absorbent above it.

During this study, the following simplifying assumptions are made :

- the absorbing surface temperature is uniform;
- both faces of the cover are considered to have the same temperature. Those two assumptions are frequently applied in the study of flat collectors;
- the distance between the cover and the absorbing surface is assumed to be small with respect to the other dimensions of the collector; this assumption entails a unit form factor between absorption surface and cover;
- the various radiative fluxes are referred to the area unit of the absorbing surface.

As it appears in figure 3, three possibilities arise as regards the relative positions of wavelengths λ_A and λ_V .

Let us consider three cases :

- case 1 : λ_V resides below λ_A , figure 3a,
- case 2 : λ_V resides above λ_A , figure 3b,
- case 3 : λ_V and λ_A are identical, figure 3c.

Whatever the case studied, the respective radiative equations of the two opto-thermal elements are expressed as follows :

— Selective absorbing surface :

$$\Phi_{ur} + \Phi_A = \Phi_{S,A} + \Phi_{V,A} + \Phi_{E,A}. \quad (13)$$

Fig. 3. — Monochromatic absorptivity α_λ versus wavelength λ for absorption surface (A) and cover glass (V) : a) $\lambda_V < \lambda_A$; b) $\lambda_V > \lambda_A$; c) $\lambda_V = \lambda_A$.

— Cover :

$$2\Phi_V = \Phi_{E,V} + \Phi_{A,V} + \Phi_{S,V} + \Phi_{S,A,V} + \Phi_{E,A,V} + \Phi_{V,A,V}. \quad (14)$$

The various fluxes which interact in those two equations are respectively :

Φ_A : flux emitted by the absorbing surface;

Φ_V : flux emitted by each of the two faces of the cover;

$\Phi_{S,A}$; $\Phi_{V,A}$; $\Phi_{E,A}$: fluxes from the sun, the cover, and the environment, absorbed by the absorption surface;

$\Phi_{S,V}$; $\Phi_{A,V}$; $\Phi_{E,V}$: fluxes from the sun, the absorbing surface and the environment, absorbed by the cover;

$\Phi_{S,A,V}$; $\Phi_{V,A,V}$; $\Phi_{E,A,V}$: fluxes from the sun, the cover and the environment, absorbed by the cover after reflection on the absorbing surface.

Let us first of all note that the fluxes $\Phi_{S,A,V}$ and $\Phi_{E,A,V}$ cross the cover before being reflected on the absorbing surface. Therefore, they are confined in the spectral range $0-\lambda_V$; as the reflection occurs within the same wavelength range, those reflected fluxes cross the cover again. Hence, we have :

$$\Phi_{S,A,V} = \Phi_{E,A,V} = 0.$$

To express the other radiative fluxes of (13) and (14), we shall use the notation k_{ij} ; this factor being defined as :

$$k_{ij} = \frac{\int_0^{\lambda_i} M_\lambda^0(T_j) d\lambda}{\sigma T_j^4}.$$

Among those fluxes, some keep the same expression, whatever the case considered. They are :

— the flux from the cover; the emission of this component residing entirely beyond λ_V :

$$\Phi_V = M_V^0(1 - k_{VV})$$

— the flux emitted by the absorbing surface; taking into account the model « A, E, λ_V » selected, it is expressed :

$$\Phi_A = M^0[Ak_{AA} + E(1 - k_{AA})]$$

— the fluxes from the sun and the environment, absorbed by the cover; as the absorption occurs within the spectral range $\lambda_V - \infty$, we have :

$$\Phi_{S,V} = CH(1 - k_{VS}); \quad \Phi_{E,V} = M_E^0(1 - k_{VE}).$$

The other fluxes contained in (13) and (14) have different expressions depending on the case considered.

a) Case 1. — The flux emitted by the cover is absorbed by the absorbing surface with an absorptivity A between λ_V and λ_A , and E beyond λ_A . Therefore, we have :

$$\Phi_{V,A} = M_V^0[A(k_{AV} - k_{VV}) + E(1 - k_{AV})].$$

— The fluxes from the sun and the environment, absorbed by the absorbing surface, have been transmitted through the cover and therefore in the spectral range $0-\lambda_v$, the value of the monochromatic absorptivity factor being A :

$$\Phi_{S,A} = ACHk_{VS}; \quad \Phi_{E,A} = AM_E^0 k_{VE}.$$

— The flux from the absorbing surface is absorbed by the cover, beyond λ_v . With regard to the relative positions of λ_A and λ_v , it takes into account a monochromatic emissivity A between λ_v and λ_A , and E beyond λ_A :

$$\Phi_{A,V} = M_A^0 [A(k_{AA} - k_{VA}) + E(1 - k_{AA})].$$

— Finally, the flux emitted by the cover, reflected by the absorbing surface, then absorbed by this same cover, has a reflection factor $1-A$ between λ_A and λ_v and $1-E$ beyond λ_A :

$$\Phi_{V,A,V} = M_V^0 [(1 - A)(k_{AV} - k_{VV}) + (1 - E)(1 - k_{AV})].$$

After replacing the various fluxes in (13) by their respective expressions, we have :

$$\begin{aligned} \Phi_{ur} = & CHAk_{VS} - M^0 [Ak_{AA} + E(1 - k_{AA})] + \\ & + M_V^0 [A(k_{AV} - k_{VV}) + E(1 - k_{AV})] + AM_E^0 k_{VE}. \end{aligned} \quad (15)$$

Some fluxes, in which the emission from the cover interferes, are involved in this relation; these fluxes are evaluated from (13) which, after laying down :

$$\begin{aligned} \chi &= A(k_{AV} - k_{VV}) + E(1 - k_{AV}) \\ \gamma &= 1 - k_{VV} + \chi \end{aligned}$$

becomes :

$$\gamma M_V^0 = CH(1 - k_{VS}) + M^0 [A(k_{AA} - k_{VA}) + E(1 - k_{AA})] + M_E^0 (1 - k_{VE}). \quad (16)$$

Finally, we obtain :

$$\begin{aligned} \Phi_{ur} = & CH \left[Ak_{VS} + (1 - k_{VS}) \frac{\chi}{\gamma} \right] - M^0 \{ Ak_{AA} + E(1 - k_{AA}) - \\ & - [A(k_{AA} - k_{VA}) + E(1 - k_{AA})] \frac{\chi}{\gamma} \} + M_E^0 \left[Ak_{VE} + (1 - k_{VE}) \frac{\chi}{\gamma} \right]. \end{aligned} \quad (17)$$

or, after laying down :

$$\alpha_e = Ak_{VS} + (1 - k_{VS}) \frac{\chi}{\gamma} \quad (18)$$

$$\begin{aligned} \varepsilon_e = & Ak_{AA} + E(1 - k_{AA}) - \\ & - [A(k_{AA} - k_{VA}) + E(1 - k_{AA})] \frac{\chi}{\gamma} \end{aligned} \quad (19)$$

$$\alpha'_e = Ak_{VE} + (1 - k_{VE}) \frac{\chi}{\gamma}. \quad (20)$$

we find :

$$\Phi_{ur} = \alpha_e CH - \varepsilon_e M^0 + \alpha'_e M_E^0. \quad (21)$$

Remark :

When the absorption surface is grey ($A = E$), we obtain immediately :

$$\alpha_e = \frac{A}{1 + A} (1 + Ak_{VS}); \quad \varepsilon_e = \frac{A}{1 + A} (1 + Ak_{VA}); \quad (22)$$

$$\alpha'_e = \frac{A}{1 + A} (1 + Ak_{VE}).$$

For the black body ($A = 1$), we actually meet the equivalent factors which had been set forth elsewhere [1].

b) *Case 2.* — Similarly as for the former case, the various fluxes which interact in (13) and (14) are evaluated.

After due calculations, the following opto-thermal parameters are obtained :

$$\alpha_e = (A - E) k_{AS} + \frac{E}{1 + E} (1 + Ek_{VS}), \quad (23)$$

$$\varepsilon_e = (A - E) k_{AA} + \frac{E}{1 + E} (1 + Ek_{VA}), \quad (24)$$

$$\alpha'_e = (A - E) k_{AE} + \frac{E}{1 + E} (1 + Ek_{VE}). \quad (25)$$

c) *Case 3.* — Since $\lambda_A = \lambda_v$, this is a limit-case between the former two. Hence the following :

$$k_{AS} = k_{VS} = k_S$$

$$k_{AA} = k_{VA} = k_A.$$

Either from relations (18), (19), (20), or from relations (23), (24), (25), we obtain here :

$$\alpha_e = Ak_S + \frac{E}{1 + E} (1 - k_S), \quad (26)$$

$$\varepsilon_e = Ak_A + \frac{E}{1 + E} (1 - k_A), \quad (27)$$

$$\alpha'_e = Ak_E + \frac{E}{1 + E} (1 - k_E). \quad (28)$$

• **SPECIAL CASES OF APPLICATION.** — The determination of the opto-thermal factors allows to modelize these various systems and therefore to evaluate the equivalent parameters A_e , E_e , λ_{ce} . We shall examine here an example for each of these cases. The temperature of the absorbing surface, still having a value of 400 K, the monochromatic factors are such that $A = 0.95$ and $E = 0.50$.

Geometric concentration factor C is equal to the unity and the incident solar flux to 800 W.m^{-2} ; cut-off wavelengths λ_v and λ_A are indicated for each specific case.

- a) *Case 1* : $\lambda_v = 3 \mu\text{m}$,
 $\lambda_A = 8 \mu\text{m}$.

The cover balance allows evaluating its flux density, thus its temperature, i.e. in this case $T_v = 345.75 \text{ K}$. The opto-thermal factors follow from relations (18), (19), (20) :

$$\alpha_e = 0.939; \quad \varepsilon_e = 0.403; \quad \alpha'_e = 0.374.$$

Then, the same process as in the application of paragraph 2 is followed. The equivalent parameters allowing the determination of the equivalent modeled selective surface (Fig. 4) have for values :

$$A_e = 0.942; \quad E_e = 0.370; \quad \lambda_{ce} = 4.85 \mu\text{m}.$$

- b) *Case 2* : $\lambda_v = 5 \mu\text{m}$,
 $\lambda_A = 3 \mu\text{m}$.

Here we find :

$$\alpha_e = 0.941; \quad \varepsilon_e = 0.345; \quad \alpha'_e = 0.337.$$

Fig. 4. — Connecting selective surface and glass cover : $A = 0.95$; $E = 0.50$; $\lambda_v = 3 \mu\text{m}$; $\lambda_A = 8 \mu\text{m}$.

Fig. 5. — Connecting selective surface and glass cover : $A = 0.95$; $E = 0.50$; $\lambda_v = 5 \mu\text{m}$; $\lambda_A = 3 \mu\text{m}$.

The equivalent modeled selective surface (Fig. 5) is defined by :

$$A_e = 0.946; \quad E_e = 0.334; \quad \lambda_{ce} = 3.95 \mu\text{m}.$$

- c) *Case 3* : $\lambda_v = 3 \mu\text{m}$,
 $\lambda_A = 3 \mu\text{m}$.

Here, the same method as that applied in cases 1 and 2 could be also applied. Nevertheless, it can be noticed that the solution of the set of equations (4), (5), (6), appears immediately.

In this application the set is expressed :

$$\begin{aligned} \left(A - \frac{E}{1+E} \right) k_s + \frac{E}{1+E} &= (A_e - E_e) k_{se} + E_e, \\ \left(A - \frac{E}{1+E} \right) k_A + \frac{E}{1+E} &= (A_e - E_e) k_{Ae} + E_e, \\ \left(A - \frac{E}{1+E} \right) k_E + \frac{E}{1+E} &= (A_e - E_e) k_{Ee} + E_e. \end{aligned}$$

The evident solution of this set is :

$$\lambda_{ce} = \lambda_c; \quad E_e = \frac{E}{1+E}; \quad A_e = A.$$

Therefore, the equivalent modeled selective surface is defined by (Fig. 6) :

$$A_e = 0.950; \quad E_e = 0.333; \quad \lambda_{ce} = 3 \mu\text{m}.$$

Fig. 6. — Connecting selective surface and glass cover : $A = 0.95$; $E = 0.50$; $\lambda_v = \lambda_A = 3 \mu\text{m}$.

3. Taking into account the convective exchanges. — So far, we did not take into account the existence of convective exchanges within the heliothermal converters. In the example that we have examined (greenhouse effect + selective surface), these exchanges

modify (13) and (14) which had been established considering the radiative exchanges only. Let $\phi_{A,v}$ and $\phi_{v,E}$ be the convective flux exchanged between the absorbing surface and the lower face of the cover and between the upper face of the same cover and the environment of the converter.

These two equations become (when considering the nullity of the radiative fluxes $\Phi_{S,A,v}$ and $\Phi_{E,A,v}$) :

$$\Phi_u + \Phi_A + \phi_{A,v} = \Phi_{S,A} + \Phi_{v,A} + \Phi_{E,A}, \quad (29)$$

$$2\Phi_v + \phi_{v,E} = \Phi_{S,v} + \Phi_{E,v} + \Phi_{A,v} + \Phi_{v,A,v} + \phi_{A,v}. \quad (30)$$

The various radiative fluxes have been evaluated in the foregoing paragraph; as for the convective exchanges, they can be deduced from correlations proposed by several authors. These correlations take into account the utilization conditions of the converter, particularly its inclination to the horizontal plane and the distance from the absorbing surface to the cover. To show clearly the order of magnitude of the modifications induced in the results obtained above (taking into account the convective exchanges), we use a simplified formula (proposed by Hottel [5]) of the convective flux ϕ_{AV} :

$$\phi_{AV} = 1.23(T_A - T_v)^{1.25}. \quad (31)$$

Concerning flux ϕ_{vE} , the following formulation is adopted, where V is the speed of the wind, parallel to the cover :

$$\phi_{v,E} = (7.5 + 4V)(T_v - T_E), \quad \text{for } 0 < V < 4 \text{ m.s}^{-1}, \quad (32)$$

$$\phi_{v,E} = 7.3 V^{0.8}, \quad \text{for } 4 < V < 40 \text{ m.s}^{-1}. \quad (33)$$

Here, we will restrain ourselves to examine case 1 only. After replacing the radiative fluxes by their expressions in (29), we have :

$$\begin{aligned} \gamma M_v^0 &= M_E^0(1 - k_{vE}) + CH(1 - k_{vS}) + \\ &+ M^0[A(k_{AA} - k_{vA}) + E(1 - k_{AA})] + \phi_{A,v} - \phi_{v,E}. \end{aligned} \quad (34)$$

This relation allows the transformation of (29); it is demonstrated very simply that it can be expressed :

$$\begin{aligned} \Phi_u &= \alpha_e CH - \varepsilon_e M^0 + \alpha'_e M_E^0 + \\ &+ \frac{\chi}{\gamma}(\phi_{A,v} - \phi_{v,E}) - \phi_{A,v}. \end{aligned} \quad (35)$$

The opto-thermal factors α_e , ε_e , α'_e as well as the coefficients χ and γ having the same definitions as in paragraph 2 (case 1), let us note here the analogy between the thermal equation (32) and the one of the

simplified converter (3); this leads us to define an equivalent term of the losses by convection :

$$P_{ce} = \phi_{AV} - \frac{\chi}{\gamma}(\phi_{AV} - \phi_{vE}) \quad (36)$$

• **SPECIAL CASE OF APPLICATION.** — The temperatures and the cut-off wavelengths are identical to those given in case 1, paragraph 2. The geometric concentration is equal to 5 and the speed of the wind $V = 10 \text{ m.s}^{-1}$.

The opto-thermal factors obtained from a calculation similar to those carried out above are :

$$\alpha_e = 0.939; \quad \alpha'_e = 0.361; \quad \varepsilon_e = 0.412.$$

The modeled selective surface corresponding to these factors is defined by :

$$\lambda_{ce} = 5.52 \mu\text{m}; \quad A_e = 0.941; \quad E_e = 0.352.$$

In the same conditions, and considering the radiative exchanges only, we would have :

$$\alpha_e = 0.939; \quad \varepsilon_e = 0.402; \quad \alpha'_e = 0.376,$$

and

$$\lambda_{ce} = 4.73 \mu\text{m}; \quad A_e = 0.942; \quad E_e = 0.373.$$

Note that taking into account the convection alters appreciably the parameters defining the equivalent modeled selective surface.

4. Conclusion. — As demonstrated and being subject to certain simplifying assumptions, it is possible to modelize the opto-thermal behaviour of a helio-thermal converter. The configuration examined (selective absorbing surface + greenhouse effect) is frequently used in this type of conversion. However, the model offers a wider generality and can be applied to other anti-loss systems [1].

We have also shown, through a simple graphic method the modelization of A_e , E_e , λ_{ce} (knowing the opto-thermal parameters). They can be implemented.

The simplifying assumptions used, are of the type of those frequently applied to determine the efficiency of converters : considering for instance the temperature of the absorbing surface as uniform, it corresponds to the notion of mean temperature ; in another connection, using correlations for convective exchanges, it does not take into account the local exchanges, which is, of course, only an approximation. Significant lessons can nevertheless be drawn from the application of such a modeling action. Considering for instance that the equivalent cut-off wavelength of the system « selective surface-cover » is the wavelength of the said selective surface, induces errors which can be of significant magnitude. We can also note that the position of this equivalent cut-off wavelength is influenced by the convective phenomena and therefore that a system under air vacuum does not present the same radiative properties as a classical system.

As a conclusion, we would like to emphasize the advantages of the modelization proposed, which makes it possible to use the results yielded by the study of the « selectivity/concentration » trade-off [6].

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