THE SUNSPACE : COMPUTATION AND IN-SITU MEASURES

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ABSTRACT

Today, it is not necessary to further demonstrate the interest of knowing with good accuracy the temperature evolution in a non-heated greenhouse.

Since over and underheating are predicted, we can **evaluate for every** greenhouse its utilization period for the inhabitants arid for the plants, and its impact on the heating demand of a house.

The program "SOLPA I" evaluates separately the convection and the interior radiation contribution, taking a non uniform distribution of solar radiation and successive reflexions into account. It also allows us to visualise the evolution of heat storage in the opaque walls during the day, arid of heat emission during the night.

The results obtained by the simulation are compared with the measures made in a particularly interesting sunspace and in an experimental cell.

INTRODUCTION

The passive use of solar energy has recently attracted much attention. A good example of its application is the use of a greenhouse oriented to south. Today, it influences the organisation of the interior, invites the inhabitants to renew with a nomadism day-night or summer-winter : sometimes extension, sometimes it imposes the retirement in a zone most insulated. if the sunspace can influence the "modus vivendi", it is also a privileged space for the senses through the surface aspects, the variations of the light, the transparencies, the presence and the odors of the plants, and the physic sensation of the outdoor climate.

For all these reasons, it is necessary to detect over and underheatings, since those determine the utilization periods for the inhabitants and for the plants.

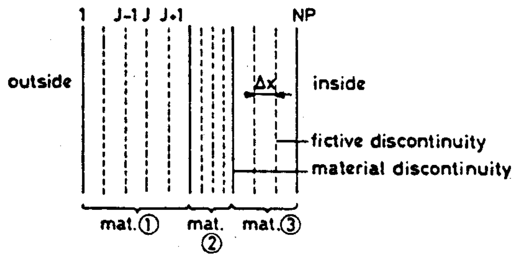
Furthermore, the knowledge of the temperature evolution within the sunspace allows us to make a more accurate computation of the heating demand of the house.

The computation of the temperature in a sunspace differs from the classical thermic formulas because great differences of temperature between walls, and between the walls and the greenhouse air exist. For this reason, the program "SOLPA 1" evaluates separately the convection and the interior radiation contribution, taking a non-uniform distribution of solar radiation and successive reflexions into account.

THEORICAL CONSIDERATIONS

The method of calculation is based on the equation expressing the balance-sheet of the energetic fluxes inside the room.

In order to calculate the thermal flux exchanged between the room and the walls, we express the thermal transmission in the walls by a finite difference procedure. This method requires the choice of a step of time and of space. Large steps implie less accurate results, but increase the rapidity of computation and therefore reduce the price. Each wall will be divided in sublayers.



Equation expressing the balance-sheet of the energetic fluxes inside the room.

$$\sum_{\ell=1}^{NP} A(\ell) h_{ci}(\ell)\left[t_{NP}(\ell) - t_i(\ell)\right] + R \rho_a c_a V (t_e - t_i) + Fc + FG = V \rho_a c_a \frac{\partial T_i}{\partial \tau} \quad (1)$$

where :

- $\sum_{\ell=1}^{NP} A(\ell) h_{ci}(\ell)[t_{NP}(\ell) - t_i(\ell)]$ represents the thermal flux exchanged between the room and the walls by convection
- $R \rho_a c_a V (t_e - t_i)$ is the load by ventilation
- Fc is the compensation flux
- FG is the free gain
- $V \rho_a c_a \, \partial T_i / \partial \tau$ is the increase of the enthalpie of the room air

Applying Taylor's series

$$\left(\frac{\partial T_i}{\partial \tau}\right)^{M+1} = \frac{3T_i^{M+1} - 4T_i^{M} + T_i^{M-1}}{2\Delta\tau}$$

where $\Delta\tau$ is the step of time

If we make the hypothesis that the air temperature is uniform in all the room, equation (1) becomes

$$\sum_{\ell=1}^{NP} A(\ell) h_{ci}^{M+1}(\ell)\left[t_{NP}^{M+1}(\ell) - t_i^{M+1}\right] + R \rho_a c_a V\left[t_e^{M+1} - t_i^{M+1}\right] + Fc^{M+1} + FG^{M+1} = V \rho_a c_a \frac{3t_i^{M+1} - 4t_i^{M} + t_i^{M-1}}{2\Delta\tau} \quad (2)$$

Equations expressing the thermal transmission in the walls.

The Fourier equation is solved by a finite difference procedure by a implicit method using ponderation factors

so $\frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial x^2}$ where ∂x is the step of space or the thickness of a sublayer

becomes

$$\frac{t_j^{n+1} - t_j^n}{\Delta\tau} = a\left(\theta \frac{t_{j-1}^{n+1} - 2t_j^{n+1} + t_{j+1}^{n+1}}{\Delta x^2} + (1-\theta)\frac{t_{j-1}^n - 2t_j^n + t_{j+1}^n}{\Delta x^2}\right) \quad (3)$$

where a is the thermal diffusivity $a = \frac{\lambda}{C_a \varphi_a}$

θ is the factor of ponderation $0 < \theta < 1$

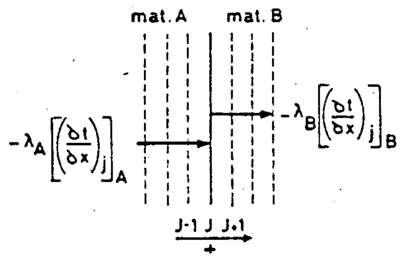
$j, j-1, j+1$ represent the sublayers of the wall

1. Fictive discontinuity.

Using $V = a\frac{\Delta\tau}{\Delta x^2}$, equation (3) becomes

$$\theta V t_{j-1}^{n+1} - (1+2\theta V)t_j^{n+1} + \theta V t_{j+1}^{n+1} = -t_j^n - V(1-\theta)(t_{j-1}^n - 2t_j^n + t_{j+1}^n) \quad (4)$$

2. Material discontinuity.



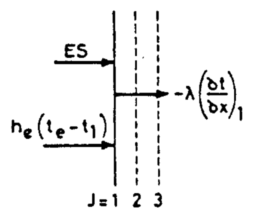
Applying Taylor's series,

$$\lambda_A\left(\frac{t_{j-2} - 4t_{j-1} + 3t_j}{2\Delta x_A}\right) = \lambda_B\left(\frac{-3t_j + 4t_{j+1} - t_{j+2}}{2\Delta x_B}\right)$$

or

$$\frac{\lambda_A}{2\Delta x_A}\left(t_{j-2}^{n+1} - 4t_{j-1}^{n+1}\right) + \frac{3}{2}\left(\frac{\lambda_A}{\Delta x_A} + \frac{\lambda_B}{\Delta x_B}\right)t_j^{n+1} + \frac{\lambda_B}{2\Delta x_B}\left(-4t_{j+1}^{n+1} + t_{j+2}^{n+1}\right) = 0 \quad (5)$$

3. Outside.



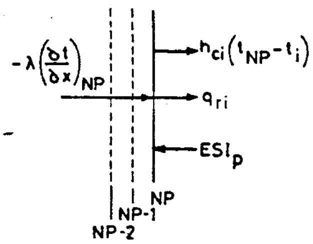
ES is the solar radiation W/m²

t_e is the outside temperature

$$ES + h_e(t_e - t_1) = -\lambda\left(\frac{\partial t}{\partial x}\right)_1 = -\lambda\,\frac{4t_2 - t_3 - 3t_1}{2\Delta x}$$

$$\left(3 + \frac{2\Delta x\, h_e}{\lambda}\right)t_1^{n+1} - 4t_2^{n+1} + t_3^{n+1} = \frac{2\Delta x}{\lambda}ES^{n+1} + \frac{2\Delta x\, h_e}{\lambda}t_e^{n+1} \quad (6)$$

4. Inside.



ESI is the internal radiation on this wall W/m²

q_{ri} is the thermal radiation to the others surfaces

$$-\lambda\left(\frac{\partial t}{\partial x}\right) = h_{ci}(t_{NP} - t_i) + q_{ri} - ESI_p = -\lambda\,\frac{4t_{NP-1} - t_{NP-2} - 3t_{NP}}{2\Delta x}$$

$$t_{NP-2}^{n+1} - 4t_{NP-1}^{n+1} + \left(3 + \frac{2h_{ci}^{n+1}\Delta x}{\lambda}\right)t_{NP}^{n+1} = \frac{2\Delta x}{\lambda}h_{ci}^{n+1}t_i^{n+1} + \frac{2\Delta x}{\lambda}ESI_p^{n+1} - q_{ri}^{n+1} \quad (7)$$

By using equation (4)

$$t_1^{n+1} = \frac{-t_2^n - V(1-\theta)(t_1^n - 2t_2^n + t_3^n) + (1+2\theta V)t_2^{n+1} + \theta V t_3^{n+1}}{\theta V}$$

and (6) becomes

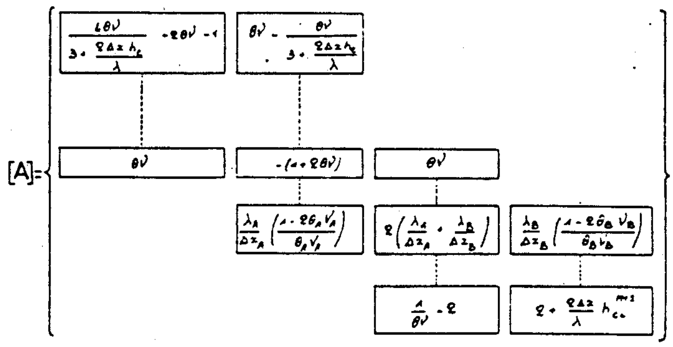
$$\left[\frac{4\theta V}{3 + \frac{2\Delta x\, h_e}{\lambda}} - 2\theta V - 1\right]t_2^{n+1} + \left[\theta V - \frac{\theta V}{3 + \frac{2\Delta x\, h_e}{\lambda}}\right]t_3^{n+1}$$
$$= -t_2^n - V(1-\theta)(t_1^n - 2t_2^n + t_3^n) - \frac{\theta V}{3 + \frac{2\Delta x\, h_e}{\lambda}}\frac{2\Delta x}{\lambda}ES^{n+1} - \frac{\theta V}{3 + \frac{2\Delta x\, h_e}{\lambda}}\frac{2\Delta x}{\lambda}h_e t_e^{n+1}$$

The equations (5) and (7) can also be modified by the same way to eliminate respectively

t_{j-2}^{n+1} and t_{j+2}^{n+1} and t_{NP-2}^{n+1}

So, for each wall we must solve

$$[A][T] = [B]$$



$$[T] = \begin{Bmatrix} t_2^{n+1} \\ \vdots \\ t_j^{n+1} \\ \vdots \\ t_p^{n+1} \\ \vdots \\ t_{NP}^{n+1} \end{Bmatrix} \quad [B] = \begin{Bmatrix} -t_2^n - \nu(1-\theta)(t_1^n - 2t_2^n + t_3^n) - \frac{\theta\nu}{1+\frac{2\Delta x h_e}{\lambda}} \frac{2\Delta x}{\lambda} ES^{n+1} \\ -\frac{\theta\nu}{1+\frac{2\Delta x h_e}{\lambda}} \frac{2\Delta x}{\lambda} h_e t_e^{n+1} \\ \vdots \\ -t_j^n - \nu(1-\theta)(t_{j-1}^n - 2t_j^n + t_{j+1}^n) \\ \vdots \\ -\left[\frac{\lambda_A}{\theta_A \nu_A \Delta x_A} D(p-1) + \frac{\lambda_B}{\theta_B \nu_B \Delta x_B} D(p+1)\right] \\ \vdots \\ \frac{2\Delta x}{\lambda} h_{ci}^{n+1} t_i^{n+1} + \frac{2\Delta x}{\lambda} ESI_p^{n+1} - 2\frac{\Delta x}{\lambda} q_{ri}^{n+1} - \frac{D(NP-1)}{\theta\nu} \end{Bmatrix}$$

We can apply the Thoma's method for the resolution of this system.
For each wall, we can write $t_{NP}^{n+1} = f_n(t_i^{n+1})$

By equation ② , we calculate t_i^{n+1} with q_{ri}^{n+1} and h_{ci}^{n+1} of the previous step and after the substitution of $t_{NP}^{n+1}(l)$

After that, we calculate t_{NP}^{n+1} for each wall.

Knowing t_{NP}^{n+1}, h_{ci}^{n+1} and q_{ri}^{n+1} can be calculated most exactly.

$$h_{ci}^{n+1} = c\,(t_{NP}^{n+1} - t_i^{n+1})^n$$

where c and n fluctuate with the slope of the wall

$$q_{ri}^{n+1} = \frac{\varepsilon_p\,\sigma (t_{NP}^{n+1})^4 - (\varepsilon_p + \tau_p) J_p}{1 - \varepsilon_p - \tau_p}$$

where σ = Stefan-Boltzmann constant
ε_p = infrared emissivity
τ_p = infrared transmitivity
J_p = total radiositie of surface p.

For the computation of Jp, we must solve

$$\begin{pmatrix} 1 & \cdots & (\varepsilon_1 + \tau_1 - 1) F_{1n} \\ \vdots & & \vdots \\ (\varepsilon_n + \tau_n - 1) F_{n1} & \cdots & 1 \end{pmatrix} \begin{pmatrix} J_1 \\ \vdots \\ J_n \end{pmatrix} = \begin{pmatrix} \varepsilon_1 T_1^4 \\ \vdots \\ \varepsilon_n T_n^4 \end{pmatrix}$$

where Fij is the shape factor of surface Ai with respect to surface Aj.
With these new values of h_{ci}^{n+1} and q_{ri}^{n+1}, we calculated t_i^{n+1}, after t_{NP}^{n+1}, and then q_{ri}^{n+1} and h_{ci}^{n+1}...
as far as stability.
The temperature in the walls $(t_2^{n+1} \ldots\ldots t_{NP-1}^{n+1})$ are determined by the resolution of the system.
The outside temperature of the wall is calculated by ⑥

Remarks about ES and ESI

The values of ES are data that the program read in a file. These values are given for each hour, each slope and each orientation.
The solar radiation entered in the room by the window l is

$$ES(l) * A_v(l) * \tau_s(l)$$

where $ES(l)$ is the solar radiation on the window l (W/m^2)
$A_v(l)$ is the area of the window
$\tau_s(l)$ is the transmission coefficient for the solar radiation, it is calculated for each incidence angle.

This solar radiation entered in the room is distributed in proportion to the shape factors. So the wall p receives $\frac{1}{A_p}\left(\sum_l A_v(l)\,\tau_s(l)\,ES(l)\,F_{lp}\right)$

where F_{lp} is the shape factor of surface A_l with respect to surface A_p

The wall p absorbs $ESI_p = \alpha_{sp} \frac{1}{A_p}\left[\sum_l A_v(l)\,\tau_s(l)\,ES(l)\,F_{lp}\right] W/m^2$

and reflects $ERI_p = (1 - \alpha_{sp} - \tau_{sp}) \frac{1}{A_p}\left[\sum_l A_v(l)\,\tau_s(l)\,ES(l)\,F_{lp}\right] W/m^2$

The wall p' absorbs

$$\alpha_{sp'} \sum_p A_p F_{pp'} ERI_p \quad W$$

$$\text{or} \quad \alpha_{sp'} \sum_p \frac{A_p F_{pp'}}{A_{p'}} ERI_p \quad W/m^2$$

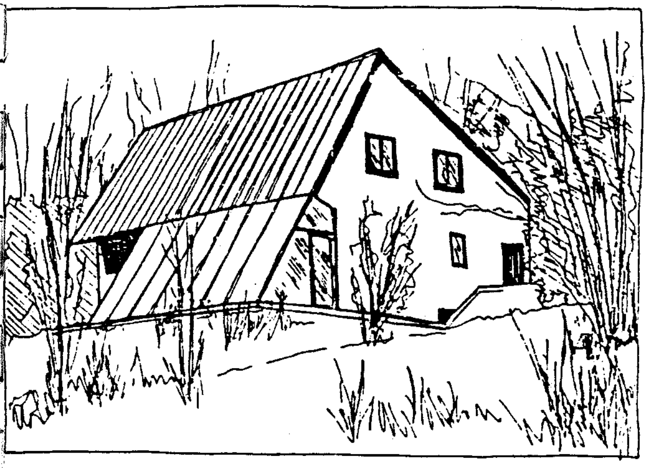
$$F_{pp'} * A_p = F_{p'p} * A_{p'}$$

Then p' absorbs $\alpha_{sp'} \sum_p F_{pp'} ERI_p$
Finally after a reflexion the wall p' has absorbed

$$ESI_{p'} = \alpha_{sp'} \left[\frac{1}{A_{p'}}\left[\sum_l A_v(l)\,\tau_s(l)\,ES(l)\,F_{lp'}\right] + \sum_p F_{p'p}(1 - \alpha_{sp} - \tau_{sp}) \frac{1}{A_p}\left[\sum_l A_v(l)\,\tau_s(l)\,ES(l)\,F_{lp}\right]\right] (W/m^2)$$

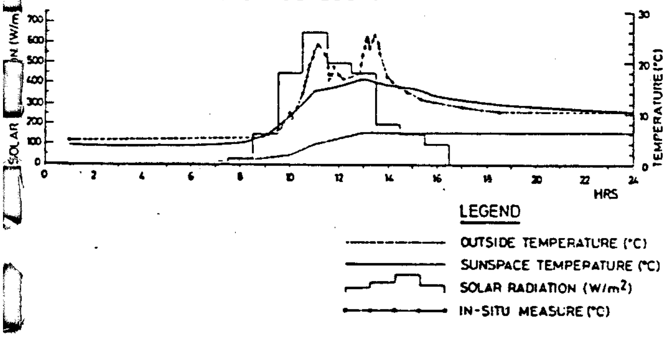
DISCUSSION

Comparison with the measures made in a sunspace.

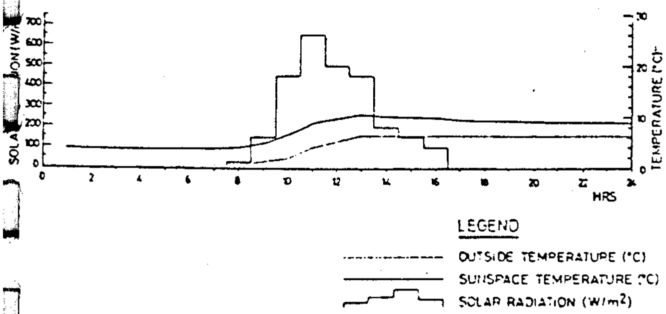


The sunspace is oriented south.
The wall between the sunspace and the house is par-
ially glazed. The floor is composed of
.02 m of basalte (absorption coefficient = 0.8)
0.1 m of concrete
0.37 m of insulation material
he floor, the wall partially opaque and the impor-
ant window frame represent the thermic mass.
The air temperatures in the sunspace, in the living and outside, the solar radiation and the door swit-
hes are measured permanently.

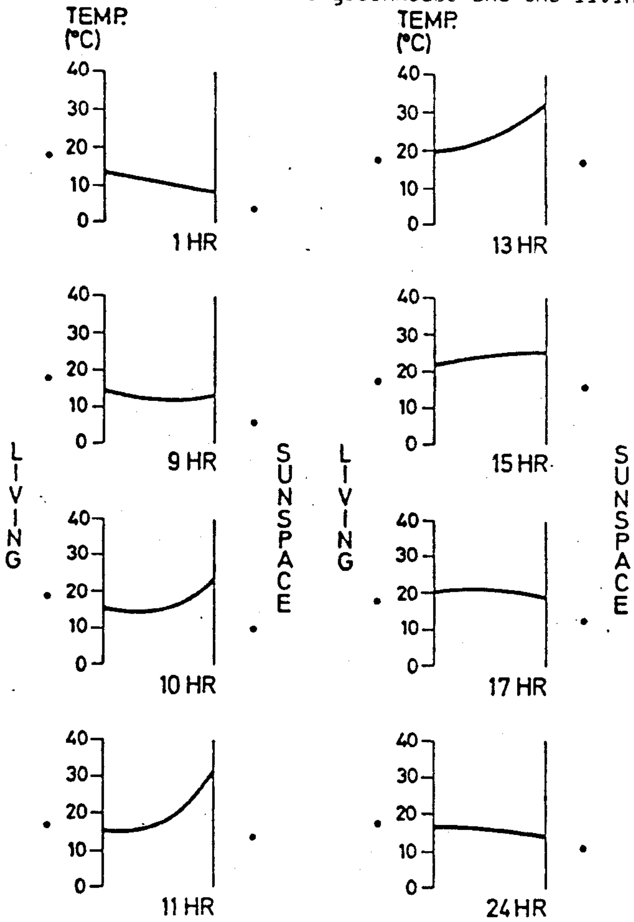
. For testing the program we have chosen a winter day during which the inhabitants were absent (december 31st), and therefore door switches in-
icate o, the doors being closed all day.
he results obtained are :



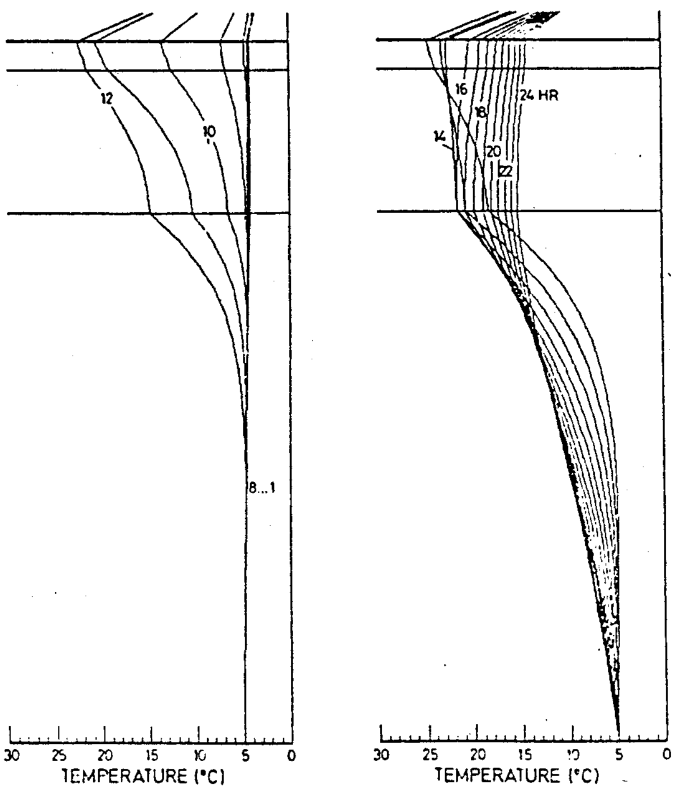
We remark that there are picks because the sondes are sunny and the temperature reduce when the sun is behind the window - frames.
Using a program based on a finite difference procedure but that doesn't take the greenhouse effect into account, we obtain



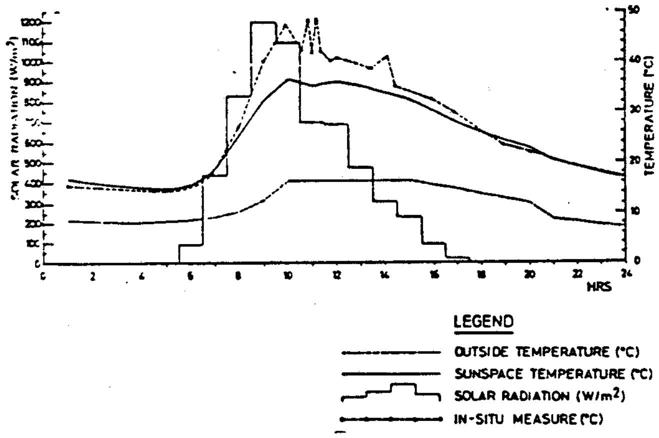
The program gives also the temperature evolution in the walls.
In the wall between the greenhouse and the living



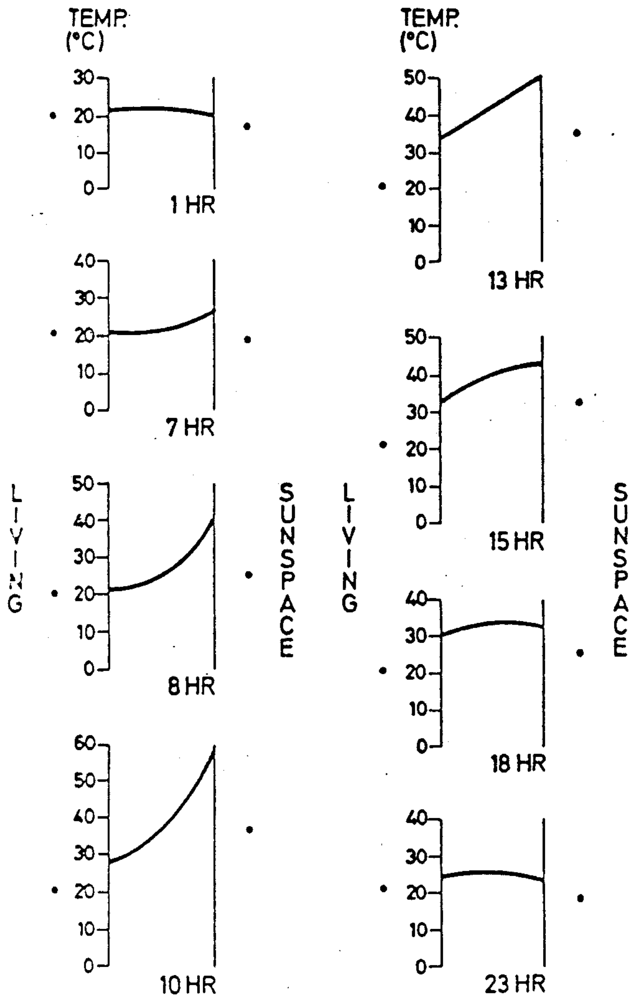
In the floor



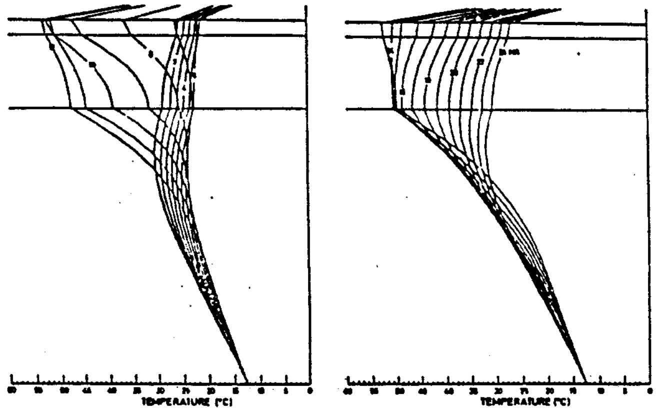
2. For a spring day (may 8st), we obtain



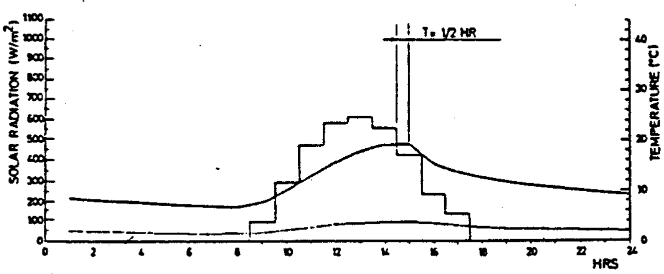
In the wall between the greenhouse and the living



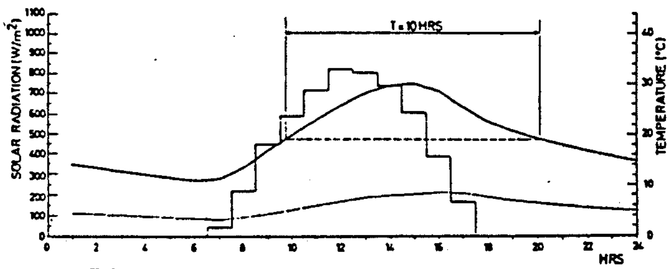
In the floor



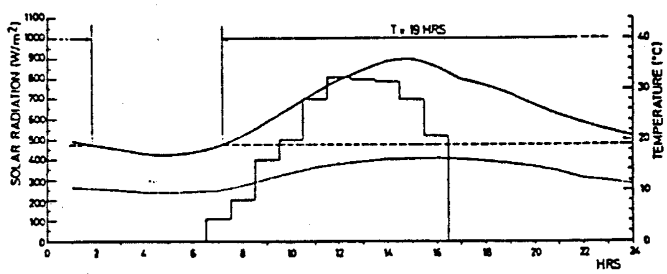
3. Evaluation of the utilization period of the greenhouse.
We have fixed the utilization period of the greenhouse over nineteen degrees. We suppose that the overheatings can be resolved by a good ventilation. The climatic data are these of the Belgium.



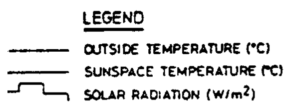
JANUARY

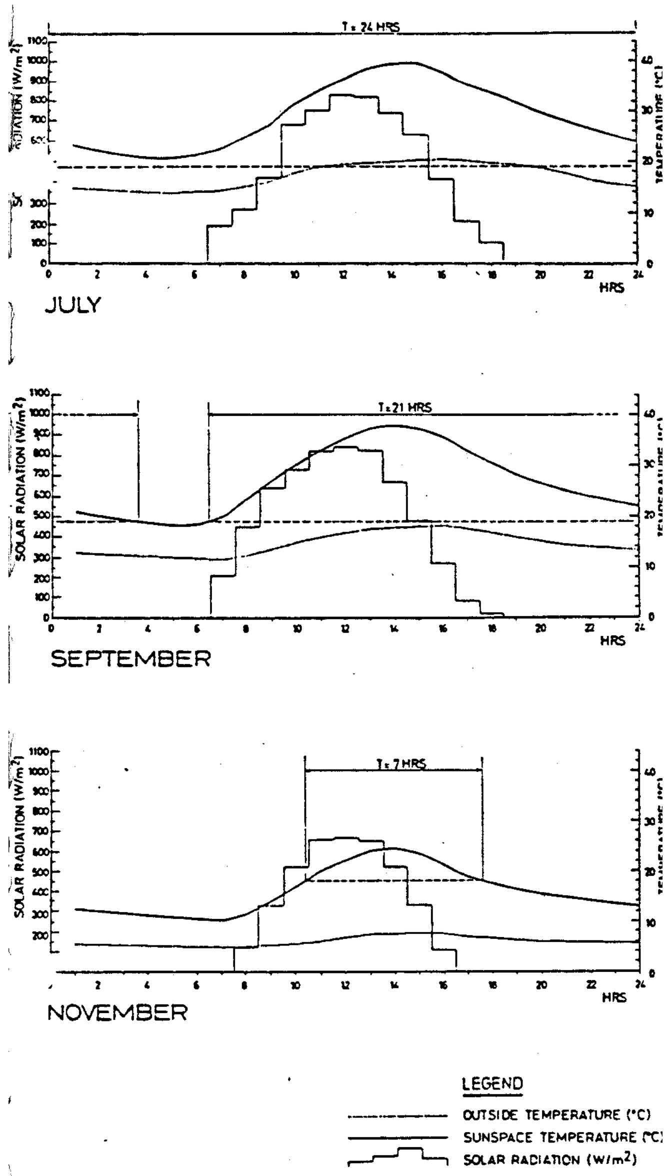


MARCH

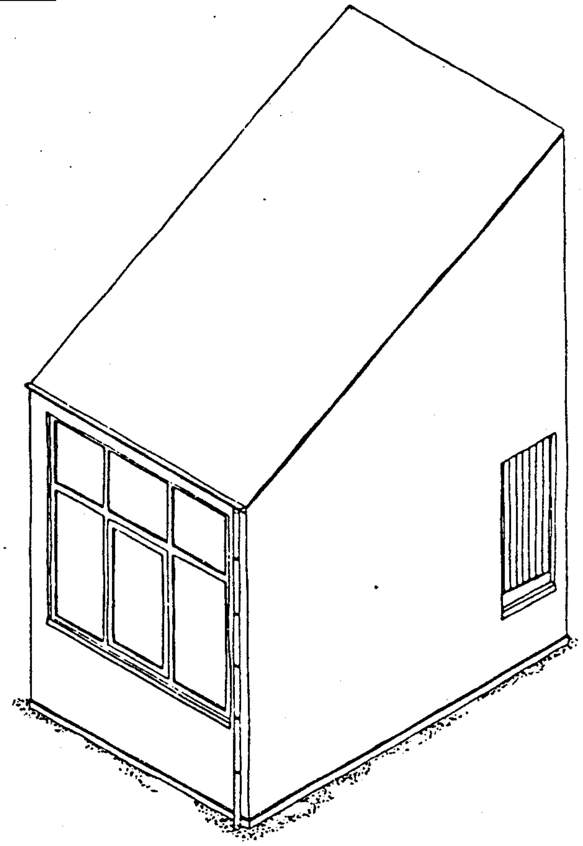


MAY

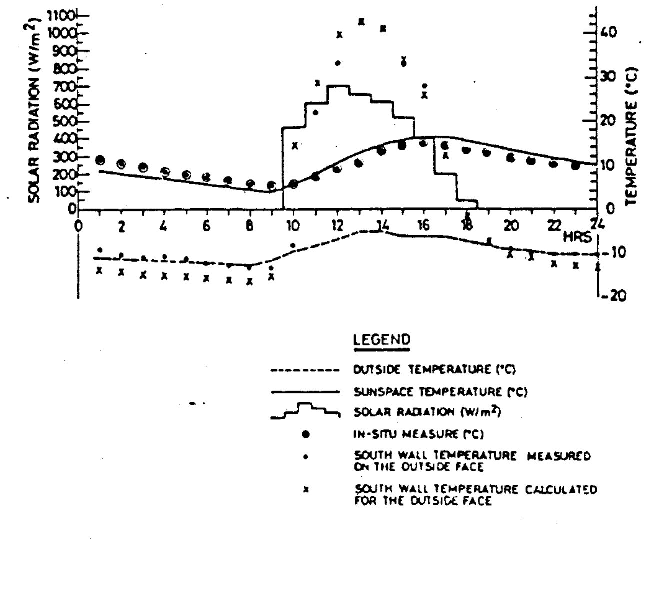




Comparison with the measures made in an experimental cell.



The south surface of the experimental cell is nearly entirely glazed. The other walls are good insulated (K = 0.26 W/m²°K).
The air temperatures in the cell, under the floor, and outside, the external superficial temperatures, the solar radiation, the wind direction and speed are measured permanently.
We have chosen a cold and sunny winter day for testing the program.



CONCLUSIONS

Program SOLPA 1 evaluates with a good accuracy the temperature evolution in a room even if it is largely glazed. It predicts the over and underheatings in a greenhouse. It also allows us to visualise the evolution of heat storage in the opaque walls during the day and of heat emission during the night. More, the computation of the heating demand of a house is influenced by the accurate knowledge of the temperature evolution of the attached sunspace.
Today, program SOLPA 1 uses 50 KBYTES and is writed in FORTRAN on HP 1000, serie A.

BIBLIOGRAPHY

- BURNAY G., FAFCHAMPS J., - Etude du comportement dynamique d'un local par la méthode des différences finies, Université de Liège.
- DOGNIAUX R., - Eclairement énergétique par ciel serein des parois orientées et inclinées. Données d'applications pour la Belgique, Institut Royal Météorologique de Belgique, Bruxelles, 1973.
- ATHANASSOULI G., MASSOUROS G., - The contribution of the Thermal Radiation of Inner Surfaces of a Room on its Thermal Losses, Energy Research, Vol. 6, 1982, pp. 111-121.
- CRASSON P., - Etude du comportement dynamique d'une serre par la méthode des différences finies, Université Catholique de Louvain, Belgique, 1984.
- OPFERGELT D., - Three examples of passif solar use - The same will to converse with the climat. International sonnenforum, Berlin, 1984.
- OPFERGELT D., - La serre ... une autre vision de la fenêtre.
  Colloque international : les fenêtres dans la conception et la maintenance des bâtiments, Goteborg, 1984.
- JASPARD Ph., - Bioclimatic architecture, theoretical consideration and concretisation.
  Int. Passive & Low energy architecture congress, Crète, 1983.
- DE HERDE A., LE PAIGE M., OPFERGELT D., - La serre, un nouvel espace de vie.
  Revue architecture Belgium, avril-mai 1983.
- DE HERDE A., - Comportement occupants et consommation énergie chauffage.
  Cellule architecture et climat - UCL - Belgique, 1983.
- DE HERDE A., MUYLDERMANS L., MABARDI J.F., SIMON Fr., - L'élément vitré dans le cadre de la climatisation naturelle.
  Cellule architecture et climat - UCL - Belgique, 1978.
- GRATIA E., - L'élément vitré dans le cadre de la climatisation naturelle - Programme SOLPA.
  Cellule architecture et climat - UCL - Belgique, 1981.

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