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ANALYSIS OF NOCTURNAL MICROCLIMATE IN SINGLE SKIN COLD GREENHOUSES IN MEDITERRANEAN COUNTRIES

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Abstract

So as to be able to evaluate the behaviour of cold greenhouses during the night in mediterranean area, a representative mathematical pattern of the nocturnal energetic balance of single plastic skin greenhouses is proposed.

Such mathematical pattern allowed a forecasting analysis of the thermal level inside the greenhouse for short time intervals; the results obtained in this way were compared to the measured values of a small frame type greenhouse without any artificial energetic contribution.

A special attention was given to the elaboration of temperature datas during the clear sky nights in the winter, whereby the thermal gradient inversion between inside and outside occurs.

1. Foreword

The large diffusion which characterizes cold greenhouses in the mediterranean area warranted by the low cost of construction and low running cost, needs a deep knowledge of the heat exchanges which take place between the confined environment and the external one (Candura et al., 1984). Such exchanges are the only existing ones in case of absence of artificial energy source, which would give an absolutely preponderant contribution to the microclimate of the greenhouse compared to the natural ones; a better knowledge of them can allow an exact evaluation even in terms of the design of the greenhouse.

2. Representative mathematical pattern of single skin greenhouses

Many authors have studied the complex of physical phenomenons produced in greenhouses which are interdependent between themselves; the mechanisms of heat transfer through the covering were studied by Nijskens et al. (1984) and by Garzoli et al. (1981); the mathematical formulation of those exchanges leads respectively to the determination of the global coefficient of transmission and to the setting and calibration of the values of the coefficients of convective exchange that best fit the experimental datas, inside and outside the covered surface.

Froehlich et al. (1979) and Avissar et al. (1982) analysed heat transfer in a whole day period; special developments on the effect that the formation of condensation on the inner covering surface has on heat transfer towards outside were at last obtained by de Halleaux et al. (1985) while Seginer et al. (1986) obtained some results on the influence of the internal thermohygrometric conditions on the value of the convective coefficient between air and soil. Major part of these researches sometimes neglects the energetic contribution coming from the soil in their consideration of heated

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greenhouses, while some other times they take this aspect into consideration but attributing values depending on parameters estimated for heated greenhouses.

We have formulated a mathematical pattern based on the following hypotesis so as to analyse the nocturnal microclimate inside single plastic skin cold greenhouses:

a) steady-state conditions in the considered time interval (1 hour);
b) no capability of heat storage of the covering layer due to reduced thickness of the plastic films usually used;
c) no capability of heat storage or release by the volume of the air contained in the greenhouse due to its neglectable thermal capacity;
d) equal temperature level for both the plastic film covering and the condensation forming on its inner surface;
e) perfectly tight joints, which implicates neglectable ventilation rate;
f) internal air relative humidity of the greenhouse at 100% during the night, as obtained in the experiments;
g) 67% of plastic film inner surface covered by condensation (Garzoli et al., 1981).

The mathematical pattern is based on the following two equations with reference to Fig. 1 and the notations on Tab. 1:

- equilibrium between energy coming in and going out of the covering;
- equilibrium between energy coming in and going out of the soil.

The first equation (Garzoli et al., 1981) is as follows:

$$H_i + R_{gi,s} + R_{gi,cv} + R_{gi,c} + D = \\ = R_{gi,s} + R_{cv,ge} + R_{cv,s} + R_{c,s} + R_{c,ge} + H_e \tag{I}$$

where the value of each contribution is:

$$H_i = A_{cv} h_i \; (T_{ai} - T_{cv}) \; ;$$
$$R_{gi,s} = 0.33 \; \sigma \; A_{gi} \; \tau \; (T_{bb,gi}^4 - T_s^4) \; ;$$
$$R_{gi,cv} = 0.33 \; \sigma \; A_{gi} \; \varepsilon_1 (T_{bb,gi}^4 - T_{cv}^4) \; ;$$
$$R_{gi,c} = 0.67 \; \sigma \; A_{gi} \; \varepsilon_2 (T_{bb,gi}^4 - T_{cv}^4) \; ;$$
$$D = A_{cv} \; h_i \; L \; (w_{ai} - w_{cv}) \; / \; c \; ;$$
$$R_{cv,ge} = \sigma \; A_{cv} \; \varepsilon_{cv} \; F_{cv,ge} \; (T_{cv}^4 - T_{bb,ge}^4) \; ;$$
$$R_{cv,s} = \sigma \; A_{cv} \; \varepsilon_{cv} \; F_{cv,s} \; (T_{cv}^4 - T_s^4) \; ;$$
$$R_{c,s} = 0.67 \; \sigma \; A_{cv} \; \varepsilon_c \; F_{cv,s} \; \tau (T_{cv}^4 - T_s^4) \; ;$$
$$R_{c,ge} = 0.67 \; \sigma \; A_{cv} \; \varepsilon_c \; F_{cv,ge} \; \tau (T_{cv}^4 - T_{bb,ge}^4) \; ;$$
$$H_e = A_{cv} \; h_e \; (T_{cv} - T_{ae}) \; .$$

where:

$$T_{bb,gi} = (\varepsilon_{gi})^{0,25} \, T_{gi} = 0.982 \; T_{gi} \; ;$$
$$T_{bb,ge} = (\varepsilon_{ge})^{0,25} \, T_{ge} = 0.982 \; T_{ge} \; ;$$
$$w_{ai} = RH \; (0.004055 + 0.0001152 \; t_{ai} + 0.00002167 \; t^2_{ai}) ;$$
$$w_{cv} = 0.004055 + 0.0001152 \; t_{cv} + 0.00002167 \; t^2_{cv} \; ;$$
$$\varepsilon_c = 0.95$$

The temperature of the sky, T_s , according to Nijskens et al.(1984), is:

$T_s = 0.0552 \; T_{ae}^{1,5}$ for clear sky; $T_s = T_{ae}$ for overcast sky.

Regarding the convective coefficient of thermal exchange between air and covering layer, the following are the expressions: $h_i = 7.2$ W/m^2 K; $h_e = 7.2 + 3.8 \; v$ W/m^2 K.

The second energy balance equation between in coming and out going energy of the soil surface (Seginer et al., 1986) is written:

$$C - H_g - R_{gi,cv} - R_{gi,c} - R_{gi,s} = 0 \tag{II}$$

whereby the terms of the equations are positive as in Fig. 1, H_g and C have the following expressions:

$H_g = A_{gi} h_g (T_{gi} - T_{ai});$
$C = k_g A_{gi} (T_j - T_{j+1}).$

In this case, the following experimental values (Seginer et al., 1986), (Zito et al., 1983) were assumed: $h_g = 2$ W/m² K; $k_g = 14$ W/m² K.

In this way, (I) and (II) constitute a system of two equations in the unknowns T_{ai} and T_{cv}; in (I) T_{cv} is in terms of 4th grade and therefore the system can be solved by trial. The solution couple (T_{ai}, T_{cv}) inside the interval of acceptable values, can be obtained once all greenhouse geometrical and optical characteristics and measured temperature values are well-known. In this way, the pattern not only allows a global energy balance but also a forecast on the nocturnal temperature condition inside the greenhouse.

The described methodology can also be considered, even though with necessary modifications, a valid instrument to face the problems related to greenhouses with heating systems. Describing the thermal balance of internal air through an equation of equilibrium between in coming and out going energy, the unknown term "E" can be introduced, representing the energy produced by the artificial energy source if present; its determination is possible when, in the projection phase, the desired microclimatic conditions (T_{ai}) are fixed.

3. Experimental tests

3.1. Materials and methods

The experimental greenhouse was built in a scale of 3 times less than the traditional commercial ones, situated in the Campus of the University of Bari without any cultivation inside the greenhouse.

The transversal section is a frame type, and the longitudinal axis was oriented towards N-S slightly turned towards W. The following are the geometrical characteristics and the view factors for radiation exchange: $A_{gi} = 27$ m² ; $A_{cv} = 55$ m² ; $F_{cv,s} = 0.5$; $F_{cv,ge} = 0.5$.

The covering material, made of a single sheet of 0.15 mm thick plasticized PVC (Plypac) film, was laid on a supporting structure made of galvanized steel. This PVC film was adequately burried in the soil at the foot of the structure; the optical characteristics of such material in medium and far infrared wavelenght are : $\varepsilon = 0.62$, $\tau = 0.33$, $\rho = 0.05$.

The temperature measurements were carried out through thermoresistant sensors (Pt100), situated in the soil at different depths (immediately under the surface layer and at a depth of 50 mm).

Both inside and outside the greenhouse, the soil (Zito et al., 1983) is lime-sandy type with dry density value of 1200 Kg/m^3 ;its thermal conductivity is: λ = 0.7 W/m K.

The air temperatures were measured using two thermoresistant sensors placed at the height of 0.50 and 1.40 m from the surface layer inside the greenhouse and other two outside the greenhouse. Inside and outside temperature values were calculated on average. The temperature values taken at hourly intervals, were recorded from a Philips PR2011 data-logger. By means of a hygrothermograph placed inside the greenhouse the value of relative internal humidity was measured.

Wind speed values were obtained through datas measured by a meteorological station near the test area.

3.2. Results and discussion

The tests were carried out in February and March 1989 and the elaboration regarded four nights chosen to be able to verify the model in different climatic conditions. The mathematical pattern described in point 2, whose results are shown in Tab. 2, was used on the basis of the temperature measurements carried out on the experimental greenhouse.

The following considerations can be formulated by the obtained results:
a) the analysis carried out allowed a demonstration of the physical phenomenon noticed during the experiment, that is the lowering of the internal air temperature of the greenhouse below that of external air with maximum gradient of about 3 K (Tab. 2). Such a phenomenon of nocturnal thermal inversion is probably due to the behaviour of the greenhouse as a body radiating towards the sky; the greenhouse, in absence of internal ventilation, increases the radiative energy emission phenomenon. Then we noticed that:
- the surface layer of the external soil has less nocturnal temperature of about 2-3 K (Tab. 2) compared to that of the external air;
- according to the results of the mathematical simulation (Tab. 2) the nocturnal temperature of the greenhouse covering, due to its radiating contribution towards the sky, is frequently lower than the external and internal air temperature.

b) We can notice that surface layer of the internal greenhouse soil, during the whole night, has a superior thermal level compared to the other bodies with which it is interacting; regarding the covering material, for example, the temperature difference is 8-12 K. The soil contribution has to do with its value of internal conductivity (λ), which depends on the type of soil and its water contents; thus, high rate of water contents should favour the release of heat from the soil to the internal environment of the greenhouse.

The influence of each energetic contribution (Tab. 2) on total heat transmission occurring on the soil surface, is shown in Fig. 2 with reference to the average of the hourly nocturnal measurements of 7 March 1989. As shown in Fig. 3, we can notice that the 32% of the covering's in coming energy is transferred directly outside the greenhouse, the 64% is absorbed and consequently redirected outside while the 4% of the energy emitted by the soil is reflected back to the soil. Such a phenomenon opposes the drop in soil temperature inside the greenhouse; the importance of the optical properties of cladding material is evident: this should have highest possible reflectance and low transmissivity in the far infrared.

Applying the mathematical pattern, it is possible to carry out an hourly forecast on the value of internal air temperature; Figg. 4, 5, 6, and 7, with reference to 18 and 20 February 89 and 7 and 15 March 89, show the temperature curves forecasted by means of the use of the pattern compared to the measured internal and external air temperatures. As can be seen, the difference between the experimental values and the calculated ones are less than 1 K in 45% of the cases and never more than 3 K.

4. Conclusions

The proposed energy balance has to do with cold greenhouses, not only because this type is diffused in the mediterranean area but also to allow more accurate evaluation of all the energetic contributions and dispersions which otherwise would inevitably be dominated by the contribution of an eventual artificial heat source. This can influence a correct interpretation of each phenomenon due to its sometimes preponderant contribution.

The calculation methodologies currently used for projecting heated greenhouses seem to be unable in designing cold greenhouses.

The resolution of the mathematical pattern elaborated to describe the nocturnal phenomenon of heat transmission, allowed the verification of datas obtained through experimental measurements. It also allowed the possibility to carry out forecast analysis of the internal thermal level of a single skin cold greenhouse giving the temperature value of the internal air with a precision of some centigrade degrees.

The contribution to programming and executing of this research must be equally divided between the Authors.

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Table 1 - Symbols used in the mathematical pattern.

NOTATIONS

H = heat transfer by convection, W;
R = heat transfer by radiation, W;
D = transfer of latent heat of condensation, W;
C = heat transfer by conduction through the soil layers, W;
T = absolute temperature, K;
t = relative temperature, °C;
A = surface, m^2;
k = coefficient of heat trasmission, W/m^2 K;
h = convective coefficient of thermal exchange, W/m^2 K;
σ = Stefan-Boltzmann constant = $5.6697\ 10^{-8}$ W/m^2 K^4 ;
ε = emissivity, %;

$$\varepsilon_1 = \frac{1}{1 + \frac{A_{gi}}{A_{cv}} \left(\frac{1}{\varepsilon_{cv}} - 1 \right)}, \% \qquad \varepsilon_2 = \frac{1}{1 + \frac{A_{gi}}{A_{cv}} \left(\frac{1}{\varepsilon_{c}} - 1 \right)}, \%$$

τ = transmissivity of the covering material, %;
L = latent heat of water condensation = 2454 kJ/kg;
c = specific heat of dry air = 1.006 kJ/kg K;
w = humidity ratio, %;
F = view factor for radiation exchange, %;
RH = relative humidity, %;
v = wind speed, m/s.

Subscripts

cv = covering;
c = condensation;
s = sky;
a = air;
bb = black body;
g = ground;
i = internal;
e = external;
j = j-th internal soil layer;
j+1 = (j+1)-th internal soil layer.

Table 2 - Nocturnal datas experimentally measured and values calculated through forecasting mathematical pattern.

Day	Hour	MEASURED VALUES				CALCULATED VALUES									
						Inside cover				Outside cover		Ground floor			
		Tai K	Tae K	Tgi K	Tge K	Tcv K	Hi W	Ri W	D W	Re W	He W	C W	Hg W	Ri W	Tai K
18/02/89	18.00	284,95	283,60	293,90	285,20	283,30	641,52	1038,68	934,81	2765,68	-178,20	604,80	483,3	1038,68	—
18/02/89	19.00	281,90	282,00	291,30	282,60	280,80	427,68	1000,40	497,73	2668,00	-712,80	945,00	507,6	1000,40	—
18/02/89	20.00	280,30	281,50	289,60	281,20	279,60	272,16	914,53	276,46	2593,14	-1128,60	1058,40	502,2	914,53	283,44
18/02/89	21.00	280,10	282,00	288,50	280,30	279,60	194,40	753,07	195,41	2599,72	-1425,60	1020,60	453,8	753,07	281,78
18/02/89	22.00	279,70	281,40	287,50	279,20	279,00	272,16	697,54	259,19	2651,06	-1425,60	1134,00	421,2	697,54	279,56
18/02/89	23.00	278,90	280,30	286,60	278,60	278,10	311,04	700,28	268,27	2655,58	-1306,80	982,80	415,8	700,28	280,17
19/02/89	00.00	278,40	280,20	285,90	278,20	277,70	272,16	654,71	221,79	2612,75	-1485,00	1020,60	405	654,71	278,76
19/02/89	01.00	278,00	279,80	285,30	277,60	277,30	272,16	627,81	210,28	2633,18	-1485,00	1171,80	394,2	627,81	278,59
19/02/89	02.00	277,05	279,10	284,80	276,70	276,50	213,84	666,11	145,44	2639,42	-1544,40	1020,60	418,5	666,11	277,72
19/02/89	03.00	276,70	278,50	284,40	276,60	276,00	272,16	680,66	172,87	2617,48	-1485,00	1020,60	415,8	680,66	277,44
19/02/89	04.00	276,10	277,90	283,70	275,90	275,40	272,16	667,02	155,61	2629,53	-1485,00	1096,20	410,4	667,02	275,96
19/02/89	05.00	275,20	277,50	282,90	274,80	274,70	194,40	648,87	94,71	2631,62	-1663,20	1360,80	415,8	648,87	272,11
19/02/89	06.00	274,50	276,70	282,60	274,30	274,00	233,28	701,91	97,62	2634,04	-1603,80	982,80	432	701,91	276,11
20/02/89	18.00	285,95	285,25	294,30	287,00	284,65	505,44	897,71	799,30	2641,09	-356,40	642,60	450,9	897,71	—
20/02/89	19.00	283,30	283,60	292,30	284,50	282,30	388,80	931,51	512,08	2587,25	-772,20	831,60	486	931,51	—
20/02/89	20.00	282,20	283,00	290,40	283,00	281,30	349,92	794,54	422,03	2580,28	-1009,80	869,40	442,8	794,54	285,32
20/02/89	21.00	281,25	282,45	289,40	282,00	280,45	311,04	767,50	345,54	2559,82	-1188,00	1171,80	440,1	767,50	281,54
20/02/89	22.00	280,35	282,40	288,50	280,90	279,90	174,96	710,06	180,96	2546,51	-1485,00	982,80	440,1	710,06	281,84
20/02/89	23.00	279,30	281,15	287,80	279,80	278,75	213,84	772,82	198,30	2573,70	-1425,60	1058,40	459	772,82	280,85
21/02/89	00.00	278,90	281,25	286,80	279,10	278,55	136,08	658,37	120,60	2573,13	-1603,80	1096,20	426,6	658,37	278,84
21/02/89	01.00	278,15	280,50	286,40	277,80	277,70	174,96	717,46	140,26	2619,03	-1663,20	1058,40	445,5	717,46	279,08
21/02/89	02.00	277,80	279,25	285,70	277,40	276,95	330,48	731,44	245,73	2650,58	-1366,20	945,00	426,6	731,44	279,77
21/02/89	03.00	276,95	278,90	285,00	277,00	276,40	213,84	707,62	143,18	2617,79	-1485,00	1020,60	434,7	707,62	278,16
21/02/89	04.00	276,90	278,90	284,80	276,50	276,30	233,28	692,63	154,34	2643,58	-1544,40	1096,20	426,6	692,63	277,14
21/02/89	05.00	276,95	279,65	284,40	276,30	276,65	116,64	586,67	79,64	2630,97	-1782,00	1134,00	402,3	586,67	275,57
21/02/89	06.00	277,30	280,05	284,20	275,90	276,85	174,96	530,32	124,54	2656,03	-1900,80	1058,40	372,6	530,32	275,72
7/03/89	18.00	287,95	285,75	298,50	288,70	286,25	822,08	1313,72	1098,85	2819,62	297,00	1323,00	575,1	1313,72	—
7/03/89	19.00	284,70	285,30	295,50	286,50	284,00	272,16	1157,04	403,06	2556,46	-772,20	1587,60	583,2	1157,04	—
7/03/89	20.00	283,30	284,70	293,70	285,00	282,90	155,52	1040,74	209,77	2529,02	-1069,20	1663,20	561,6	1040,74	282,81
7/03/89	21.00	281,95	283,75	292,30	283,50	281,65	116,64	1009,62	141,29	2525,32	-1247,40	1398,60	558,9	1009,62	283,44
7/03/89	22.00	281,05	282,10	290,90	282,80	280,40	252,72	990,76	277,42	2536,40	-1009,80	1512,00	531,9	990,76	281,18
7/03/89	23.00	280,00	281,60	289,90	281,30	279,50	194,40	967,07	193,36	2550,78	-1247,40	1587,60	534,6	967,07	279,18
8/03/89	00.00	279,60	280,60	289,20	280,60	278,80	311,04	969,65	291,29	2599,36	-1069,20	1701,00	518,4	969,65	277,58
8/03/89	01.00	278,75	280,30	288,20	279,70	278,20	213,84	907,44	183,87	2587,89	-1247,40	1587,60	510,3	907,44	277,17
8/03/89	02.00	278,55	280,05	287,70	279,10	277,95	233,28	872,35	195,03	2622,28	-1247,40	1323,00	494,1	872,35	279,01
8/03/89	03.00	277,65	279,45	286,80	278,30	277,15	194,40	853,55	145,06	2599,33	-1386,20	1474,20	494,1	853,55	276,48
8/03/89	04.00	276,95	279,60	286,60	277,70	276,80	58,32	865,15	40,28	2561,24	-1663,20	1512,00	521,1	865,15	275,67
8/03/89	05.00	276,30	278,90	285,90	276,70	276,10	77,76	863,36	48,18	2596,57	-1663,20	1398,60	518,4	863,36	276,10
8/03/89	06.00	275,15	276,95	285,40	276,00	274,65	194,40	993,79	93,68	2610,29	-1366,20	1436,40	553,5	993,79	276,23
15/03/89	18.00	289,65	286,45	298,00	289,40	287,45	855,38	1067,97	1646,56	2911,97	594,00	1058,40	450,9	1067,97	—
15/03/89	19.00	288,10	286,60	295,90	288,40	286,50	622,08	872,41	1115,29	2740,42	-59,40	1096,20	421,2	872,41	—
15/03/89	20.00	287,20	286,30	294,50	287,40	285,70	583,20	773,76	993,18	2686,78	-356,40	982,80	394,2	773,76	288,66
15/03/89	21.00	286,60	286,20	293,70	286,80	285,30	505,44	709,70	834,03	2662,01	-534,60	793,80	383,4	709,70	289,02
15/03/89	22.00	286,35	285,90	292,90	286,20	284,90	563,76	649,93	910,90	2667,97	-594,00	1020,60	353,7	649,93	286,19
15/03/89	23.00	284,90	285,30	292,30	283,80	283,80	427,68	713,82	633,38	2755,45	-891,00	1058,40	399,6	713,82	285,41
16/03/89	00.00	285,85	286,40	292,30	285,40	284,80	408,24	567,12	646,87	2646,81	-950,40	1058,40	348,3	567,12	284,71
16/03/89	01.00	283,40	284,15	290,80	283,20	282,35	408,24	701,47	540,93	2634,98	-1069,20	1134,00	399,6	701,47	283,07
16/03/89	02.00	282,50	284,50	290,10	282,30	282,00	194,40	640,03	244,74	2588,49	-1485,00	1134,00	410,4	640,03	281,79
16/03/89	03.00	281,85	283,25	289,40	281,20	281,05	311,04	680,55	365,27	2663,25	-1306,80	1171,80	407,7	680,55	281,11
16/03/89	04.00	281,30	282,95	288,50	280,50	280,55	291,60	621,67	328,26	2654,23	-1425,60	1285,20	388,8	621,67	278,79
16/03/89	05.00	279,90	281,05	288,20	279,40	279,05	330,48	793,53	319,10	2701,16	-1188,00	1436,40	448,2	793,53	278,15
16/03/89	06.00	279,05	280,30	287,30	278,50	278,20	330,48	783,76	289,40	2697,91	-1247,40	1285,20	445,5	783,76	278,57

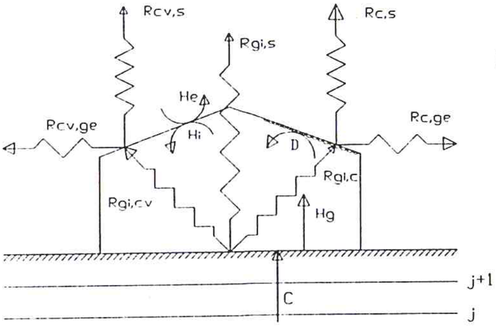

Figure 1 - Scheme of the experimental greenhouse with indications of each term of energetic balance.

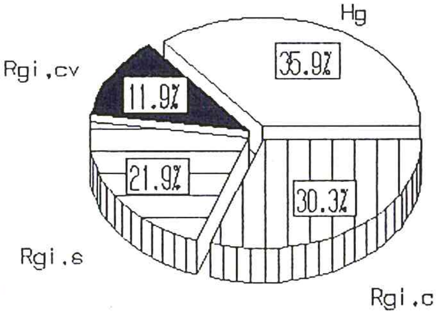

Figure 2 - Percentage sharing of the energetic contributions on the air-soil interface layer inside the greenhouse.

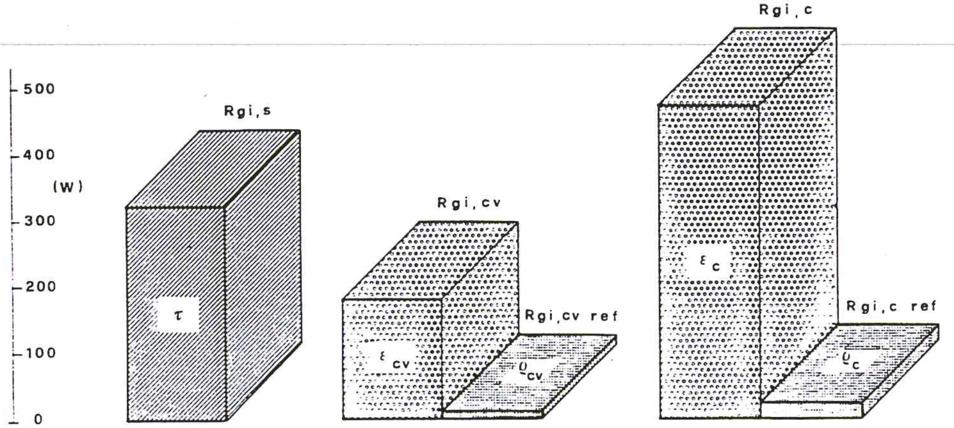

Figure 3 - Sharing between the energy transmitted outside the greenhouse, absorbed and redirected outside, and reflected back to the soil.

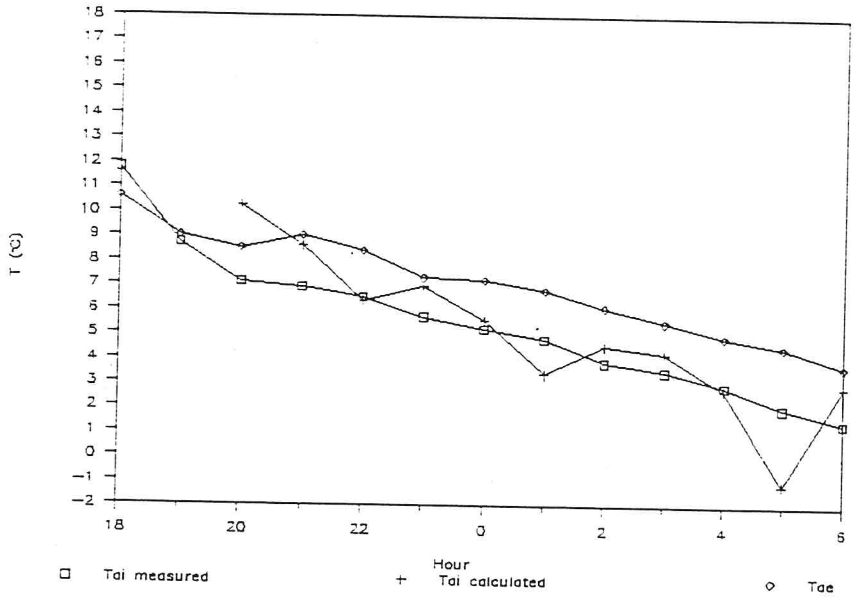

Figure 4 - Comparison between hourly temperatures measured inside and outside the greenhouse and that calculated through the forecasting pattern for the night of 18 February 1989.

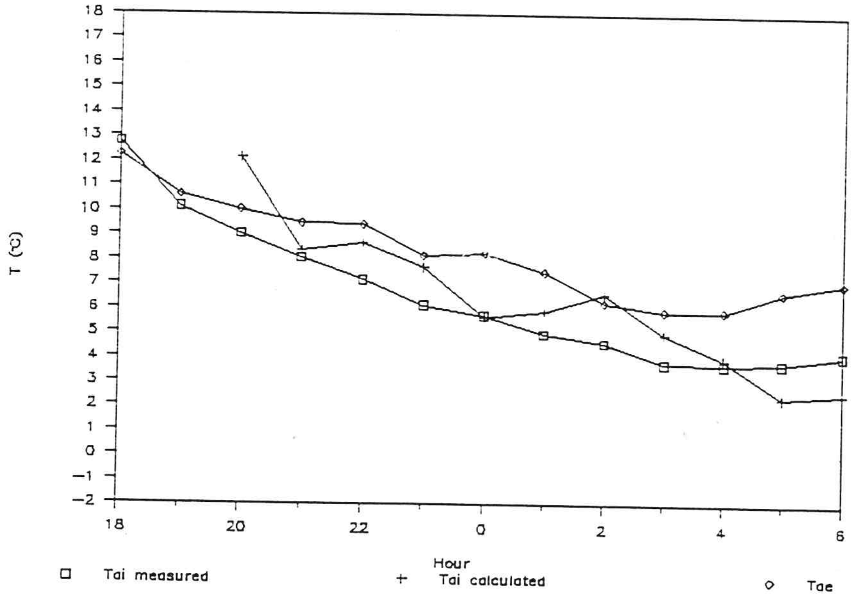

Figure 5 - Comparison between hourly temperatures measured inside and outside the greenhouse and that calculated through the forecasting pattern for the night of 20 February 1989.

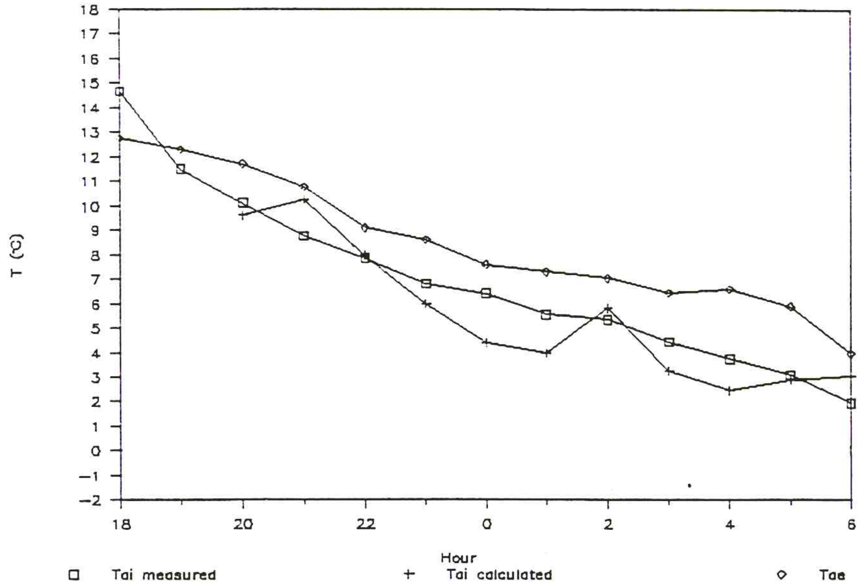

Figure 6 - Comparison between hourly temperatures measured inside and outside the greenhouse and that calculated through the forecasting pattern for the night of 7 March 1989.

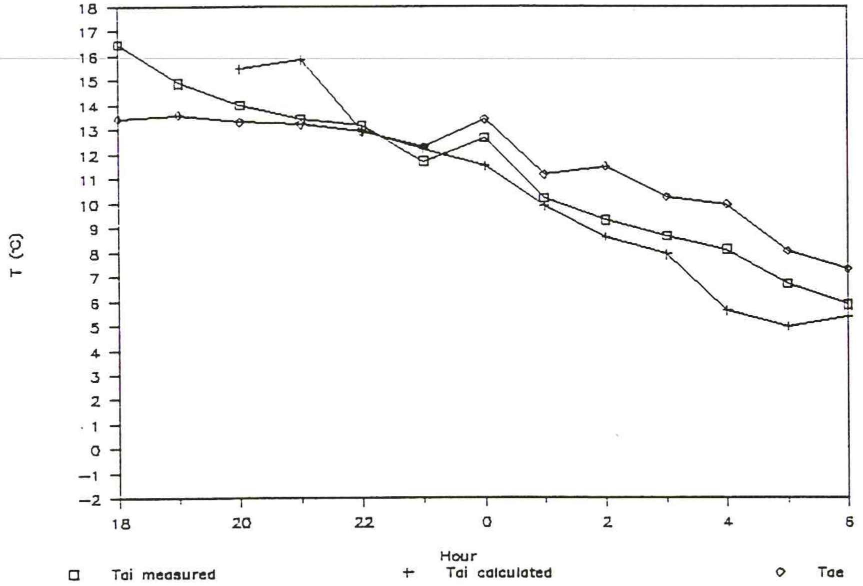

Figure 7 - Comparison between hourly temperatures measured inside and outside the greenhouse and that calculated through the forecasting pattern for the night of 15 March 1989.