

Night energy balance in a heated low-cost plastic greenhouse

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Abstract

This paper analyses the night energy balance of an air-heated greenhouse in mild-winter climatic conditions (Almería, South-eastern Spain). The components of the energy balance of the air volume, soil and cover surfaces were determined in a low-cost plastic structure (parral-type), devoid of crop, under continuous and constant inflow of heat into the inside air at moderate (62 W m^{-2}) and at high (134 W m^{-2}) heating input. For typical winter weather conditions and heating practices in the Almería region, corresponding to the moderate heating input, the energy balance at the soil–air interface showed that the soil heat flux provided most of the energy to compensate for the radiative ground losses, and only a very small amount of sensible energy, of the same order of magnitude as the residual soil evaporation ($<5 \text{ W m}^{-2}$), was exchanged between the air and the soil surface. In the greenhouse air volume, energy losses mainly occurred through air–inner cover convective exchange ($\approx 50 \text{ W m}^{-2}$). At the cover, losses mostly occurred by radiative exchange, the convective component being relatively small (between $\pm 10 \text{ W m}^{-2}$). For the high heating input, the soil radiative losses were compensated by both the soil conduction flux (about 15 W m^{-2}) and the soil-to-air convective heat transfer (about 20 W m^{-2}). Radiative losses were also found to be the major component of the cover losses, whereas the convective component reached one-third of the total cover loss. For the two heating levels, leakage losses reached up to 35% of the heating input at high wind speed. The increase in leakage losses with wind speed led to a consequential decrease of the cover convective fluxes and to a negative relationship between the latter and the wind speed. Estimates of the convective heat transfer coefficients between the inside air and surfaces (soil and inner cover), and between the outside air and the outer cover, supply values within the range reported in the literature. The influence of the air mixing due to the air heating systems on the inside air-to-cover heat coefficient was demonstrated. In conclusion the measures to improve the energy efficiency would be: (i) to improve the air tightness of the greenhouse, (ii) to reduce radiative losses by means of thermal screens or IR-opaque plastic covering materials, and (iii) to increase the soil efficiency in storing solar energy and releasing it during the night.

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Keywords: Heating system; Energy balance; Convective heat loss; Radiative heat loss; Heat transfer coefficient

1. Introduction

During the last 30 years, low-cost plastic greenhouses have dramatically expanded in Europe as well as in other

countries of the world, such as North Africa, South America and China, presently covering more than 1 MM ha worldwide. In Europe, the greenhouse industry gradually migrated from temperate regions towards warmer ones, with the development of extensive greenhouse areas located in the mild-winter climates coastal areas of the Northern and Southern Mediterranean Basin (Briassoulis et al., 1997). In particular, the Almería

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Nomenclature

A_c	cladding area (m^2)
A_g	ground area (m^2)
c_p	specific heat of air ($\text{J kg}^{-1} \text{K}^{-1}$)
C_s	conduction flux at the soil surface (W m^{-2})
E_h	release rate of water vapour from the heater ($\text{kg m}^{-2} \text{h}^{-1}$)
E_s	soil evaporation rate ($\text{kg m}^{-2} \text{h}^{-1}$)
$h_{c,e}$	outer cover to outside air convective heat transfer coefficient reported to cladding area ($\text{W m}_{cl}^{-2} \text{K}^{-1}$)
$h_{c,i}$	inner cover to inside air convective heat transfer coefficient reported to cladding area ($\text{W m}_{cl}^{-2} \text{K}^{-1}$)
h_s	soil to inside air convective heat transfer coefficient reported to ground area ($\text{W m}_{gr}^{-2} \text{K}^{-1}$)
$H_{c,e}$	convective heat transfer between the outer cover and the outside air reported to ground area (W m_{gr}^{-2})
$H_{c,i}$	convective heat transfer between the inner cover and the inside air reported to ground area (W m_{gr}^{-2})
H_f	total convective heat transfer by leakage (W m^{-2})
$H_{f,l}$	latent heat exchange by leakage (W m^{-2})
$H_{f,s}$	sensible heat transfer by leakage (W m^{-2})
H_s	convective heat transfer between the inside air and the ground surface (W m^{-2})
N	leakage rate (h^{-1})
q_e	outside air mixing ratio (g kg^{-1})
q_i	inside air mixing ratio (g kg^{-1})
Q_h	sensible heat delivered by the heating system (W m^{-2})
r	ratio between the leakage losses and the heat input (%)
R_a	long-wave radiation emitted by the sky (W m^{-2})
$R_{c,e}$	long-wave radiation emitted by the outer cover surface (W m^{-2})
$R_{c,i}$	long-wave radiation emitted by the inner cover surface (W m^{-2})
$R_{n,e}$	net radiation outside the greenhouse (W m^{-2})
$R_{n,i}$	net radiation inside the greenhouse (W m^{-2})
R_s	long-wave radiation emitted by the ground surface (W m^{-2})
$T_{c,e}$	outer cover surface temperature ($^{\circ}\text{C}$)
$T_{c,i}$	inner cover surface temperature ($^{\circ}\text{C}$)

T_e	external air temperature ($^{\circ}\text{C}$)
T_i	greenhouse air temperature ($^{\circ}\text{C}$)
T_s	soil surface temperature ($^{\circ}\text{C}$)
V	outside wind speed (m s^{-1})
V_g	greenhouse air volume (m^3)

Greek symbols

λ	latent heat of vaporisation (J kg^{-1})
ρ	air density (kg m^{-3})

Province (South-Eastern Spain) represents the largest area of greenhouses (25,000 ha, Pérez-Parra, 2002) in Europe. The most typical structure in this region is the “parral-type” greenhouse, made of a wooden or light metallic structure covered by a plastic film.

Low-cost plastic structures are generally characterised by some common traits, such as low height and flat roof, which induced low values of solar transmission, insufficient ventilation rate and poor air tightness, and therefore hindered efficient climate control. Some of these characteristics were gradually improved throughout the years, especially the transmission for solar radiation, the structural strength and the design of improved ventilation systems (Wittwer and Castilla, 1995; Pérez-Parra et al., 2004). In contrast, because nocturnal climate control (heating) was not considered as economically viable for such low-cost structures, little attention has been paid to study the nocturnal energy balance and the heating efficiency of these greenhouses. In the case of the Almería region, periods with outside daily minimum air temperature of 2–3 $^{\circ}\text{C}$ can occur during the coldest months (January and February), along with conditions of high air humidity during the night due to the proximity of the sea (Montero et al., 1985). These two factors may negatively affect yield and quality of the marketable production, therefore justifying the investment and running costs of a heating system (López et al., 2002).

In order to optimise the heating equipment and strategy, and to assess the feasibility of greenhouse heating in Mediterranean areas, a precise estimation of heating inputs and costs is necessary (Bailey and Chalabi, 1994; López, 2003). As a first step, this requires a deeper insight into the energy balance of plastic greenhouses equipped with low-cost heating systems, such as convective air-heaters, and in the relative magnitude of the energy loss components (convection, radiation and leakage). To our knowledge, only few studies (e.g. De Halleux, 1989) were devoted to a detailed quantification of all the greenhouse energy balance components, allowing a sound-based diagnosis of the greenhouse behaviour and heating system efficiency.

Within this context, the main scientific objective of this study was to perform a comprehensive analysis of the energy balance components of low-cost plastic greenhouses. To meet this aim, a detailed in situ characterization of the energy balance and heat losses was carried out in a parral-type plastic structure. From the experimental data, the magnitude of the energy fluxes and heat transfer coefficients was obtained and compared to the results obtained in previous studies. Special focus was devoted: (i) to the interactions between fluxes, as no attention has been paid to this point before, and (ii) to the characterisation of the cover radiative losses as they are presently poorly documented, due to the difficulty in measuring the radiative components under plastic cover material. In conclusion, the critical issues that need to be tackled in order to reach higher energy efficiency in heated plastic greenhouses are addressed.

2. Materials and methods

2.1. Site and greenhouses

The experiments were conducted in a block of six identical parral-type greenhouses at Las Palmerillas-Cajamar Research Station, located 30 km from Almería (36° 48' N, 2° 3' W) in the coastal area of Southeast Spain. Each greenhouse, E–W oriented, consisted of a light structure formed by steel tubes and tensioned galvanised steel wires on the roof, with asymmetrical roofs of 13° south and 25° north slopes, covered with a 0.2 mm thick thermal polyethylene film tied to the main structural wires. Ground area (A_g) was 432 m², cladding area (A_c) was 717 m², and air volume was about 1500 m³. The plastic film had the following optical characteristics in the thermal IR: emissivity = 0.75 and transmissivity = 0.25 (manufacturer data). Each greenhouse had two lateral side-ventilation slots and one continuous roof vent that were kept closed during the measurement periods. Heating was applied by means of a mobile air-convection heating system, provided with an integrated propane burner directly discharging the flue gases into the greenhouse. During the 1997 experiments, the heating power was 27 kW (62 W m⁻²_{gr}, moderate heating level), and in 1998, 58 kW (134 W m⁻²_{gr}, high heating level). The air flow-rate was 1500 and 5800 m³ h⁻¹, respectively (manufacturer data). The air heater, located in the eastern part of each greenhouse, was activated in the evening and worked continuously during the night until the morning. No air temperature control system was operating and the greenhouse air temperature evolved during the night

until reaching an equilibrium state when the outside conditions became constant. The microclimate conditions prevailing during the February 1997 experiments represented fairly well those observed in commercial heated greenhouses in Southeast Spain, where the heating system is activated at the beginning of the night and stopped at sunrise, thus maintaining temperatures ranging from 14 to 18 °C depending on the outside weather conditions. The high heating level and inside conditions during the 1998 measurements do not represent the current heating practices, but were applied to widen the range of data and to provide supplementary case studies for analysing the behaviour and energy efficiency of the Parral greenhouse.

The soil within the greenhouse was a typical layered soil which is widely used in the greenhouses of the Almería region (Wittwer and Castilla, 1995). This soil is formed by placing a 30 cm layer of imported clay-loam, then a shallow (2 cm) layer of dried farmyard manure, and above that a 10 cm mulch layer of coarse sand, over the naturally occurring, gravely sandy-loamy soil. During the measurement periods (February 1997 and March 1998), no crop was grown and the soil was maintained dry. However, a small residual evaporation was present during the experiments, as confirmed by the analysis of the mass balance of the empty greenhouse, presented in the following section. The other source of water vapour in the greenhouse was that released by the gas burner, which was estimated to be about 1.6 kg per m³ of propane. From measurements of the gas consumption per hour, the amount of water vapour released in the greenhouse (E_h , kg m⁻² h⁻¹) was calculated to be, on average, 4 and 9 g m⁻² h⁻¹ for the moderate and high heating levels, respectively. These amounts are equivalent to a latent energy flux (λE_h) of 3 and 6 W m⁻², where λ (J kg⁻¹) is the latent heat of vaporisation.

2.2. Measurements

Net radiation inside and outside the greenhouse were measured with two net radiometers (mod. 7.1415.20, Thies Clima, Göttingen, Germany) located 1 m above the ground and above the roof, respectively. These sensors measured separately the total radiation fluxes reaching the upward and downward surfaces of each radiometer sphere. Net radiation outside the greenhouse ($R_{n,e}$) was calculated as the difference (Eq. (1)) between the atmospheric radiation (R_a) and the radiation emitted by the outer surface of the cover ($R_{c,e}$), while net radiation inside the greenhouse ($R_{n,i}$) was derived as the difference (Eq. (2)) between the radiation emitted by the

inner cover surface ($R_{c,i}$) and the radiation emitted by the ground (R_s):

$$R_{n,e} = R_a - R_{c,e} \quad (1)$$

$$R_{n,i} = R_{c,i} - R_s \quad (2)$$

Dry and wet bulb air temperatures were measured inside and outside the greenhouse with two aspirated shielded psychrometers (mod. 1.1130, Thies Clima), located 1.5 m above the ground. Inner and outer cover temperatures ($T_{c,i}$ and $T_{c,e}$, respectively) were measured with two contact Pt-100 sensors (mod. 2.1260, Thies Clima). Wind speed (V) was measured with a cup anemometer (mod. 4.3303.22, Thies Clima) located 2 m above the ground in a nearby weather station separated 100 m from the experimental greenhouse. Soil surface temperature (T_s) was derived from the measurements of R_s assuming the sand emissivity to be 0.97 (Brutsaert, 1984). The heat conducted into the soil (C_s) was determined by means of a heat flux plate (Rimco HP3, McVan Instruments, Mulgrave, Australia) located at a depth of 1 cm in the sand layer. Soil temperature at the same depth was measured during the 1998 experiments by means of a Pt-100 sensor. Gas consumption was recorded with a volumetric meter. The analogue signals from all the sensors were sampled at 2 s intervals, averaged every 10 min, and stored in a data logger (3497 A, Hewlett Packard, Loveland, USA).

2.3. Greenhouse energy balance

The analysis of the greenhouse energy balance was restricted to periods with steady microclimatic conditions, i.e. when values of the different fluxes and state-variables were stationary during a time interval of 1 h. The criteria were: (i) an hourly variation of the radiative and conductive fluxes less than $\pm 2 \text{ W m}^{-2}$ and (ii) variations lower than $\pm 0.2 \text{ }^\circ\text{C}$ and $\pm 0.1 \text{ kPa}$ in the temperature variables and in the air vapour pressure deficit, respectively. Under these quasi-stationary conditions, the components of the nocturnal energy balance of the inside air volume, soil surface and greenhouse cover (Fig. 1) were calculated at hourly intervals, following the calculation steps detailed below.

2.3.1. Soil surface energy balance

The convective heat transfer from the inside air to the ground surface (H_s) was determined as the residual term of the surface soil energy balance (Fig. 1) in steady state conditions:

$$R_{n,i} + H_s + C_s + \lambda E_s = 0 \quad (3)$$

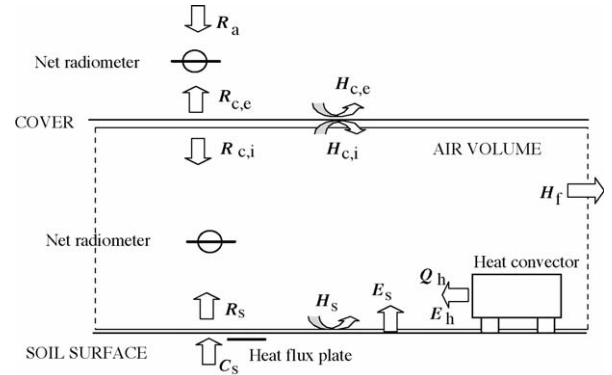


Fig. 1. Schematic representation of the energy fluxes in the air volume and at the soil and cover surfaces. Symbols: see Nomenclature.

where all fluxes are expressed per m^2 of ground area. By convention, the direction of each term in Eq. (3) is positive towards the surface, and negative away from the surface.

Values of $R_{n,i}$ and C_s were measured and λE_s , the latent heat of soil evaporation, was estimated from the mass energy balance of the air volume:

$$\lambda E_s = H_{f,1} - \lambda E_h \quad (4)$$

assuming that, under steady conditions, the latent heat lost by leakage, $H_{f,1}$, was equal to the sum of the latent heat sources in the greenhouse, λE_s and λE_h .

The soil-to-air heat transfer (h_s , $\text{W m}^{-2} \text{ K}^{-1}$) was calculated as:

$$h_s = \frac{H_s}{T_i - T_s} \quad (5)$$

2.3.2. Air volume energy balance

The sensible energy balance of the greenhouse air volume (Seginer and Kantz, 1986; Albright, 1990; Day and Bailey, 1999), delimited by the ground and the greenhouse internal cover (Fig. 1), was expressed as:

$$Q_h + H_s + H_{c,i} + H_{f,s} = 0 \quad (6)$$

where all fluxes are expressed per m^2 of ground area. Q_h is the sensible heat supplied by the heating system, $H_{c,i}$ the convective heat transfer between the inside air and the inner cover surface and $H_{f,s}$ is the exchange of sensible heat by leakage, determined as presented below.

2.3.2.1. Determination of the leakage losses. The total leakage losses, H_f , are the sum of two components:

$$H_f = H_{f,s} + H_{f,1} \quad (7)$$

where $H_{f,s}$ and $H_{f,l}$ represent the sensible and latent leakage losses, respectively. $H_{f,s}$ and $H_{f,l}$ were calculated from the temperature ($\Delta T = T_i - T_e$) and mixing ratio ($\Delta q = q_i - q_e$, g kg^{-1}) differences between the inside and outside air, using the following equations:

$$H_{f,s} = \frac{N}{3600} \frac{V_g}{A_g} \rho c_p \Delta T \quad (8)$$

$$H_{f,l} = \frac{N}{3600} \frac{V_g}{A_g} \rho \lambda \Delta q \quad (9)$$

where N is the leakage rate expressed in number of air volume renewals per hour (h^{-1}), V_g the greenhouse air volume (m^3), ρ the air density (kg m^{-3}) and c_p is the heat capacity of air ($\text{J kg}^{-1} \text{K}^{-1}$). N is generally assumed to depend on the greenhouse air tightness and on the outside wind speed (Bailey, 1988).

Prior to the heating experiments, values of N and its dependence on external wind speed were determined for the greenhouse used in this study (López et al., 2001) by means of the tracer gas technique (Nederhoff et al., 1984; Fernandez and Bailey, 1992; Baptista et al., 1999). The decay rate of the gas (CO_2) was measured in the greenhouse devoid of plants. Six sampling points were distributed in the greenhouse at a height of 1.5 m and one measuring point was placed outside. The six sampling points were all at the same distance from the infrared gas analyser (APBA-250E, Horiba, Kyoto, Japan). Gas concentration was measured every 2 s and data were averaged and registered every minute. Simultaneously, external wind speed (V) and direction were measured. The following linear relationship between N and V was found:

$$N = 0.29V + 0.76 \quad R^2 = 0.81 \quad (10)$$

in which N is in h^{-1} and V in m s^{-1} .

2.3.2.2. Determination of $H_{c,i}$. $H_{c,i}$ was determined as the residual term of the air volume energy balance (Eq. (6)), knowing Q_h , H_s and H_f . Values of $H_{c,i}$ were further used to derive the convective heat transfer coefficient between the internal air and the inner cover surface ($h_{c,i}$, $\text{W m}^{-2} \text{K}^{-1}$) through:

$$h_{c,i} = \frac{A_g}{A_c} \frac{H_{c,i}}{T_i - T_{c,i}} \quad (11)$$

2.3.3. Greenhouse cover energy balance

In absence of condensation, the energy balance of the cover can be expressed, neglecting its thermal mass, as:

$$R_{n,e} + R_{n,i} + H_{c,e} + H_{c,i} = 0 \quad (12)$$

where $H_{c,e}$ ($\text{W m}^{-2} \text{K}^{-1}$) is the convective heat transfer from the outer cover surface to the outside air, reported to the ground area.

By convention, the direction of each term in Eq. (12) is positive towards the surface, and negative away from the surface. As $R_{n,i}$ and $R_{n,e}$ were measured, and $H_{c,i}$ was known from the air energy balance (Eq. (6)), $H_{c,e}$ was deduced as the residual term of Eq. (12). The convective heat transfer coefficient between the outer cover surface and the outside air ($h_{c,e}$, $\text{W m}^{-2} \text{K}^{-1}$) was determined from:

$$h_{c,e} = \frac{A_g}{A_c} \frac{H_{c,e}}{T_e - T_{c,e}} \quad (13)$$

As condensation events in the walls were not detected throughout the periods of measurements, Eqs. (12) and (13) were used for estimating $h_{c,e}$.

3. Results and discussion

3.1. Microclimate

Table 1 presents the mean values of the microclimatic variables measured inside and outside the greenhouse during the two measurement periods. In February 1997, the heating system, delivering 62 W m^{-2} , maintained the inside air temperature (T_i) at $17\text{--}18^\circ\text{C}$, when outside temperature (T_e) varied between 8.5 and 12°C . In March 1998, the heating system, delivering 134 W m^{-2} , maintained T_i between 24 and 28°C , whereas T_e ranged from 10 to 17°C . All measurements were carried out under clear sky conditions. In February, the nocturnal atmospheric radiation was practically constant ($R_a = 290 \pm 2 \text{ W m}^{-2}$), while in March both the mean and the standard deviation of R_a were slightly higher ($299 \pm 12 \text{ W m}^{-2}$), probably due to some periods of high atmospheric turbidity and/or haze. Wind speed (V) was low to moderate, with a maximum observed hourly value of approximately 4 m s^{-1} .

3.2. Leakage losses

H_f varied between 15 and 18 W m^{-2} during February 1997, and between 16 and 43 W m^{-2} during March 1998. Fig. 2 shows the evolution of the H_f components, $H_{f,s}$ and $H_{f,l}$, determined at 10 min interval during the nights of 7 February (Fig. 2a) and 16 March (Fig. 2b). The partition of H_f between $H_{f,s}$ and $H_{f,l}$ was about 60 and 40%, respectively (Table 2).

Table 1

Values of microclimatic variables measured inside and outside the greenhouse, averaged over the period of February 1997 (18 observations) and March 1998 (51 observations)

Period	Outside				Inside	
	T_e (°C)	q_e (g kg ⁻¹)	V (m s ⁻¹)	R_a (W m ⁻²)	T_i (°C)	q_i (g kg ⁻¹)
February 1997, low heating level	10.3 (±1.5)	4.3 (±1.0)	1.1 (±0.3)	290.0 (±1.5)	17.9 (±1.0)	6.9 (±0.7)
March 1998, high heating level	12.8 (±2.5)	5.4 (±1.9)	1.5 (±0.8)	298.9 (±12.0)	26.9 (±1.8)	9.7 (±1.3)

In parenthesis: standard deviation; symbols: see Nomenclature.

The analysis of H_f indicated that it was dependent, both in absolute and relative values (i.e. in % of the heat input), on wind speed. The ratio of H_f on heat input (r , %) showed a curvilinear trend (Fig. 3) in the range of measurements ($0 < V < 4$ m s⁻¹). Assuming a tendency towards an asymptotic value for $V > 4$ m s⁻¹, the following function was used to describe the relation between r and V :

$$r(\%) = a_0 + a_1 \frac{V}{V + a_2} \quad (14)$$

where a_0 corresponds to the relative leakage losses at $V = 0$.

The fit of Eq. (14) to the hourly data of February and March gave $a_0 = 17\%$, $a_1 = 64\%$ and $a_2 = 10.5$ m s⁻¹, with $R^2 = 0.92$ and a standard error of 3.4%. On average, leakage losses represented about 20% of the total greenhouse air heat losses during calm night periods ($V < 2$ m s⁻¹) and reached up to 35% for values of V close to 4 m s⁻¹. These relatively high values of r , similar to those quoted by von Zabeltitz (1992) for plastic greenhouses (10–30% of the total greenhouse losses), were due to the poor air tightness of the parral-type greenhouse.

3.3. Soil surface energy balance

The average values of the components of the soil surface energy balance (Eq. (3)) are presented in Table 3 for the two periods, together with the corresponding mean values of the soil surface temperature (T_s), the soil-to-inside air temperature difference (ΔT_s) and the soil-to-air heat transfer coefficient (h_s).

3.3.1. Conduction into the soil

In all the experiments, the measurements of the soil conduction flux (C_s) indicated that the sand layer was transferring heat upwards, thus positively contributing to the soil surface energy balance. In the case of the low heating input, C_s was the main positive flux (19.2 W m⁻²), supplying enough energy to compensate for the radiative losses, which represented the main loss component (−19 W m⁻²). H_s and λE_s were very small (about 3 W m⁻²) and of opposite sign, H_s being positive, i.e. the air supplied heat to the soil surface. Under the high heating input, the air contributed significantly more to the soil surface heating ($H_s = 15.1$ W m⁻²) and was similar to the soil heat flux ($C_s = 16.5$ W m⁻²), both compensating for the radiative losses (−26.4 W m⁻²) and the residual soil

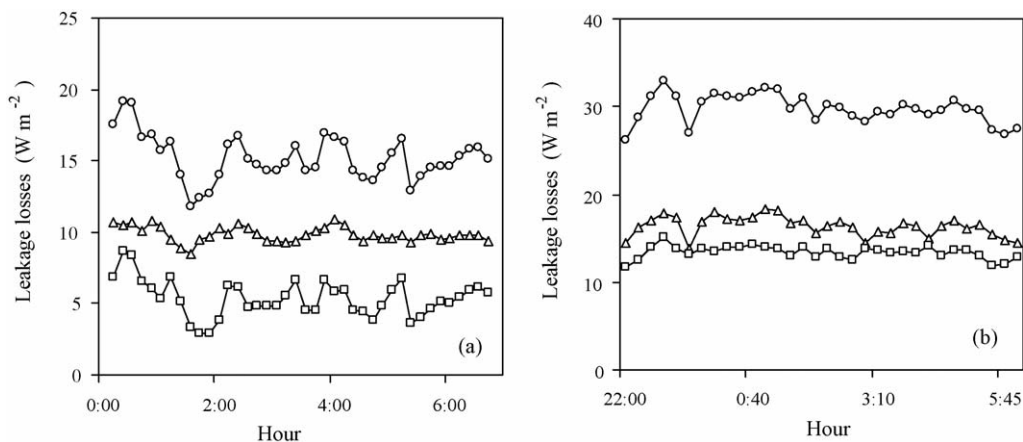


Fig. 2. Evolution of the total H_f (○), sensible $H_{f,s}$ (△) and latent $H_{f,l}$ (□) leakage losses during the night. Points are 10 min averages. (a) February 7, 1997, heat input = 62 W m⁻²; (b) March 16, 1998, heat input = 134 W m⁻².

Table 2

Values (referred to ground area) of the total leakage loss and its components, averaged over the period of February 1997 (18 observations) and March 1998 (51 observations)

Period	Total infiltration loss, H_f (W m^{-2})	Sensible component, $H_{f,s}$ (W m^{-2})	Latent component, $H_{f,l}$ (W m^{-2})
February 1997, low heating level	16.4 (± 2.0)	9.8 (± 0.4)	6.6 (± 2.0)
March 1998, high heating level	31.5 (± 5.2)	19.5 (± 4.0)	12.0 (± 3.1)

In parenthesis: standard deviation; symbols: see Nomenclature.

evaporation rate (-5.1 W m^{-2}). These results confirmed those of Garzoli and Blackwell (1981), who reported a positive heat contribution from the soil in a greenhouse heated by direct burning of propane gas. The average values of C_s in February (19.2 W m^{-2}) and March (16.5 W m^{-2}) are equivalent to an energy release from the soil, during a 12-h night period, of about 0.9 and 0.7 MJ m^{-2} , respectively. These estimates were in agreement with those reported by Baille (1999) for heated greenhouses of temperate European areas (values of the daily energy stored in the soil and released to the greenhouse air during the night within the range $0.5\text{--}1.0 \text{ MJ m}^{-2} \text{ d}^{-1}$). In most studies of greenhouse energy balance, the values of C_s were assumed to be relatively small and thus neglected (Roy et al., 2002). This assumption may be valid in the case of greenhouses with high-density crops, where the soil is largely shaded by the canopy, or in strongly heated greenhouses, in which the relative weight of the soil flux contribution is small. On the contrary, in greenhouses with low leaf area crops or in moderately heated greenhouses, the soil energy storage and release over a 24 h cycle is far from being negligible. This was confirmed in the case of the moderate heating level, the

contribution of the soil representing about 40 % of the heating input, compared to only 15% in the case of the high input level.

3.3.2. Soil–air heat exchange

Values of T_s and T_i were very similar in the experiments carried out in February with moderate heating input, leading to very small values of ΔT_s and H_s (Table 3) which hindered the derivation of reliable estimates of h_s . By contrast, the values of ΔT_s and H_s from the March period (high heating level) were one order of magnitude higher, allowing the derivation of plausible hourly estimates of h_s , whose mean value was $4.7 \text{ W m}^{-2} \text{ K}^{-1}$ (Table 3). Plotting the hourly values of h_s versus ΔT_s (Fig. 4) shows that h_s varied within a lower and an upper limit, respectively corresponding to the functions proposed by de Halleux (1986) ($h_s = 1.86\Delta T_s^{0.33}$ for a greenhouse equipped with heating pipes) and Silva (1988, cited by Roy et al., 2002) ($h_s = 10\Delta T_s^{0.33}$ for an unheated plastic greenhouse with bare soil). Our results appeared to be coherent with those obtained by de Halleux, as the air heating system used in this study is known to enhance air mixing and turbulence compared to a heating pipe system, and therefore promotes a higher soil-to-air heat transfer coefficient. The relatively large standard deviation of h_s ($\pm 2.5 \text{ W m}^{-2} \text{ K}^{-1}$) can be ascribed, in part, to the experimental errors in the determination of the other fluxes of the soil surface energy balance and to the relatively low magnitude of H_s (about 15 W m^{-2}). Another factor to explain this variability could be the influence of the outside wind velocity on the air flow inside the greenhouse and, consequently, on h_s . The analysis of h_s versus V indicated a positive relationship ($R^2 = 0.33$), while that of h_s versus ΔT_s was poor and negative. This suggests that h_s might predominantly be governed by forced convection due to the air movements near the soil surface and, therefore, cannot adequately be described by classical free convection formulae, such as those given in Fig. 4. It has to be pointed out that a relatively high spatial heterogeneity of h_s , inherent to the point-source heating system and to the air leakage, probably prevailed in the greenhouse.

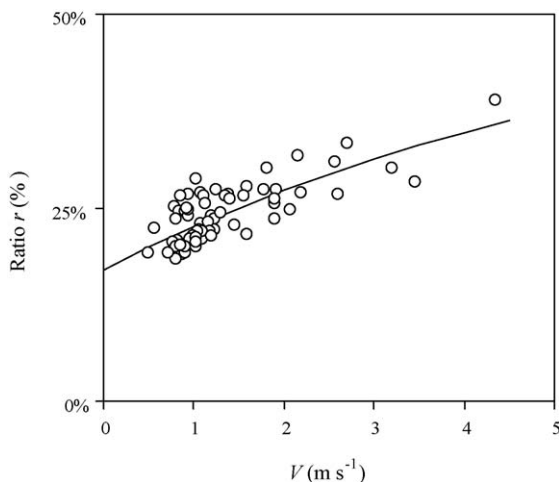


Fig. 3. Relative leakage heat losses, r , as a function of outside wind speed, V . Pooled hourly data of February and March. The curve is Eq. (14).

Table 3

Values (referred to ground area) of the components of the soil surface energy balance, and of the corresponding soil surface temperature, T_s , inside air temperature, T_i , their difference, ΔT_s , and the soil-to-air heat transfer coefficient, h_s , averaged over the period of February 1997 (18 observations) and March 1998 (51 observations)

Period	C_s (W m^{-2})	H_s (W m^{-2})	$R_{n,i}$ (W m^{-2})	λE_s (W m^{-2})	T_s ($^{\circ}\text{C}$)	T_i ($^{\circ}\text{C}$)	ΔT_s ($^{\circ}\text{C}$)	h_s ($\text{W m}^{-2} \text{K}^{-1}$)
February 1997, low heating level	19.2 (± 2.3)	3.2 (± 2.7)	-19.0 (± 1.1)	-3.4 (± 2.0)	17.6 (± 0.9)	17.9 (± 1.0)	0.3 (± 0.2)	^a
March 1998, high heating level	16.5 (± 2.9)	15.2 (± 3.8)	-26.6 (± 4.2)	-5.1 (± 3.0)	23.9 (± 1.9)	26.9 (± 1.8)	3.0 (± 0.7)	4.7 (± 2.5)

Energy losses from the soil surface are expressed as negative values. In parenthesis: standard deviation; symbols: see Nomenclature.

^a No reliable estimates were available.

This heterogeneity cannot be assessed from the present data and the energy balance analysis used in this study. For practical applications, the average value of h_s ($4.7 \text{ W m}^{-2} \text{K}^{-1}$) can be considered as a reasonable estimate for this type of greenhouse and heating system.

3.4. Greenhouse energy balance

Table 4 presents the average values of the components of the greenhouse air sensible energy balance during the two periods, together with the corresponding values of the inner cover temperature ($T_{c,i}$) inner cover-to-air gradient ($\Delta T_{c,i}$) and inner cover-to-air heat transfer coefficient ($h_{c,i}$).

The main process responsible for the energy losses from the air volume was the convective exchange between the greenhouse air and the inner cover ($H_{c,i}$), which represented about 4/5 of the heat input. Hourly

average values of $h_{c,i}$, estimated from $H_{c,i}$ and $\Delta T_{c,i}$ ($=T_{c,i} - T_i$) are presented in Fig. 5, along with different empirical functions proposed in the literature (Roy et al., 2002). For the low heating input, $h_{c,i}$ values were similar to those obtained using the formula of Papadakis et al. (1992), while for the high input they are near those derived from the functions of Kittas (1986) and Garzoli and Blackwell (1981). It should be pointed out that $h_{c,i}$ depends on several factors, and especially on the type of heating system and on the slope of the greenhouse roof. As observed in previous studies, $h_{c,i}$ values were generally higher with pulsed air heating systems (Garzoli and Blackwell, 1981; Kittas, 1986) than with non-convective heating systems (De Halleux, 1989; Papadakis et al., 1992). The significant higher value of h_i observed for the high input heating with respect to the low one could be due to conditions of higher turbulence and mixing generated by the former, rather than to an increase in $\Delta T_{c,i}$. This result indicated that the air movements induced by the heating system play a major role in determining $h_{c,i}$. For a given heating level, the data presented little scattering (standard deviation of 0.2 and $0.5 \text{ W m}^{-2} \text{K}^{-1}$ for the low and high heating input, respectively). Correlation analysis showed that $h_{c,i}$ was poorly and negatively correlated with both $\Delta T_{c,i}$ and V , supporting the previous statement that the influence of the air flow induced by the air heating system was predominant. It can be concluded that, as for h_s , a forced convection regime was driving the heat exchanges between the inside air and the inner cover. However, $h_{c,i}$ did not appear to be affected by V as was observed for h_s . The reason could be that the air flow near the roof walls was less affected by the leakage rate than the lower part of the greenhouse.

It should be noted that high and positive linear correlations were found between the hourly values of T_i and $T_{c,i}$ (Fig. 6), with slopes near unity for both data sets. This implies that, for the air heating system used in this study, a variation of T_i practically resulted in an

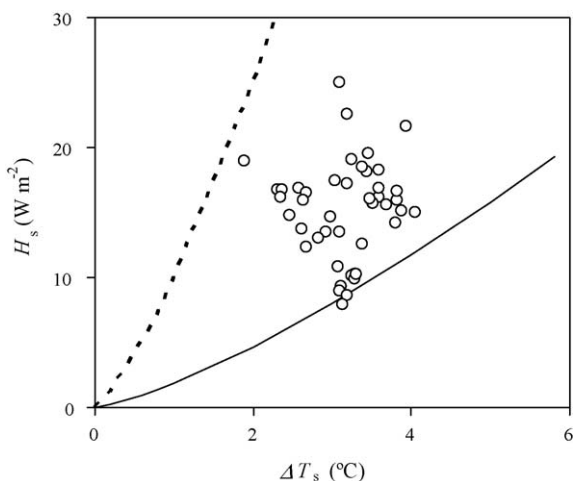


Fig. 4. Values of the soil-to-air convective heat exchange, H_s (W m^{-2}) vs. the soil-to-air temperature difference, $\Delta T_s (=T_s - T_i)$. (O) Experimental data (hourly values, high heating input, March 1998); (—) function proposed by De Halleux (1989) ($H_s = 1.86\Delta T_s^{1.33}$); (- -) function proposed by Silva (in Roy et al., 2002) ($H_s = 10\Delta T_s^{1.33}$).

Table 4

Values (referred to ground area) of the components of the greenhouse air sensible energy balance, inner cover temperature, $T_{c,i}$, inner cover-to-air temperature gradient, $\Delta T_{c,i}$, and inner cover-to-air heat transfer coefficient, $h_{c,i}$

Period	Q_h ($W\ m^{-2}$)	H_s ($W\ m^{-2}$)	$H_{c,i}$ ($W\ m^{-2}$)	$H_{f,s}$ ($W\ m^{-2}$)	$T_{c,i}$ ($^{\circ}C$)	$\Delta T_{c,i}$ ($^{\circ}C$)	$h_{c,i}$ ($W\ m_{cl}^{-2}\ K^{-1}$)
February 1997, low heating level	62 (–)	–3.2 (± 2)	–49.0 (± 2.7)	–9.8 (± 0.4)	10.3 (± 1.2)	7.6 (± 0.2)	4.4 (± 0.2)
March 1998, high heating level	134 (–)	–15.0 (± 4.2)	–99.5 (± 6.3)	–19.5 (± 2.4)	16.9 (± 4.0)	10.0 (± 0.5)	6.7 (± 0.5)

Values are averages over the period of February 1997 (18 observations) and March 1998 (51 observations). Energy losses from the control volume are expressed as negative values. In parenthesis: standard deviation; symbols: see Nomenclature.

equal variation of $T_{c,i}$ (or vice versa). For a given heating input, the gradient $\Delta T_{c,i}$ was rather constant, with mean values of $7.6 (\pm 0.2)$ and $10.0 (\pm 0.5)$ $^{\circ}C$ for the February and March data, respectively.

3.5. Greenhouse cover energy balance

Table 5 presents the average values of the components of the cover energy balance during the two periods, together with the corresponding values of $\Delta T_{c,e}$ and outer cover-to-air heat transfer coefficient, $h_{c,e}$.

3.5.1. Convective exchange between the outer cover and the outside air

The moderate heating regime induced an outer cover temperature ($T_{c,e}$) that was very close to T_e .

The difference ($\Delta T_{c,e}$) varied between $-1^{\circ}C$ and $+0.5^{\circ}C$ during February, with a mean value of $-0.3^{\circ}C$ (Table 5). This was consistent with the low values of the outer convective heat transfer ($H_{c,e}$) determined from Eq. (12). The mean value of $H_{c,e}$ was slightly positive ($4.8\ W\ m^{-2}$) in February, with a large standard deviation ($\pm 5.7\ W\ m^{-2}$), indicating that this flux was either slightly negative (i.e. the cover, warmer than the outside air, was losing heat) or slightly positive (i.e. the cover, cooler than the outside air, was gaining heat). The latter situation has been reported to occur rather frequently under unheated polyethylene-covered greenhouses during cold, calm and cloudless nights (Montero et al., 1985; Papadakis et al., 1989). Under such conditions, the cover radiation losses are very high and the cover temperature may drop several degrees below the outside air temperature (Papadakis et al., 2000).

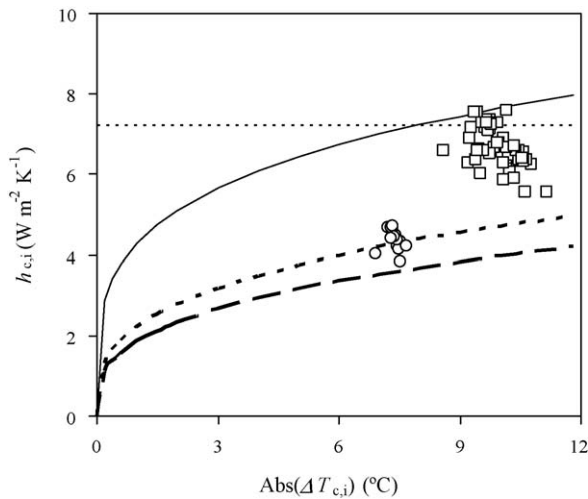


Fig. 5. Values of the inner cover-to-air convection heat coefficient, $h_{c,i}$ ($W\ m^{-2}$) vs. absolute values of the temperature difference $\Delta T = (T_{c,i} - T_i)$. (○) Low heating input; (□) high heating input. The curves represent empirical formulas proposed by: (---) Garzoli and Blackwell (1987); (—) Kittas (1986); (---) Papadakis et al. (1992) and (—) De Halleux (1989).

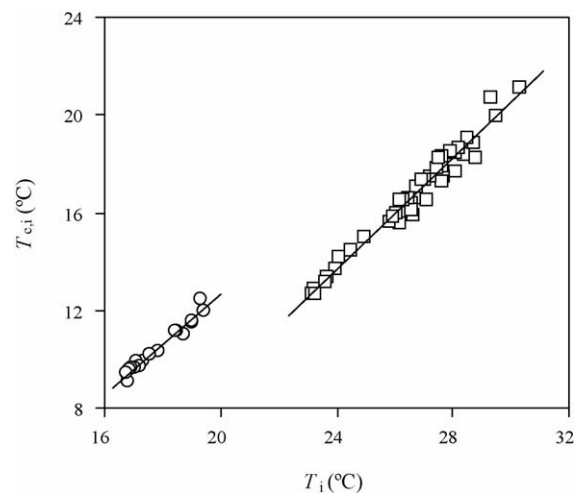


Fig. 6. Hourly values of the inner cover temperature ($T_{c,i}$) vs. the greenhouse air temperature (T_i). Data of February 1997 (○) and March 1998 (□). Regression lines are: February: $T_{c,i} = 1.00T_i + 7.37$, $R^2 = 0.98$; March: $T_{c,i} = 1.07T_i + 12.00$, $R^2 = 0.95$.

Table 5

Values (referred to ground area) of the components of the cover energy balance, and of the corresponding values of $\Delta T_{c,e}$ and the outer cover-to-air heat transfer coefficient, $h_{c,e}$

Period	$H_{c,i}$ (W m^{-2})	$R_{n,s}$ (W m^{-2})	$R_{n,e}$ (W m^{-2})	$H_{c,e}$ (W m^{-2})	$\Delta T_{c,e}$ ($^{\circ}\text{C}$)	$h_{c,e}$ ($\text{W m}_{\text{cl}}^{-2} \text{K}^{-1}$)
February 1997, low heating level	49.0 (± 2.7)	19.0 (± 1.9)	-73.8 (± 3.6)	4.8 (± 5.7)	-0.3 (± 0.6)	^a
March 1998, high heating level	99.5 (± 6.3)	26.4 (± 4.2)	-85.2 (± 7.6)	-29.0 (± 9.8)	4.0 (± 1.5)	4.7 (± 1.1)

Values are averaged over the period of February 1997 (18 observations) and March 1998 (51 observations). Energy losses of the cover are expressed as negative values. In parenthesis: standard deviation; symbols: see Nomenclature.

^a Reliable estimates of $h_{c,e}$ were not available for the low heating input.

A peculiarity of our case-study is that $T_{c,e}$ varied only slightly from the outside temperature ($\pm 1^{\circ}\text{C}$), probably depending on the wind speed and on the magnitude of the leakage losses.

With the high heating input, $T_{c,e}$ was on average 4°C higher than T_e , and consistent with the calculated values of $H_{c,e}$, which varied between -25 and $-60 \text{ W m}_{\text{gr}}^{-2}$. The average value of $H_{c,e}$ was $-40.7 \text{ W m}_{\text{gr}}^{-2}$ and the corresponding mean value found for $h_{c,e}$ ($6.6 \pm 2.6 \text{ W m}_{\text{cl}}^{-2} \text{K}^{-1}$) agreed with the order of magnitude derived from several formulae proposed in the literature (Roy et al., 2002). However, no clear correlation was found between the hourly values of $h_{c,e}$ and V . This could be due to the influence of other external factors, such as wind direction and the turbulence created by nearby obstacles on the air flow characteristics near the greenhouse roof.

The basic characteristic of the air heating system used in this study was that it supplied a continuous and

constant inflow of heat into the greenhouse air volume throughout the night, whatever the outside meteorological changes. Consequently, any increase in wind speed increased the leakage losses (Fig. 3) and led to a concomitant decrease in the convective heat fluxes on both sides of the cover, as it can be deduced from the air (Eq. (6)) and cover (Eq. (12)) energy balance equations. This effect is clearly illustrated in Fig. 7, for the data of March (high heating input), where it can be seen that the convective fluxes at the cover, both internal and external, decreased in absolute values with V . This seems a rather paradoxical conclusion, but logical when analysing the air greenhouse energy balance. The other consequence of this feedback is that $H_{c,i}$ and $H_{c,e}$ were correlated, as shown in Fig. 8. Pooling the hourly data of February and March gives the following linear relationship between $H_{c,e}$ and $H_{c,i}$:

$$H_{c,e} = -0.94H_{c,i} + 34.9 \quad R^2 = 0.90 \quad (15)$$

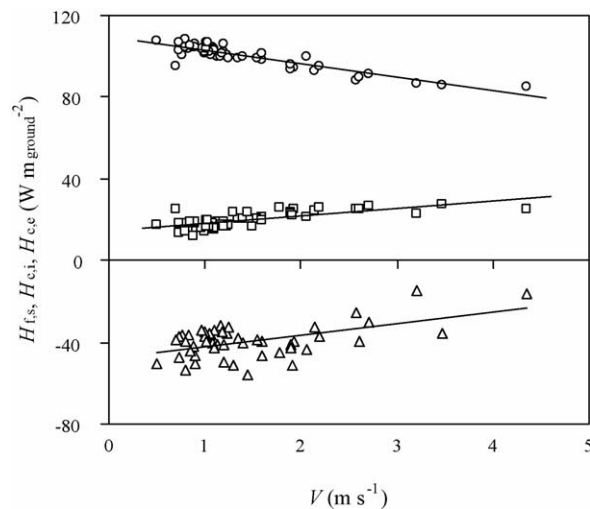


Fig. 7. Hourly values of sensible loss by leakage, $H_{f,s}$ (\square), and convective fluxes at the inner cover, $H_{c,i}$ (\circ), and outer cover, $H_{c,e}$ (\triangle), vs. outside wind speed, V . Data of March 1998, high heating input. Lines are best-fit regression to the data.

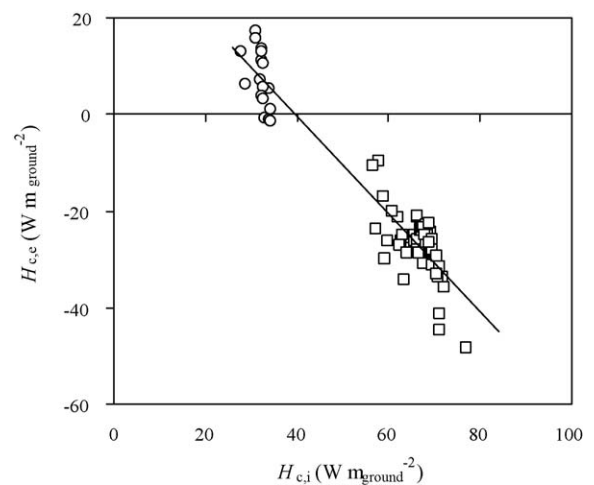


Fig. 8. Hourly values of the outer cover convective heat flux, $H_{c,e}$, vs. inner cover convective heat flux, $H_{c,i}$. The regression line to the pooled data of February (\circ) and March (\square) is $H_{c,e} = -0.94H_{c,i} + 34.9$, $R^2 = 0.90$.

Table 6

Values (referred to ground area) of the radiative fluxes measured above and inside the greenhouse, averaged over the period of February 1997 (18 observations) and March 1998 (51 observations)

Period	Above outside cover			Above soil		
	R_a (W m^{-2})	$R_{c,e}$ (W m^{-2})	$R_{n,e}$ (W m^{-2})	$R_{c,i}$ (W m^{-2})	R_s (W m^{-2})	$R_{n,i}$ (W m^{-2})
February 1997, low heating level	290.0 (± 2)	-364.2 (± 3.4)	-74.2 (± 3.6)	375.4 (± 5.0)	-394.3 (± 5.1)	394.3 (± 5.1)
March 1998, high heating level	298.9 (± 12.0)	-384.1 (± 116)	-85.2 (± 7.6)	401.9 (± 7.9)	-428.3 (± 10.6)	-26.4 (± 4.2)

By convention, positive values are radiation impinging on the outer cover or the soil and negative values correspond to the radiation leaving these surfaces. In parenthesis: standard deviation; symbols: see Nomenclature.

Eq. (15) suggests that the inner and outer convective heat exchanges were rather tightly linked, mainly through $T_{c,i}$ and $T_{c,e}$, which differed only by some tenths of a degree. The slope of the regression, near unity, also indicates that any change in the convective flux from one side of the cover corresponded to a similar magnitude change from the other side.

3.5.2. Radiative exchanges at the cover

The heat supply to the inner cover was mainly represented by the convective component ($H_{c,i}$), which was two to three times higher than the radiative gain, $R_{n,i}$ (Table 5). The reverse was also true for the outer cover, where the predominance of the radiative losses was clear. The net radiation of the outside cover ($R_{n,e}$) reached high values compared to the heating input, especially during February, when the radiative losses (-75 W m^{-2}) exceeded the heating input (62 W m^{-2}). With the high heating input, $R_{n,e}$ was only slightly more negative (-85 W m^{-2}) than the value observed with the moderate heating input, but still contributed to the major part of the cover energy losses, representing about twice the convective ones (Table 5). The predominance of the cover radiative losses was therefore clearly established in our case study, but their relative importance decreased with the heating input (Table 6).

4. Conclusions

This study provides a better insight into the energy behaviour and thermal performance of low-cost plastic greenhouses in the climatic context of coastal Mediterranean regions. Besides, it can be considered as a useful contribution to the understanding of the energetic behaviour of a greenhouse, whatever its structure, dimension and shape. In these aspects, the following results can be highlighted:

- (ii) Radiative losses are by far the major component of the total cover heat losses. In the moderate-heating regime, radiative losses were found to be higher than the heating input, implying and highlighting the role played by the soil as a heat source during the night. The relative importance of the convective losses increased with increasing heating input.
- (iii) The analysis of the leakage losses and the wall convective losses suggested the existence of a negative feedback between these two processes. This result can probably be ascribed to the specificity of the greenhouse (high leakage rate) and of the heating system (constant heat input).
- (iii) Overall, estimates of the convective heat transfer coefficients between the inside air and surfaces (soil and inner cover), and between the outside air and the outer cover, supply values within the range reported in the literature. It should be noted that the air movements induced by the convective air-heating system appear to play a major role in determining the internal cover-to-air transfer coefficient. Other results showed the close relationship found between the internal and external sensible heat fluxes.

Concerning the practical issue of improving the heating efficiency of plastic structures under typical winter weather conditions and heating practices in Mediterranean greenhouse areas, the following conclusions can be drawn:

- As radiative exchange is the most important process in dissipating energy at the greenhouse cover, aluminised screens or cover materials with low transmissivity or emissivity in the long-wave band, could represent an efficient means for reducing the overall greenhouse losses (Critten and Bailey, 2002).

- Leakage losses are usually significant in low-cost structures. Therefore, increasing its air-tightness would be a straightforward way for improving the heating system efficiency.
- The soil acts as a relatively important source of heat during the night (about 20 W m^{-2} on average in February), when compared with the heating requirements of the greenhouse (about 70 W m^{-2} on average for maintaining $16\text{--}18 \text{ }^\circ\text{C}$ in February, the coldest winter month). This suggests that simple passive or active solar systems increasing solar heat storage in the soil during the day and releasing the energy during the night (Baille, 1999) could significantly enhance the overall greenhouse efficiency, especially in the climatic context of Southern Spain, which receives a significant input of solar radiation even during the winter heating period.

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