Journal of the Association of Arab Universities for Basic and Applied Sciences (2010) **9**, 27–37

University of Bahrain
Journal of the Association of Arab Universities for Basic and Applied Sciences
www.elsevier.com/locate/jaaubas
www.sciencedirect.com

ORIGINAL ARTICLE

Experimental study of the energy balance of unheated greenhouse under hot and arid climates: Study for the night period of winter season

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Available online 16 December 2010

KEYWORDS
Greenhouse;
Energy balance;
Convective;
Heat transfer coefficients

Abstract In regions with warm and hot climates as is the case of several countries of the Mediterranean basin, it is interesting to study the energy balance inside a greenhouse and to quantify the heat transfers along the building components (roof, walls and ground) in winter and during night time. The present experimental work was conducted in an unheated glasshouse without crop in the region of Batna, Algeria. Three types of measurements were done from January to March: the first one is at a cloudy night; the second one at a windy night and the third one at a cloudless night. The results indicate that the greenhouse ground is considered as a significant heat source which can compensate the energy losses through the walls especially during a night preceded by a significant diurnal insulation. In addition, the convection heat transfer coefficients inside and outside the greenhouse were estimated and analysed. A good agreement with the models reported in the literature was found.

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Peer review under responsibility of University of Bahrain.
doi:10.1016/j.jaubas.2010.12.007

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1. Introduction

The microclimate parameters inside a greenhouse, not only influence the growth of vegetation, but can also be critical factors affecting the spread of epidemics inside the crops. The energy balance of greenhouse has been described for more than 40 years, in the pioneering works of Businger (1963) and Walker (1965). Later on, several models of the energy balance have been developed in order to understand the relationship between the outdoor and indoor microclimates and to characterize the mean behaviour of particular elements in the greenhouse, such as the inside air, the surrounding environment, and the shape and the greenhouse cover (Kimbal, 1973; Bot, 1983; Nijskens et al., 1984; Joliet, 1991; Zhang and Margolin, 1997). Other studies have analysed the thermal energy of greenhouses equipped with a heating system (de Halleux, 1989), or investigated the processes of heat exchange (Kittas, 1986; Papadakis et al., 1992). Although most of these works produced reasonable estimations of heat transfers, very few models have been used in practice for predicting greenhouse microclimate over long continuous periods, and under semi-arid conditions. Recently, Singh et al. (2006) developed an algebraic model and implemented a data-processing code, in order to simulate the micro climate of a greenhouse located in a hot and dry climate zone. Impron et al. (2007) established a dynamic model to be used as a design tool of greenhouses in tropical lowlands. The characterization of the energy balance of the greenhouses for each bioclimatic zone of the world becomes fundamental in order to evaluate the greenhouse feasibility, to improve its microclimate control (management and profitability), and to assess the effects of the latitude on the growth. During the last two decades, the use of greenhouses in Algeria has gradually emigrated from the littoral zones towards the South of the country which is characterized by high winter insulation, varying from 10.5 to 14 h/day between October and March. The region of Batna is characterized by cold and dry winters, with average minimal temperatures between −5 and 2 °C during the night periods of January and March, and with low levels of moisture. These two factors may negatively affect the quality and the quantity of crops. To our knowledge, very few studies on the energy balance of greenhouses set up in the arid and semi-arid area of the Southern Mediterranean basin have been carried out (Mesmoudi et al., 2008), and little attention was paid to the analysis of the heating efficiency of these greenhouses. It is, therefore, relevant to investigate the night energy balance of a greenhouse under arid or semi-arid conditions during the winter season.

Within this context, the objectives of the present study were: (i) to quantify the night heat transfers of a greenhouse, by performing a comprehensive analysis of the energy balance components of the shelter; (ii) to estimate the energy losses of the greenhouse; (iii) to evaluate the energy effectiveness of the ground; and (iv) to investigate the feasibility of a greenhouse deprived of any heating system under these specific climatic conditions. To reach these objectives, an experimental greenhouse was equipped with a set of probes in order to measure the different components of the energy balance. From the experimental results, the magnitude of the energy flux and heat transfer coefficients were obtained, and compared with the results from the literature.

2. Materials and methods

2.1. Site, greenhouse description, and measurements

The experimentation was carried out in a closed glasshouse of 32 m^2 surface area, without any crop and deprived of any artificial heating system. The experimental device was located at the department of agronomy of the University of Batna (6°11′ East, 35°33′ North). The greenhouse was a standard 4 m wide Venlo type glasshouse (3.60 m high under ridge and 3.20 m high under gutter), with a global volume of 92.75 m^3 (Table 1). It was orientated East–West. The greenhouse was built with metallic frames and was covered with a horticultural glass of 4 mm thickness.

Table 1 Geometrical characteristics of the greenhouse components.

Name of constant	Symbol	Value	Remark
Length of the greenhouse	L	8 m	
Width of the greenhouse	l	4 m	
Volume of the greenhouse	V	92.75 m^3	Calculated
Surface of the ground sheltered by the greenhouse	S_g	32 m^2	Calculated
Surface of the cover of the greenhouse	S_c	69.25 m^2	Calculated
Total surfaces of leakage in the greenhouse	S_f	0.22 m^2	Calculated
Thickness of the layer of the sheltered ground	z_g	0.4 m	
Thickness of the cover of the greenhouse	z_c	0.05 m	
Shape factor for the interior wall to the ground of the greenhouse	f_{cig}	0.46	Calculated
Shape factor for the outside wall of the cover to the sky	f_{csky}	0.73	Calculated
Shape factor for outside wall to the external ground	f_{cege}	0.27	Calculated

The average spectral properties of the glass, provided by the manufacturer, are reported in Table 2. The analysis of the ground of the greenhouse to a depth of 50 cm reveals the following results: 30.62% of clay, 25.60% of fine silt, 17.13% of coarse silt, 15.41% of fine sand, and 11.24% of coarse sand. The ground density and thermal conductivity were measured for sample locally collected, whereas its spectral properties (Table 2) were inferred from the study carried out by Capderou (1985). For the three periods of measurement, the ground of the greenhouse was bare; however, evaporation was present, which was confirmed by the analysis of the energy balance on the surface of the ground and on the interior air. The main source of the water vapour was the quantity of water contained in the ground (21.57%).

Fig. 1 provides a schematic view of the facility and shows the different probes used to measure the temperature and the relative humidity. All the measurement points are distributed along a cross-section at the centre of the greenhouse in the same vertical plane, and at different heights. The temperature and relative humidity of the air (interior air and surrounding air) were recorded by means of a data logger (OAKTON Logger Plus) which is a system of remote measurements. This system consists of six thermohygrometers, six transmitters and a recording box. The temperatures of the solid surfaces (surface ground, underground and walls surface of the cover) were measured every 2 s with thermocouples, and then averaged over 30 min periods. All the above-mentioned measurements were collected on a data logger system (Campbell Scientific Micro logger, CR3000). The outside climatic conditions were measured by a weather station. The energy balances of the components of the greenhouse have been established for three measurement series: the first was from 24 to 25 January 2007 and is representative of the cloudy night; the second was from 20 to 21 February 2007 and is representative of the windy night; the third was from 17 to 18 March 2007 and is representative of the cloudless night. The climatic conditions observed

Table 2 Thermal and spectral characteristics of the greenhouse components.

	ρ (kg m^{-3})	λ (W m^{-1} K^{-1})	C (J kg^{-1} K^{-1})	Under visible wave length	Under long infra-red wave length	Reference
Ground	1625.91*	2.541*	1491.62*	$r_g = 0.25$ $\alpha_g = 0.75$ $\tau_g = 0$	$\varepsilon_g = 0.9$ $r_{gt} = 0.2$ $\alpha_{gt} = 0.8$	Capderou (1985)
Air	101,354/(287.05T_{ai})	$(2.510^2 T_{ai}^{1/2})/(T_{ai} + 194.44)$	1004	–	–	Molina-Aiz et al. (2004)
Cover glass	840	0.76	2700	$r_c = 0.1$ $\alpha_c = 0.15$ $\tau_c = 0.75$	$\varepsilon_{ct} = 0.93$ $r_{ct} = 0.1 \alpha_{ct} = 0.9$ $\tau_{ct} = 0.0$	Manufacturer's data

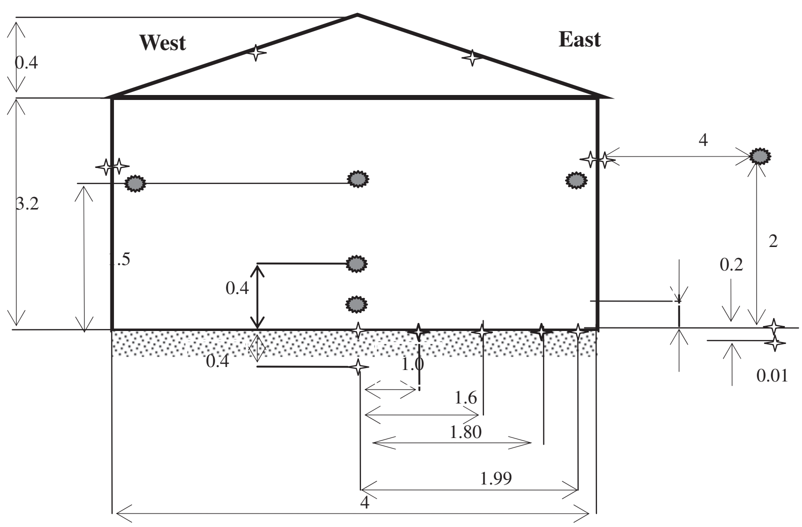

Figure 1 Experimental setup view (lengths in meter): humidity and temperature sensors (●); thermocouples (✧).

during the three periods of experimentation are reported in Table 3.

2.2. Greenhouse energy balance

The energy balance analysis was carried out only during the periods of stable climatic conditions when the heat flux and the state variables were relatively stationary. Over a 30 min period, the variations of the radiation and the conduction of heat fluxes were lower than ± 2.02 W m^{-2}, and the variations of the recorded temperatures were lower than ± 0.42 K. Under these conditions which could be considered as stationary, the energy balance of each component was calculated. By convention, the direction of each term of the equations described below is negative away from the surface, and positive towards the surface of the component. Fig. 2 depicts the different heat fluxes exchanged between the elements of the greenhouse and with the outside environment.

The energy balance for each component of the greenhouse may then be established. In this section, all heat fluxes are expressed per m^2 of ground surface S_g in W m^{-2}.

2.3. Soil surface energy balance

The surface ground energy balance of the greenhouse under steady state conditions is described by the equation

$$Q_g^{inf} + Q_{gai}^{cov} + Q_{gai}^{lat} + Q_g^{cod} = 0 \quad (1)$$

where Q_g^{inf} is the net radiation heat flux emanating from the ground surface of the greenhouse. Q_{gai}^{lat} is the latent heat flux associated with the evaporation of the ground surface. It is deduced from the latent heat balance on the interior air (Eq. (4)). The conduction heat flux between two layers corresponding to the surface of the bare soil and of the layer located at 40 cm above the surface inside the ground Q_g^{cod}. The convective heat flux exchanged between the ground surface and the interior air Q_{gai}^{cov} is given directly from a residual calculation of Eq. (1) and from the coefficient of heat transfer by convection between the ground surface and the interior air h_{gai} (W m^{-2} K^{-1}) inferred from Eq. (2)

$$h_{gai} = \frac{Q_{gai}^{cov}}{(T_{ai} - T_g)} \quad (2)$$

where T_{ai} is the temperature of the interior air and T_g is the temperature of the ground surface in K.

2.4. Interior air energy balance

Assuming that the infra-red radiations are not absorbed by the air, only the convective and latent exchanges are considered, two interdependent equations may then be written: the sensible and the mass energy balance of the greenhouse air volume, which may be expressed as:

Table 3 Energy balance components values of the greenhouse ground surface.

Periods	Q_g^{cod} (W m^{-2})	Q_{gai}^{cov} (W m^{-2})	Q_{gai}^{lat} (W m^{-2})	Q_g^{inf} (W m^{-2})	T_g (K)	T_{ai} (K)	ΔT_{gai} (K)	h_{gai} (W m^{-2} K^{-1})
Cloudy night January 25, 2007	44.03 (±2.6)	−6.85 (±1.50)	−9.09 (±0.52)	−28.09 (±2.85)	283.98 (±0.85)	283.09 (±1.0)	0.89 (±0.21)	07.7 (±2.13)
Windy night February 21, 2007	42.23 (±4.13)	−8.37 (±1.85)	−9.26 (±0.47)	−24.62 (±3.21)	281.05 (±0.70)	280.07 (±1.32)	0.98 (±0.18)	08.54 (±1.86)
Cloudless night March 18, 2007	38.70 (±3.2)	−6.29 (±1.23)	−9.88 (±0.61)	−22.13 (±2.22)	279.39 (±0.65)	278.35 (±1.0)	1.04 (±0.07)	6.55 (±1.56)

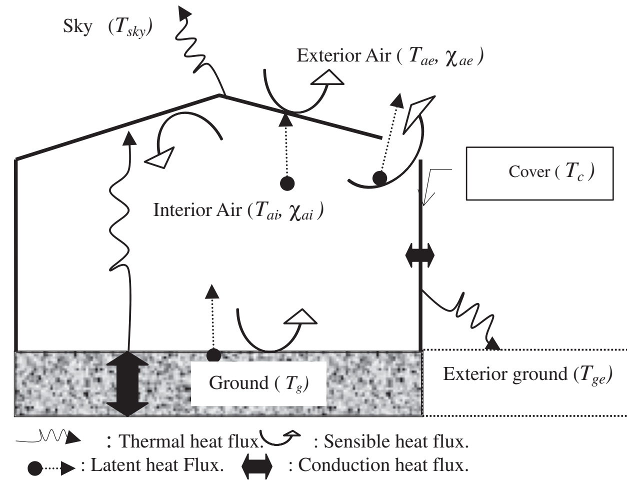

Figure 2 Greenhouse physic model and energy balance.

$$Q_{aici}^{cov} + Q_{gai}^{cov} + Q_{aiae}^{cov} = 0 \quad (3)$$

$$Q_{gai}^{lat} + Q_{aiae}^{lat} + Q_{aici}^{lat} = 0 \quad (4)$$

where Q_{aici}^{cov} is the convective heat flux exchanged between the interior air and the interior wall surface of the cover, and Q_{aiae}^{cov} is the sensible heat flux due to the leakage losses through the structure of the greenhouse. Q_{aiae}^{lat} is the leakage losses of enthalpy, and Q_{aici}^{lat} is the latent heat flux of condensation on the interior wall of the cover. The sensible and latent heat fluxes Q_{aiae}^{cov} and Q_{aiae}^{lat} due to the leakage losses, are calculated using the temperatures of the relative humidity measured in the air (interior and exterior) according to the formula provided by Fernandez and Bailey (1992) (Eqs. (5) and (6)):

$$Q_{aiae}^{cov} = \frac{\rho_a \Re V C_a}{3600 S_g}[T_{ai} - T_{ae}] \quad (5)$$

$$Q_{aiae}^{lat} = \frac{\rho_a \Re V L_v}{3600 S_g}[\chi_{ai} - \chi_{ae}] \quad (6)$$

$$Q_{aici}^{lat} = \varphi_{vap} L_v \quad (7)$$

where ρ_a is the density of the air (kg m^{-3}), V, the volume of the greenhouse (m^{-3}), C_a is the mean specific heat of the air and is equal to 1004 J kg^{-1} K^{-1}, T_{ae}, the temperature of the surrounding air (K), χ_{ai}, the absolute humidity of the air inside the greenhouse, and χ_{ae}, the absolute humidity of the air outside the greenhouse (g_{water} kg_{air}^{-1}). L_v is the latent heat of vaporization of water (J kg^{-1}). The renewal rate of the air $\Re$ (m^3 s^{-1}) is given as a function of the wind speed U_e (m s^{-1}) and the temperature gradient ($\Delta T_{aiae} = T_{ai} - T_{ae}$). The latent heat flux of condensation on the interior wall of the cover Q_{aici}^{lat} is calculated from the condensed water vapour flux φ_{vap} using Eq. (7). The sensible heat flux exchanged between the interior air and the interior wall of the cover Q_{aici}^{cov} is then deducted from Eq. (3). The coefficient of heat transfer by convection h_{aici} between the interior air and the interior wall is given according to:

$$h_{aici} = \frac{S_g Q_{aici}^{cov}}{S_c(T_{ai} - T_{ci})} \quad (8)$$

where T_{ci} is the temperature of the interior wall of the cover, and S_g, S_c are, respectively, the surfaces of the ground and cover (m^2).

2.5. Energy balance of the cover

Because of the absence of condensation on the external wall of the glazing during the three periods of measurements, this phenomenon was neglected in the calculation of the energy balance of the outside wall of the cover (Eq. (10)). Thus the heat balance on both the internal and the external surfaces of the walls, under steady state conditions, are governed by Eqs. (9) and (10), respectively:

$$Q_{aici}^{cov} + Q_{aici}^{lat} + Q_{c}^{cod} + Q_{ci}^{inf} = 0 \quad (9)$$

$$Q_{ceae}^{cov} + Q_{c}^{cod} + Q_{ce}^{inf} = 0 \quad (10)$$

These two equations include new parameters: the flux of conduction through the cover Q_{c}^{cod}, and the infra-red radiation heat fluxes on both faces of the cover, namely Q_{ci}^{inf} and Q_{ce}^{inf}. These three heat fluxes are calculated, respectively, by Eqs. (A2), (A14) and (A15) provided in the Appendix, using the measured temperatures, the thermophysical characteristics of the components, and the geometrical characteristics of the greenhouse (Table 1). The convective heat flux exchanged between the outside wall of the cover and the surrounding air Q_{ceae}^{cov} is then inferred directly from Eq. (10). The coefficient of exchange by convection h_{ceae} between the exterior wall surface of the cover and the surrounding air is calculated using Eq. (11) below, where T_{ci} is the temperature of the exterior wall of the cover:

$$h_{ceae} = \frac{S_g Q_{ceae}^{cov}}{S_c(T_{ce} - T_{ae})} \quad (11)$$

3. Analysis and discussion of the results

All reported results are based on data collected in the greenhouse (with reference cover and geometry) during one growing season, from October 2007 to March 2008 with indoor climate as summarised in Tables 3–5.

3.1. Soil surface energy balance

The average values of the components of the energy balance of the ground surface described by Eq. (1) are represented in Table 3 for the three nights of experimentation.

3.2. Conduction inside the greenhouse ground

During the three periods, the conduction of heat flux through the surface ground Q_{g}^{cod} was ascending (positive), so the sand layer was transferring heat upwards, and the heat accumulated in the soil was released to the greenhouse during night time. This process can compensate the radiation losses of the surface ground, which represented the principal heat losses of this component (Table 3).

During the first night for instance, with a mean positive flux of 44.03 W m^{-2}, Q_{g}^{cod} was supplying enough energy to compensate the radiative losses, which represented the main loss component 28.09 W m^{-2}.

The heat fluxes Q_{gai}^{cov} and Q_{gai}^{lat} were small at that time (about 8 W m^{-2}) and of opposite sign. In most studies of the energy balance of greenhouses, the values of Q_{g}^{cod} were assumed to be relatively small and thus neglected. According to Roy et al. (2002), the contribution of the heat conduction flux of

Table 4 Energy balance components values of the interior air.

Periods	Q_{gai}^{cov} (W m^{-2})	Q_{aici}^{cov} (W m^{-2})	Q_{aiae}^{cov} (W m^{-2})	Q_{gai}^{lat} (W m^{-2})	Q_{aici}^{lat} (W m^{-2})	Q_{aiae}^{lat} (W m^{-2})	T_{ai} (K)	T_{ci} (K)	ΔT_{aici} (K)	h_{aici} (W m^{-2} K^{-1})
Cloudy night January 25, 2007	6.85 (±1.50)	−4.19 (±0.2)	−2.66 (±0.10)	9.09 (±0.52)	−3.95 (±0.15)	−5.14 (±0.20)	283.09 (±1.32)	282.35 (±1.25)	−0.74 (±0.10)	2.60 (±0.23)
Windy night February 21, 2007	8.21 (±1.85)	−2.93 (±0.11)	−5.28 (±0.11)	9.26 (±0.47)	−4.62 (±0.11)	−4.64 (±0.16)	280.07 (±1.56)	279.43 (±1.23)	−0.64 (±0.06)	2.10 (±0.21)
Cloudless night March 18, 2007	6.29 (±1.23)	−4.96 (±0.16)	−1.33 (±0.08)	9.88 (±0.41)	−4.53 (±0.13)	−5.35 (±0.23)	278.35 (±1.06)	276.10 (±1.0)	−2.25 (±0.04)	1.01 (±0.06)

Table 5 Energy balance components values of the cover two walls.

Periods	Interior wall				Exterior wall						
	T_{ci} (K)	Q_{ci}^{inf} (W m^{-2})	Q_{aici}^{cov} (W m^{-2})	Q_{aici}^{lat} (W m^{-2})	T_{ce} (K)	T_{ae} (K)	Q_{ce}^{inf} (W m^{-2})	Q_{cice}^{cod} (W m^{-2})	Q_{ceae}^{cov} (W m^{-2})	ΔT_{ceae} (K)	h_{ceae} (W m^{-2} K^{-1})
Cloudy night January 25, 2007	282.35 (±1.25)	14.88 (±2.30)	4.19 (±0.20)	3.95 (±0.15)	282.28 (±2.3)	281.5 (±2.4)	−16.25 (±2.32)	23.02 (±2.38)	−6.12 (±1.23)	0.80 (±0.02)	3.60 (±1.1)
Windy night February 21, 2007	279.43 (±1.23)	25,35 (±1.66)	2.92 (±0.11)	4.62 (±.11)	279.33 (±2.12)	278.2 (±2.2)	−22.68 (±2.89)	32.89 (±3.51)	−10.21 (±1.63)	1.13 (±0.52)	4.15 (±1.03)
Cloudless night March 18, 2007	276.1 (±1.0)	23.34 (±2.69)	4.96 (±0.16)	4.53 (±0.13)	276.00 (±1.11)	277.49 (±1.8)	−53.11 (±4.59)	32.83 (±3.42)	+20.29 (±4.62)	−1.69 (±0.33)	5.47 (±1.7)

the soil may be considered as negligible in cases where the ground of the greenhouse is largely shaded by vegetation, or in greenhouses equipped with a heating system. On the contrary, in unheated greenhouse or those with low leaf area crops, the soil energy storage and release over 24 h period are far from being negligible. Considering a moderately heated greenhouse, Baille et al. (2006) have shown that the contribution of the soil represented approximately 40% of the heating input, compared to only 15% in the case of a high input level of heat. In our case – an unheated and closed greenhouse with bare soil – the average values of the conduction flux for the three periods correspond to an energy release from the ground of 44.03, 42.23, and 38.7 W m^{-2}, respectively, which is equivalent to an energy release from the soil during a 12-h night of: 1.63, 1.56 and 1.47 MJ m^{-2}. These results are twice the energy release (daily energy stored in the soil and released to the greenhouse interior air during the night time) found by Baille et al. (1985) and by Baille (1999) for greenhouses with tomato crops under temperate climatic conditions. The results obtained in the present study are not surprising given the climatic conditions of semi-arid regions which are characterized by high winter insulation. Moreover, the experimental results show that the soil storage represents between 20% and 25% of the captured solar energy, in agreement with the conclusions of Joliet (1991) who observed that the energy stored in the soil was proportional to the solar radiation contribution.

3.3. Convective heat exchange at the interface soil surface and the interior air

For the three nights of measurement, the temperature gradient values ΔT_{gai} are rather low (±1 K), by contrast the average values of the coefficient h_{gai} are rather high (mean value 7.2 W m^{-2} K^{-1}). This coefficient remains negative, which means that the greenhouse ground provides heat to the interior air. Plotting the h_{gai} values versus the temperature gradient ΔT_{gai}, Fig. 3, shows that h_{gai} varied within a lower and an upper limit, corresponding respectively to the models proposed by Lamrani et al. (2001) ($h_{gai} = 5.2\Delta T_{gai}^{0.33}$) for a greenhouse equipped with heated soil system, and by Silva (1988) ($h_{gai} = 10\Delta T_{gai}^{0.33}$) for an unheated plastic greenhouse with bare soil. The standard deviation of h_{gai} (±1.85 W m^{-2} K^{-1}) may be ascribed to the experimental errors and to the models used for the determination of

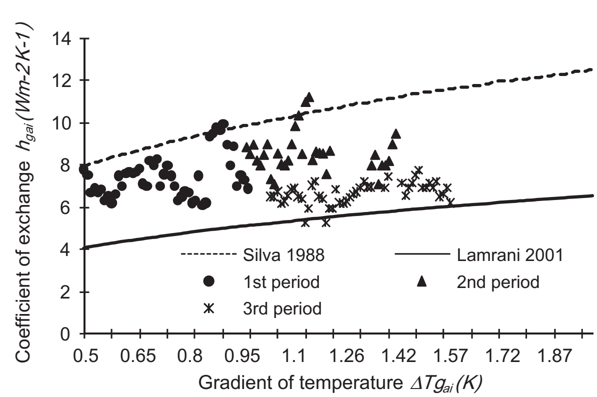

Figure 3 Convection exchange coefficient values at the surface of the soil according to the temperature gradient during the three measurement periods compared with the models of Silva (1988) and Lamrani et al. (2001).

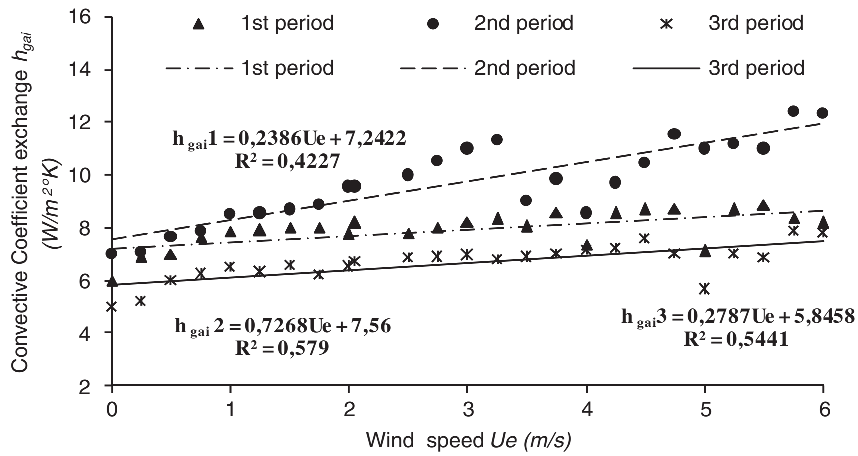

Figure 4 Convection exchange coefficient between the surface of the sheltered ground and the interior air of the greenhouse as a function of the wind speed during the three periods of measurement.

the radiation fluxes. Another factor to explain this variability could be the influence of the wind velocity on the air flow inside the greenhouse. The h_{gai} variation versus the wind speed U_e (Fig. 4) is almost linear with a coefficient of determination R^2 within the range [0.42–0.72]. h_{gai} appears to be also a function of the wind speed even inside the greenhouse, which suggests that h_{gai} could be also governed by forced convection. For practical applications, the average value of h_{gai} ($= 7.2\ \mathrm{W\,m^{-2}\,K^{-1}}$) could be considered as a reasonable estimate in the case of an unheated greenhouse located in an area belonging to a semi-arid zone.

3.4. Interior air energy balance

Table 4 presents the average values of heat fluxes which appear in the energy balance of the interior air during the three periods of measurements. Fig. 5 shows the coefficient variation h_{aici} versus the temperature gradient ΔT_{aic} and the results of the empirical models proposed byTantau (1975) cited by Roy et al. (2002), Kittas (1986), and Garzoli and Blackwell (1987).

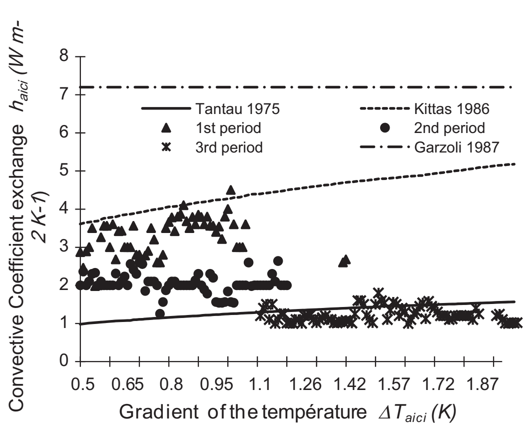

Figure 5 Convective coefficient as a function of the temperature gradient ΔT_{aici} during the three measurement periods and comparison with the models of Tantau (1975), Kittas (1986) and Garzoli and Blackwell (1987).

For the first period (January 24th) the coefficient h_{aici} approaches the value obtained from the model of Kittas (1986) ($h_{aici} = 4.3\Delta T^{0.25}$) while for the two other periods (February 21st and March 18th) h_{aici} is almost similar to that deduced from the model of Tantau (1975) ($h_{aici} = 1.247\Delta T^{0.33}$). It should be pointed out that the convective exchange coefficient h_{aici} depends on several factors especially on the heating system type and on the greenhouse roof slope. In the present study, all the observations lead to relatively h_{aici} low values. This may be due to the turbulence absence in our case (unheated and closed glasshouse), whereas in the work of Kittas (1986)), who considered a greenhouse heated by hot pulsated air, relatively high values of h_{aici} were reported. Halleux (1989) reported similar observations from experiments carried out in a greenhouse heated by heating pipes.

Low values of h_{aici} may thus be due to the absence of heating equipments which, if present, could enhance air movement inside the greenhouse and cause mixing and turbulence. It is well known that the air movement induced by a heating system and by the associated convection mode plays a major role in determining the convection exchange coefficient. In addition, it should be noted that positive linear correlations were found between the values of T_{ai} and T_{ci} (Fig. 6) with slopes near unity for all datasets ($R^2 = 0.95$ for the two first periods). This implies that the heating mode in the greenhouse (i.e., heat release by the ground) causes a proportional change between the two temperatures, i.e., a variation of T_{ci} practically resulted in the same variation of T_{ai}.

3.5. Energy balance on the cover

Table 5 provides the average values of the components of the energy balance of the interior and exterior walls of the greenhouse during the three periods, together with the corresponding values of ΔT_{ceae} and outer cover-to-air heat transfer coefficient h_{ceae}.

3.6. Convective exchange between the cover and the outside air

The average value of the coefficient h_{ceae} is $4.15 \pm 1.03\ \mathrm{W\,m^{-2}\,K^{-1}}$. For two periods (1st night and 2nd night) the coefficient h_{ceae} is in agreement with the model proposed by

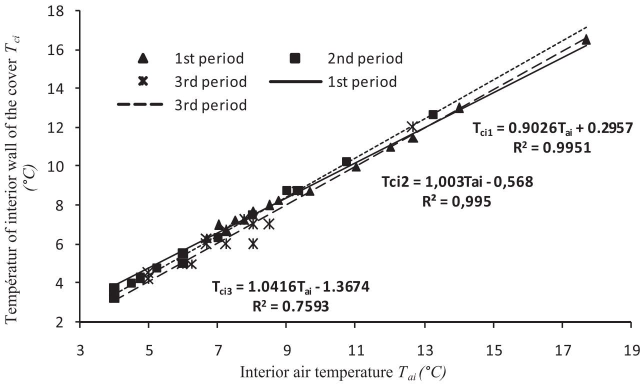

Figure 6 Temperature variations at the interior wall according to the interior air temperature T_{ai} during the three periods of measurement and the corresponding linear fit.

Bot (1983) (h_{ceae} = 2.8 + 1.2U_e), but seems underestimated compared to the model of Kittas (1986) ($h_{ceae} = 1.22\Delta T_{ceae}^{0.25} + 3.12U_e^{0.8}$). It can be ascribed in part to the convective heat exchange which is generally considered to be forced and mainly influenced by the external wind speed U_e along the outside surface of the cover. A good correlation was found (R^2 = 0.946) between the variation of the coefficient h_{ceae} and the wind speed, for the three periods of measurement (Fig. 7). For the third night, the temperature gradient ΔT_{ceae} is the highest compared to the two preceding periods. It varies between −1.69 ± 0.33 K. The corresponding heat transfer coefficient h_{ceae} has a value of 5.47 ± 1.70 W m^{-2} K^{-1} corresponding to a convective heat flux $Q_{ceae}^{cov} = 20.3 \pm 4.62$ W m^{-2}, which is positive for the three quarters of the period (the cover was cooler than the outside air and, therefore, was gaining heat). This process is known as the inversion phenomenon and has been reported to occur rather frequently for unheated greenhouses during calm and cloudless nights (Montero et al., 1985; Papadakis et al., 1992). Under such conditions, the radiation losses through the cover are very high and the cover temperature may drop several degrees below the outside air temperature.

3.7. Radiative exchanges at the cover

The interior wall receives thermal energy from the inside air by the convective and latent heat fluxes Q_{aic}^{cov} and Q_{aic}^{lat} and from the greenhouse soil by the radiative heat flux emitted by the soil surface. For the three periods of measurement, the net heat flux radiation on the interior wall Q_{ci}^{inf} was positive (Table 5) and represented the main part of the heat supply to the wall, which was twice higher than the sum of convective and latent heat fluxes. The reverse was also true for the outside wall, where a predominance of the radiation losses was clear. For the first period, the net radiation on the outside wall Q_{ce}^{inf} was negative and lower than the flux of conduction coming from the internal face. For the second period (windy night, February 21st, 2007), the same trend was observed and the net radiation Q_{ce}^{inf} still contributed to the major part of the wall energy losses.

The net radiation on the outside wall reached a high negative value $Q_{ce}^{inf} = -53.11$; W m^{-2} compared with the heat gain $Q_{cice}^{cod} = +32.38$ W m^{-2} and $Q_{ceae}^{cov} = +20.29$ W m^{-2} especially during the night of March 19th, 2007. This phenomenon frequently happens during nights with cloudless sky. For the three periods, the predominance of the outside wall radiative losses was, therefore, clearly established. Their intensity, however, decreases with the nebulosity of the sky and the period of sunset which just proceed the night period. These results are in agreement with those of Mesmoudi et al. (2008) who reported a positive contribution of the low nebulosity of the sky on the decrease/decay of the wall radiative losses.

It is clear that the heat losses mainly include the radiation losses through the external wall surface of the cover (≈50 W m^{-2}) for a cloudless night and the sensible losses along this wall (≈20.29 W m^{-2}). The radiative heat exchange on the inner wall represented the main heat supply to this wall and found to be two times higher than the sum of convective and latent heat fluxes exchanged with the interior air. Inside the greenhouse the energy exchange mainly occurred between the air and the ground. The latent losses were low and the losses by leakages were proportional to the wind velocity and temperature gradient (inside–outside). For the three periods of measurements the energy balance at the soil–air interface

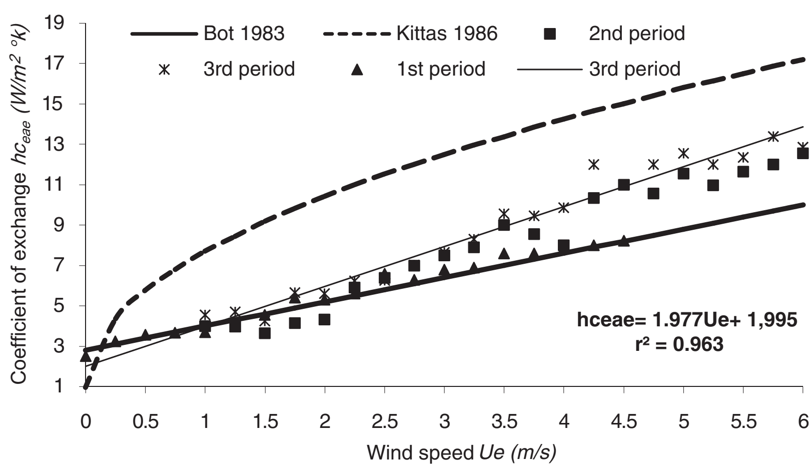

Figure 7 Heat transfer coefficient as a function of the wind speed. Comparison with the models suggested by Bot (1983)and Kittas (1986) for a fixed gradient of temperature ΔT_{ceae} = 1.5 K.

showed that the soil heat flux provided most of the energy to compensate for the radiative ground losses (≈44, ≈42, and ≈38 W m^{-2}). In the greenhouse air volume, energy losses mainly occurred through air-inner wall of the cover convective and latent exchange (≈8.14, ≈5.52, and ≈9.49 W m^{-2}). At the outer wall of the cover, losses mostly occurred by radiative exchange (≈16.25, ≈22.68, and ≈53.11 W m^{-2}).

4. Conclusions

The present study, based on experiments conducted in Batna, Algeria, provides a methodology to analyse the thermal behaviour of greenhouses installed in areas characterized by semi-arid climate of the southern Mediterranean basin. Moreover, this work can be regarded as a useful contribution to the comprehension of the energy balance of the unheated greenhouses. Concerning these aspects, the following results could be pointed out:

1. The greenhouse soil is an important heat source during the night time. It can provide up to approximately (44.03 W m^{-2}) in the case of a night preceded by a significant diurnal insulation. Compared with an artificial heating system, approximately 78 W m^{-2}, would be necessary under similar outside climatic conditions to maintain the temperature of the air inside the greenhouse between 15 and 18 °C.
2. The estimation of convection exchange coefficients between the components of the greenhouse are in agreement with the models reported in the literature. The convection mode inside the greenhouse induced by the type of heating system seems to play a significant role in the determination of the convective exchange coefficient.
3. The radiation losses are the main components of the greenhouse energy losses, mainly for the cover outside wall. This phenomenon is enhanced when the sky is relatively clear (low nebulosity).

Concerning the feasibility of building greenhouses and their extension in the area, the following conclusions may be drawn: (i) since the process of thermal exchanges is dominated by the dissipation of heat through the cover, the implementation of heat shields, or the use of covers (plastic, glass) with a low thermal emissivity could generate substantial economies; (ii) the losses by leakage could be overcome by increasing the air tightness of the structure of the greenhouse; (iii) the ground of the greenhouse is a significant source of heat in Mediterranean countries which could be extracted and stored for other applications. This solution could increase significantly the thermal efficiency of the greenhouses in strongly sunny areas.

Appendix. Expressions of the heat fluxes

Most model parameters of the heat fluxes can be estimated from literature. The heat flux of conduction Q_g^{cod} between the surface of the soil and the point situated at the depth z_g, and the heat flux of conduction Q_c^{cod} through the thickness of the wall of the cover are given by Eq. (A1) and (A2) respectively:

$$Q_g^{cod} = \frac{\lambda_g}{z_g}(T_g - T_{g1}) \tag{A1}$$

$$Q_c^{cod} = \frac{\lambda_c . S_c}{z_c S_g} . (T_{ci} - T_{ce}) \tag{A2}$$

where λ_g is the mean thermal conductivity of the ground, and T_g, T_{g1} are the temperature of the surface of the ground and of the point located at a depth z_g respectively. λ_c is the mean thermal conductivity of the cover, and T_{ci} and T_{ce} are the temperatures of the interior and exterior walls respectively. S_c and S_g are the surface of the cover and ground and z_c is the thickness of the cover.

The ventilation rate $\mathfrak{R}$ given by the Eq. (A3) is used for the calculation of the air infiltration inside the building. The formula is inferred from the works of Joliet (1988) who considered the losses due to leakage in a closed Venlo glasshouse. S_f is the surface of the escapes, U_e, the wind speed, and T_{ai} and T_{ae} are the temperatures of the inside and outside air respectively.

$$\mathfrak{R} = S_f \sqrt{0.046 U_e^2 + 0.020(T_{ai} - T_{ae})} \tag{A3}$$

The latent heat of condensation on the interior wall of the cover Q_{gai}^{lat} is given by:

$$Q_{gai}^{lat} = \phi_{vap} L_v \tag{A4}$$

where ϕ_{vap} is the water vapour flux of condensation calculated by the Eq. (A5).

$$\phi_{vap} = \kappa \frac{S_c}{S_g} \rho_{ai} (\chi_{ai} - \chi_{aic}^*) \tag{A5}$$

$$\text{with } \chi_{ai} = \frac{M_w}{M_{ai}} \frac{e_{ai}}{Pa} \tag{A6}$$

L_v is the latent heat of vaporization of water, κ is the conductance of the mass transfer of the water vapor, ρ_{ai} is the density of the interior air, χ_{ai} is the humidity of the interior air and χ_{aic}^* is the saturate humidity of the air near the inside wall.

According to Eq. (A4), (A5) and (A6), the latent heat flux of condensation Q_{gai}^{lat} may be written as:

$$Q_{gai}^{lat} = \kappa \rho_{ai} \frac{S_c M_w}{S_g M_{ai} Pa} (e_{ai} - e_{aic}^*) \tag{A7}$$

where M_w and M_{ai} are the water and air molar mass respectively, Pa is the atmospheric pressure, e_{ai} is the vapour pressure of the inside air, and e_{aic}^* is the vapour pressure at saturation of the inside air.

Stanghellini (1995) indicated that the conductance of the mass transfer of the water vapor can be calculated starting from the virtual temperatures of the interior air $\ddot{T}_{ai}$ and the interior wall of the cover $\ddot{T}_{ci}$ according to Eq. (A8).

$$\kappa = 1.64.10^{-3} (\ddot{T}_{ai} - \ddot{T}_{ci}) \tag{A8}$$

Each virtual temperature is determined by Eq. (A9) given by Hill (2006).

$$\ddot{T} = \frac{T}{1 - 0.37 \frac{e_{ai}}{Pa}} \tag{A9}$$

Hence the latent heat flux of condensation on the internal walls of the cover may be written in the form:

$$Q_{aici}^{lat} = 1.64.10^{-3} (\ddot{T}_{ai} - \ddot{T}_{ci}) L_v \rho_{ai} \frac{S_c}{S_g} \frac{M_w}{M_{ai}} \left[\frac{(e_{ai} - e_{aici}^*)}{Pa} \right] \tag{A10}$$

$$\text{with} \quad M_w = 0.018\text{kg/mol} \quad M_a = 0.029\text{kg/mol}$$

The vapor pressure of saturation of the air is given by the Eq. (A11), according to the NASA (2005) cited by Impron et al., (2007).

$$e_{ai}^* = 2.22 \; 10^{11} e_{ai}^{\left(\frac{-5385}{T_{ai}}\right)} \tag{A11}$$

The vapor pressure of the air is given by the formula of Tetens (1973) (A12):.

$$e_{ai} = 6.1070\ 10^{7.5T_{ai}/(237.3+T_{ai})} \quad \text{(A12)}$$

The net Radiative heat flux on the surface ground of the greenhouse Q_g^{inf} is described by Eq. (A13) according to Singh et al. (2006) where ε_g is the emissivity of the surface ground, σ is the Stefan Boltzmann constant, ε_c is the emissivity of the cover, f_{cig} is the shape factor for the interior wall to the ground of the greenhouse, and α_{ct} is the infrared coefficient of absorption of the cover.

$$Q_g^{inf} = (-\varepsilon_g \sigma T_g^4 S_g + \varepsilon_c \sigma T_{ci}^4 S_c \alpha_{gt} f_{cig})/S_g \quad \text{(A13)}$$

The net radiative heat flux on the interior wall of the cover Q_{ci}^{inf} is described by Eq. (A14) according to Singh et al. (2006). This equation comprises the radiative heat flux emitted by the surface of the ground of the greenhouse, and the radiative heat flux emitted by the interior wall of the cover towards the ground of the greenhouse.

$$Q_{ci}^{inf} = (-f_{cig}\varepsilon_c \sigma T_{ci}^4 S_c + \alpha_{ct}\varepsilon_g \sigma T_g^4 S_g)/S_g \quad \text{(A14)}$$

According to Kittas (1986) and Singh et al. (2006), the net Radiative heat flux on the outside wall of the cover Q_{ce}^{inf}can be calculated starting from: the radiative heat flux emitted by the wall towards the outside, the radiative heat flux intercepted from the sky, and the radiative heat flux emitted by the external ground towards the cover (A15). f_{ceky} is the shape factor for the outside wall of the cover to the sky, α_{ct} is the infrared coefficient of absorption of the cover, ε_{sky} is the emissivity of the sky, T_{sky} is the temperature of the sky, $f_{cege}$is the shape factor for the outside wall of the cover to the outside ground, ε_g is the emissivity of the ground, and T_{ge} is the temperature of the outside ground.

$$Q_{ce}^{inf} = (-f_{cesky}\varepsilon_c \sigma T_{ce}^4 S_c + f_{cesky}\alpha_{ct}\varepsilon_{sky}\sigma T_{sky}^4 S_c + f_{cege}\alpha_{ct}\varepsilon_g \sigma T_{ge}^4 S_c)/S_g \quad \text{(A15)}$$

Finally, the temperature of the sky T_{sky} is given according to Eq. (A16) provided by Aubinet (1994), with T_{ae} the temperature of the outside air, E_g, the total solar radiation, and N_{ub} the nebulosity of the sky.

$$T_{sky} = 94 + 12.6\ln(E_g) - 13N_{ub} + 0.34T_{ae} \quad \text{(A16)}$$

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