Influence of Condensation and Evaporation on the Greenhouse Climate and its Regulation

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ABSTRACT

A dynamic greenhouse climate model was used to simulate the effect of condensation and evaporation on the auxiliary heating requirements, on the inside air humidity and temperature and on the vegetation temperature in greenhouses covered with 12 different cladding materials.

Condensation was shown to increase the auxiliary heating requirements for materials having a far infrared radiation transmittance lower than 0.18, while it reduces them for all other materials. Savings ranged between +25 % for PP and -17 % for standard glass. The thermal insulation properties of dry claddings were shown to depend on their far infared radiation transmittance, while in the presence of condensation, the outside surface emittance was predominant. Materials reflecting all far infrared radiation could be shown to be best insulating under both wet and dry conditions.

It was also demonstrated that neglecting condensation and evaporation gives rise to an overestimation of the yearly mean inside air relative humidity of about 10 % for most materials. Since condensation fluxes were found to be lowest in greenhouses cladded with low emissivity materials, yearly average relative humidities were somewhat lower in this kind of greenhouses, while the relative contribution of condensation to the nighttime water vapour removal from the inside air was found to be lower for low emissivity cladded greenhouses (79-83 %) than for the other greenhouses (88-89 %). Evaporation fluxes from the cover as well as condensation fluxes to the floor were shown to be negligible when compared to condensation fluxes to the cover.

Neglection of condensation was shown to have nearly no effect on the simulated temperature of an active greenhouse, whereas it can result in an overestimation or an underestimation of the vegetation temperature, according to the cladding’s far infrared radiation transmittance, high transmittances giving rise to underestimates. Since these errors were found to vary throughout the year, it was argued that the vegetation temperature should also be controlled by greenhouse climate systems and that models used for inclusion in such systems will have to describe condensation phenomena in the greenhouse in a detailed way.

1. INTRODUCTION

During the last decades, greenhouses have become much more energy efficient. In the 1970's, this evolution started as a consequence of high energy prices. Nowadays, this economic justification has been reinforced by ecological considerations, such as the reduction of the CO_2-emission resulting from human activities and the depletion of fossil energy sources. In this way, the primary energy consumption of greenhouses was highly reduced by using waste heat or other renewable energy sources, by introducing new covering materials having other radiative properties, better climate regulation algorithms, etc.

Another way of saving energy was making greenhouses much more air-tight to reduce the heat loss by air leakage. In this way, less sensible heat was lost to the external environment. At the same time, more latent heat was kept inside the greenhouse, so that the inside air became more humid. But since the luminosity inside the greenhouse must be kept as high as possible, greenhouse cladding materials are rather poorly insulating when compared to residential, industrial or other agricultural building materials. As a consequence, their surface temperatures are often very low. This combination of low surface temperatures and high inside air humidity makes condensation on the walls and the roofs of recently built greenhouses unavoidable during most of the time.

Consequences of condensation in greenhouses are often disadvantageous. Condensation on plastics is mostly dropwise, so that drops can fall onto the crop, adversely affecting the fruit quality and favouring the development of fungal diseases. Nor are these falling drops appreciated from an ergonomic point of view. Furthermore, the presence of drops can drastically reduce the light transmittance of greenhouse cladding materials (Pieters et al., 1996a; Pieters et al., 1997).

As far as the interaction between condensation and energy consumption of the greenhouse is concerned, the role of condensation is much less unambiguously defined. On the one hand, during the condensation process latent heat is transferred to the cover, normally causing a cover temperature and thus a heat loss increase. On the other hand, the presence of a condensation layer can totally change the radiative properties of the cladding material, so that the radiative heat loss eventually can be reduced.

In this paper, a TRNSYS-based dynamic greenhouse climate model will be used to simulate the sensible and latent heat fluxes as well as the auxiliary heating requirements in greenhouses, covered with 11 different widely used single cladding materials. Furthermore, simulation results for an imaginary ideal cladding material will be used as a reference. For all materials, the impact of condensation and evaporation on the inside climate (humidity and temperatures) and its impact on the greenhouse climate regulation strategy will be discussed.

2. LITERATURE REVIEW

Theoterical and practical studies on the effect of condensation on the greenhouse climate can be divided among two groups according to the way they treat the external and consequently the internal climate conditions. Most theoretical studies on the condensation phenomenon in greenhouses deal with static climate circumstances, i.e. they assume a dynamic heat transfer equilibrium. Reports on dynamic studies on the condensation effect are rather difficult to find in literature.

2.1. Static circumstances

Silveston et al. (1980), Garzoli and Blackwell (1981), de Halleux et al. (1985b) and Seginer & Kantz (1989) simulated the nighttime heat transfer from greenhouses, tunnels or vertical greenhouse walls of glass and PE under several static weather conditions. One of the conclusions they had in common was that during condensation the static heat transfer coefficient increases for glass, while it decreases for PE. This well known effect is to be ascribed to the lowering of the transmittance for far infrared radiation from 0.8 for dry PE to almost 0 for wet PE. In this way, the supplemental latent heat transfer during condensation is more than compensated for by the decrease of the direct radiative heat transfer from the vegetation and the soil through the covering material to the sky. As glass is always totally opaque to far infrared radiation, and since its emittance in this range of the spectrum nearly equals that of water, the presence of a water layer has no important influence on the radiative heat fluxes. Laboratory experiments of Lacroix (1987), who used a kind of hot box / cold box system, confirmed these findings.

More recently, Pieters et al. (1994) demonstrated that the static heat transfer coefficient is a function of the inside air relative humidity. For low values of the relative humidity, not giving rise to condensation, this coefficient is constant. From a certain threshold value of the relative humidity on, condensation starts to form. At this threshold value, the heat transfer coefficient decreases drastically for PE and all other cladding materials transparent to far infrared radiation, at least if their transmittance is about 0.4 to 0.5 or higher (Pieters, 1996). The numerical value of this relative humidity threshold was shown to be a function of material characteristics and climate conditions (Pieters et al., 1995). Beyond the condensation threshold, the heat transfer coefficient increases for increasing values of the relative humidity, so that it can possibly become greater than the heat transfer coefficient for the dry material.

2.2. Dynamic circumstances

Dynamic studies on condensation and heat transfer have mostly been experimental. Walker and Walton (1971) and Feuilloley et al. (1994) measured the heat transfer from greenhouses and hot boxes placed in the open and covered by several cladding materials, on which condensation was produced artificially by electrically heating water, placed in the greenhouses and boxes. Qualitatively, they came to the same conclusions as for the static studies.

Many authors, among whom we can cite Stoffers (1990) and Yang et al. (1990) modelled the greenhouse climate dynamically. Most of these describe some condensation phenomena on the cover, on the wall or on other elements of the greenhouse. A survey of the treatment of latent heat fluxes in several dynamic greenhouse climate models can be found in Lacroix (1988) and in de Halleux (1989). In Table 1, it is only mentioned if some attention is paid to condensation and evaporation in some of these models.

It should be clear, however, that because of the great number of elements involved in heat transfer (soil, vegetation, ...) and because of the four heat transfer modes (conduction, convection, solar and far infrared radiation and phase change), these models are extremely complicated, so that condensation is nearly always treated in an off-handed way and rarely receives specific attention.

To overcome this problem, Pieters et al. (1996b) modified an existing model for a detailed description of condensation and evaporation phenomena on the cover, on the vegetation and on the floor and applicated it to the case of a standard glass covered greenhouse (Pieters et al., 1996c). For the circumstances of their simulations, they found that neglecting the condensation phenomena in dynamically simulating the greenhouse climate leads to an underestimation of the yearly fossil heating requirements of about 15 %. As this model will also be used for the simulations in this study, a short description of this model will be given in the next section.

Table 1 Survey of the treatment of (C) condensation and (E) evaporation on the (wi) inner and (wo) outer wall surface, on the (v) vegetation and on the (f) floor in some dynamic greenhouse climate models (after Lacroix (1988) and de Halleux (1989))

	wi	wi	wo	wo	v	v	f	f
	E	C	E	C	T	C	E	C
Takakura et al. (1971)		x			x		x	
Selcuk (1970)		x			x		x	
Soribe & Curry (1973)		x		x	x		x	
Van Bavel & Sadler (1979)	x	x			x		x	
Kindelan (1980)		x			x			
Glaub & Trezek (1981)		x						
Avissar & Mahrer (1982)		x		x	x		x	
Ahmadi & Glockner (1982)		x		x	x		x	
Cooper & Fuller (1983)		x			x		x	x
Bot (1983)		x		x	x		x	
Arinze et al. (1984)		x			x		x	
Cormary & Nicolas (1985)	x	x			x		x	x
Kimball (1986)					x			

3. SIMULATION MODEL

The model used here was originally developed as the Gembloux Greenhouse Dynamic Model (G.G.D.M.) by the "Centre d'Etude pour la Régulation Climatique des Serres" of the "Faculté des Sciences Agronomiques de Gembloux". Descriptions of this model can be found in de Halleux et al. (1985a), Deltour et al. (1985), de Halleux (1989), Nijskens et al. (1991) and Pirard et al. (1994). The model has been and is still being continuously improved and extended, which resulted in the most recent version, called the Universal Dynamic Greenhouse Climate Model, described in full detail in Pieters & Deltour (1997). As a consequence, only a short description of the model, allowing for a complete understanding of the results presented here, and with emphasis on the description of the latent heat flux phenomena, needs to be given in this section.

3.1. General lay-out

The U.D.G.C.M. is a semi-one-dimensional greenhouse climate model, describing the energy and mass exchanges between 7 internal layers (4 soil layers, 1 vegetation layer, 1 inside air layer, 1 cover), which form the system, and 3 external layers (subsoil, outside air and sky) which constitute, together with the solar radiation, the boundary conditions. For each of the layers, heat loss or gain by solar radiation, far infrared radiation, conduction, convection, and latent heat is described mathematically. Furthermore, a mass transfer equation for vapour is considered.
The model also allows to simulate the effect of regulation procedures for maintaining the inside air temperature in a zone of optimal values. To this end, several possibilities of heating and ventilating strategies, among which the user can choose, are built in the model. A scheme of the model is given in Fig. 1.

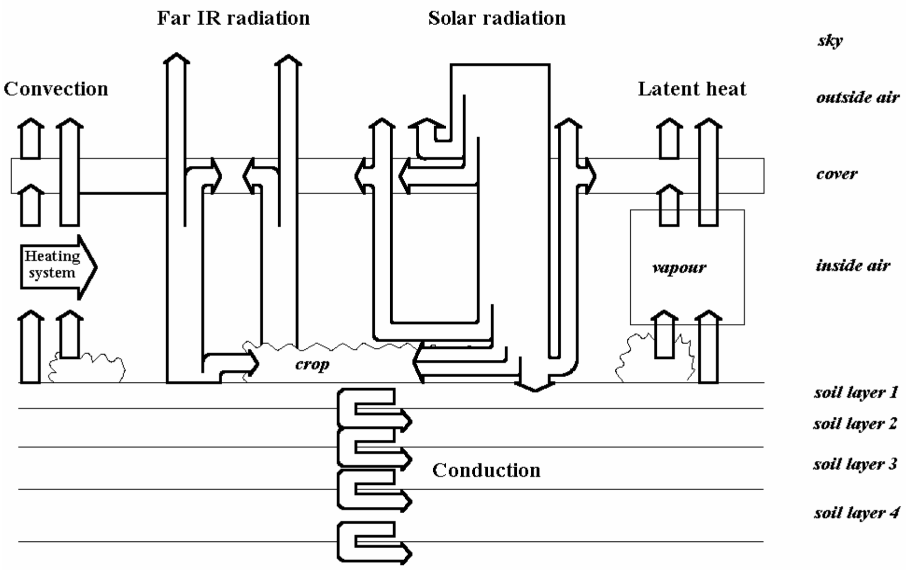

Fig. 1 Global scheme of the U.D.G.C.M.

3.2. Modelling of the latent heat transfers

3.2.1. Condensation on and evaporation from the cover

Condensation and evaporation at the outer surface of the cover are neglected, since they are rarely met in practice (Pieters et al., 1995). At the inside, however, condensation as a film or as drops is assumed to form on the cover as soon as the temperature of the cover falls below the dewpoint temperature of the inside air. At the start of condensation, the thickness of this film or the equivalent film thickness in the case of dropwise condensation increases (phase 1 - building of the film) till a certain maximum thickness - hereafter referred to as the maximum (equivalent) film thickness - is reached. If condensation goes on, water drips down the cover to the condensate gutters and is evacuated from the greenhouse at the same rate as condensate is formed (phase 2 - steady state). As condensation ceases and evaporation starts, the water film on the greenhouse cover gets thinner and disappears gradually (phase 3 - evaporation of the condensate film). When all the condensation water has been evaporated, the cover becomes dry and no further evaporation can take place (phase 4 - dry cover and no evaporation).

As greenhouse covers and certainly plastic film covers are very thin, their heat capacity per unit cover area is very small. Since the heat capacity of water is very high and since the equivalent condensate film thickness can be more than 100 µm, the influence of the condensate film on the cover heat capacity is not negligible. Therefore, the total heat capacity (always expressed per unit cover area) is expressed as the sum of the heat capacities of the covering material and the water film.

Of course, the far infrared radiative properties of the covering material are replaced with those of water when condensation is present on the cover. For covering materials highly transparent to this radiation (as is e.g. the case for polyethylene), this change in radiative regime at the onset of condensation is so drastic that for some values of the relative humidity the model becomes unstable. If the surface is totally wet at those values of the relative humidity, the high radiative flux absorbed by the cover will cause the latter to warm up, so that evaporation will occur; if the surface is dry (thus highly transparent and weakly absorbing) at the same value of the relative humidity, the low radiative flux absorbed by the inner surface of the greenhouse cover will allow its temperature to fall below the dewpoint of the inside air and condensation will occur. For these cases, a model using a totally wet / totally dry surface for the greenhouse cover cannot simulate what is really happening. This problem is solved by introducing an equivalent water-covered surface factor, p, expressing what fraction of the surface is wetted. In these cases the cover behaves as if a fraction p of its surface were wet (having the radiative properties of water) and a fraction (1-p) were dry (having the radiative properties of the dry covering material). Of course, this is only an equivalent value, since condensation on greenhouse covers is almost never uniformly spread. As a first approximation, this equivalent wet fraction of the cover p is computed as the ratio of the actual equivalent film thickness and the maximum (equivalent) film thickness.

3.2.2. Condensation on and evaporation from the floor

Since the floor is assumed to be entirely covered by a white PE foil, all the water that condenses onto the floor must reevaporate again, so that there is no run-off. Futhermore, the contribution of the condensate film to the heat capacity of the first soil layer may always be neglected. Here again, the far infrared radiative properties of water are used for a wet floor. As the floor is always opaque to far infrared radiation, the model stability is never in danger here.

3.2.3. Condensation on the vegetation

The presence of a water film on the vegetation must be avoided in view of the prevention of plant diseases. As the thickness of the water film is unimportant, condensation flux densities on the leaves are not calculated. It is only controlled whether the leaf temperature is below the dewpoint temperature of the air or not.

3.2.4. Transpiration of the crop

The U.D.G.C.M. - though very flexible - has been developed, calibrated and validated for a soilless culture of tomato plants. Since for the study of condensation phenomena in greenhouses, it is important to know the transpiration flux of the canopy fairly accurately, it is necessary to use a tomato crop transpiration model including at least the two most important factors influencing the transpiration: the solar radiation flux density reaching the plant, and the water vapour pressure deficit between the leaves and the surrounding air. Here again, the U.D.G.C.M. allows the user to choose among several possiblities or to add additional descriptions. The transpiration rate is calculated by considering the canopy as a "big leaf". The model for the description of the stomatal resistance used for the present study was the one of Jolliet & Bailey (1994), while the mass transfer resistance of the boundary layer of the leaves was calculated according to boundary layer theory.

3.3. Practical implementation

The system of differential equations is worked out by TRNSYS, a computer package developed by the "Solar Energy Laboratory" at the "University of Wisconsin-Madison" for the treatment of solar energy problems, and described in Klein et al. (1988). The timestep for integration is normally one minute. In this way, simulating a whole year on a 486DX2-66MHz PC takes about 0.75 hours.

4. METHODOLOGY

By means of the above described model, simulations of the internal greenhouse climate were carried out for a whole year and for 12 different single layer greenhouse claddings. To investigate the influence of condensation on the energy demand, on the several heat fluxes and on the inside climate, the simulations were run twice: once by means of the complete model, taking into account the latent heat fluxes, and once with a modified version of the model, in which all the latent heat fluxes (except for the transpiration of the crop) were fixed at 0. Comparing both series of simulation results then allowed for an evaluation of the importance and impact of condensation.

4.1. Greenhouse description

The characteristics of the greenhouse system, except for the parameters related to the cladding material, were taken from Pirard et al. (1993), who determined these values for the validation of the model on a multispan Venlo type greenhouse. These characteristics can also be found in Pieters et al. (1996c).

Values of the solar radiation characteristics of the several claddings were taken from Nijskens et al. (1985). According to measurements for claddings on actual greenhouses, their values were to be lowered by about 6-7 % to account for the effect of dust and ageing. Values for the far infrared radiative properties (emittance ε, transmittance τ and reflectance ρ) were taken from Nijskens et al. (1984). Since they are predominant for the thermal insulation properties of the cladding materials, these values for clean new materials are listed in Table 2, where the common abbreviations for plastics are used.

Table 2 Far infrared radiative properties of the claddings [-]

	ε (outs.)	ε (ins.)	τ	ρ (outs.)	ρ (ins.)
EVA	0.59	0.59	0.38	0.03	0.03
Thermal PE “PEth”	0.79	0.79	0.18	0.03	0.03
PVC (film) “PVCf”	0.62	0.62	0.33	0.05	0.05
Reinforced PVC “PVCr”	0.69	0.69	0.16	0.15	0.15
Standard glass “SG”	0.90	0.90	0.00	0.10	0.10
Low emiss. glass “LEG”	0.20	0.90	0.00	0.80	0.10
PMMA	0.93	0.93	0.00	0.07	0.07
PC	0.91	0.91	0.00	0.09	0.09
PCt	0.81	0.81	0.10	0.09	0.09
PVC (plate) “PVCp”	0.85	0.85	0.08	0.07	0.07
PP	0.45	0.45	0.50	0.05	0.05
Ideal material “IM”	0.00	0.00	0.00	1.00	1.00

The ideal material is an imaginary one, not intercepting the solar radiation but totally reflecting the far infrared radiation. It is clear that such material is not likely to be found or developed. It is only used as a reference, allowing to assess some maximal performance of the greenhouse.

4.2. Climate data and setpoints

The climatic data were those of the typical reference year, established by Dogniaux et al. (1978) and containing weather data for every 30 minutes of a typical year in Belgium (having a temperate maritime climate). It was built by taking the climate registration data of several periods (mostly one month) of the 1950's, 1960's and 1970's, considered as being most representative for the Belgian climate during that period of the year and by bringing them together till a whole year was covered.

Active greenhouses were assumed. Hence, setpoint temperatures for ventilation and heating had to be specified. During the whole simulation period a constant heating and ventilation temperature regime was maintained. During daytime - determined by an astronomical clock - the heating setpoint temperature was fixed at 19 °C, while the ventilation setpoint temperature was 20 °C. For nighttime, these values were 17 °C and 18 °C, respectively. A linear light dependent increase of the daytime ventilation setpoint temperature was provided from a global solar energy flux density of 200 $W \cdot m^{-2}$ on and with a maximum of 2 °C (i.e., the maximum ventilation setpoint temperature was 22 °C) for a solar energy flux density of 500 $W \cdot m^{-2}$ or higher. Two transition periods between night- and daytime, in which intermediate setpoint temperatures and maximum setpoint temperature change rates were imposed, were introduced to avoid abrupt temperature changes in the greenhouse and to prevent an overload of the heating system.

The air renewal rate was assumed to be proportional to the difference between the actual inside air temperature and the ventilation setpoint temperature. For a difference of 0 °C or lower, a minumum air renewal rate of 0.2 hr^{-1} was adopted, while for a difference of 3 °C or higher, the air renewal rate was limited at its maximal value of 40.2 hr^{-1}.

Since the auxiliary heating requirement is one of the parameters of interest in this study, a perfect heating system was assumed, i.e., for temperatures above the heating setpoint temperatures the heating system was not active, while in all other cases, the desired temperature was reached for every minute of the year.

4.3. Vegetation data

In the simulations, the culture started on 1 December, the plants having a leaf area index (LAI), expressed per unit cultivated greenhouse floor area, of 1.5 and a vegetation mass surface density of 0.5 $kg{\cdot}m^{-2}$. After 3.5 months the LAI was assumed to have reached linearly its maximum value of about 4.5, after which it remained constant. The vegetation mass surface density first increased slowly to about 1 $kg{\cdot}m^{-2}$ after 1.5 months, then rapidly increased towards its maximum and final value of 10 $kg{\cdot}m^{-2}$ after 5 months. In a similar way, the cultivated fraction of the greenhouse floor area was assumed to grow from 0.1 on 1 December to its final value 0.9 after 3.5 months. The leaf area index LAI_g, expressed per unit greenhouse floor area, which is simply obtained as the product of the leaf area index LAI (expressed per unit cultivated greenhouse floor area) and the cultivated fraction of the greenhouse floor area, thus increased from 0.15 to 4.05 during the growing season.

These linear growth functions were based on the measurements of Pirard et al. (1992). The linear approach of the smooth growth curves is certainly acceptable since defoliations and other human interventions disturb the normal development of the tomato plants. Furthermore, it was found that, for thermodynamic simulation, the results are loosely bound to the detailed shape of these growth curves.

5. RESULTS AND DISCUSSION

5.1. Auxiliary heating requirements

Table 3 summarizes the auxiliary heating requirements (AHR) for the several greenhouses, as simulated by the complete model and by the model omitting the condensation and evaporation phenomena. Materials are ranked in order of AHR, simulated by the complete model. The last column gives the ranking number obtained when condensation and evaporation are not included. The error made in the latter case is expressed as the fraction of the AHR obtained by means of the complete model.

The absolute values are rather low, due to the simulation circumstances that were adopted. Furthermore, calculating the heat requirement implies that heat losses in pipes and less than unity efficiencies of the heating system are not taken into account. Since for this comparative study, only the relative values are important, this is of course no problem. From Table 3 it can be concluded that when condensation is neglected, the sequence of the materials from lowest to highest AHR is the same as the sequence from lowest to highest transmittance for far infrared radiation. This sequence is also the one that can be established by means of the standardized overal heat transmission coefficients (so-called k- or U-values), at least if the far infrared radiative properties are included. However, for comparing the performances to be expected on a yearly basis under real circumstances, this method seems to be too simple for greenhouses where condensation occurs during most of the time. As can be seen in Table 3, the occurrence of condensation completely alters the heat transfer through the several materials

Table 3 Survey of the AHR for the several greenhouses simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation

# / +	cladding	τ (IR)	AHR / + [MJ/(m^2·yr)]	AHR / - [MJ/(m^2·yr)]	Error [%]	# / -
1	IM	0.00	1076	589	-45	1
2	LEG	0.00	1282	1075	-16	2
3	PP	0.50	1431	1785	+25	12
4	EVA	0.38	1483	1705	+15	11
5	PVCf	0.33	1510	1652	+9	10
6	PVCr	0.16	1525	1442	-5	6
7	PEth	0.18	1552	1547	-0	9
8	PCt	0.10	1588	1447	-9	8
9	PVCp	0.08	1606	1446	-10	7
10	PMMA	0.00	1619	1380	-15	5
11	SG	0.00	1629	1357	-17	3
12	PC	0.00	1632	1365	-16	4

and consequently, the order from best to worst insulating material is completely changed. This can be explained by the following (opposite effects) of condensation :

- on the opacity to far infrared radiation;

  Since water is opaque to far infrared radiation, the presence of a condensate layer eliminates the direct radiative heat loss from the vegetation and the floor through the cladding to the sky. For a cladding already opaque in the dry state, this effect is not a benefit.
- on the inner surface emittance;

  Water has a very high far infrared radiation emittance of 0.93. This implies that the net radiative heat flux from the floor and the vegetation will be higher if the cover is wet for nearly all the materials under investigation.
- on the latent heat flux.

  During the condensation process, latent heat is brought from the inside air to the cover.

For materials that are highly transparent to far infrared radiation, the effect of the eliminated direct radiative heat loss from the vegetation and the floor to the sky is much higher than the effect of the latent heat transfer and the higher radiative heat flux to the inner cover surface (due to the increased emittance). As a consequence, the magnitude of the reduction or increase of the AHR due to the neglection of inclusion of condensation effects is of course related to the radiative properties of the claddings : the higher the transmittance the more important the reductions are. Values for the actually used materials are seen to be situated between -17 % for SG and +25 % for PEth. From column 6 of Table 3, it can be concluded that for these simulation circumstances, the “break-even” value for the transmittance is about the one for PEth, namely 18 %, which is rather low when compared to the values found by Pieters (1996) for static circumstances and in the absence of solar radiation, which were mentioned in the Literature review.

The fact that in the presence of condensation only the outside radiative properties differ for the different cladding materials, explains why the performance of the materials in the presence of condensation is almost completely determined by their outside surface emittance.

As a general conclusion, it can be stated that for both dry and wet circumstances, materials having a very high reflectance to far infrared radiation give rise to the lowest AHR. This is also clearly demonstrated by the results for the ideal material, which performed best for both series of simulations. As can be seen, low emissivity glass, having an outside reflectance of about 0.80, approaches this ideal situation the best.

It was also observed that for all materials the reduction or the increase of the AHR is subjected to small seasonal variations. Fig. 2 gives the monthly AHR for PCt obtained with both models (including and neglecting condensation and evaporation).

As can be seen, the relative effect of condensation is generally smallest during summer. The highest relative difference between the results for the two versions of the model is not found during winter but during April. This is to be explained by the fact that during winter, the transpiration flux densities of the little plants are very small, so that transpiration flux densities are also small. This results in a rather small condensation flux density to the cover, but at the same time in an almost complete coverage of the cladding by water, annuling the direct radiative heat fluxes from the inside to the sky. From Fig. 2, it can be seen that during the first month of the culture period (December), the beneficial effect of condensation is the strongest, in contrast to the situation for the other months.

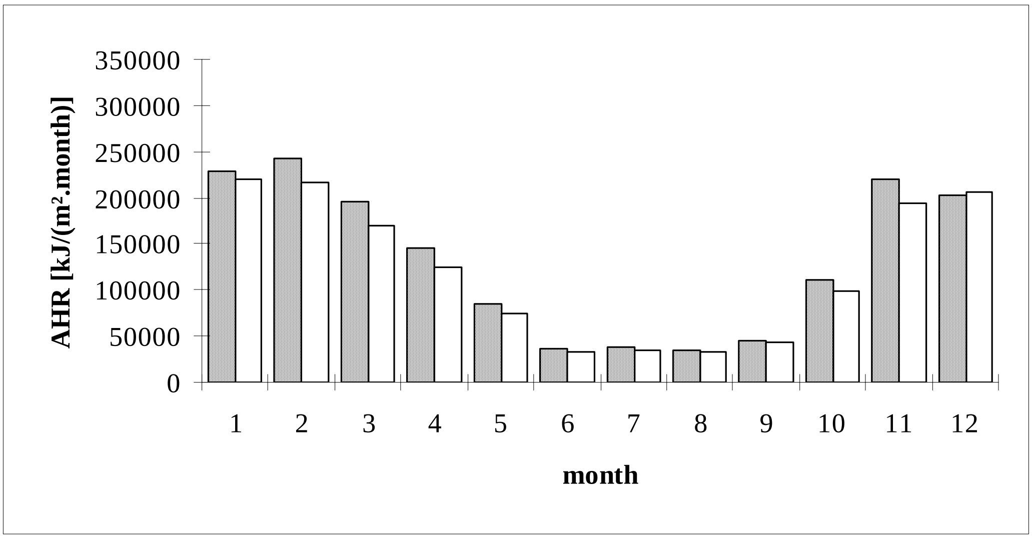

Fig. 2 Monthly AHR for a PCt covered greenhouse, simulated by the complete model (grey bars) and by the model neglecting condensation phenomena (white bars)

5.2. Humidity levels and latent heat fluxes

Table 4 gives the yearly average daytime and nighttime relative humidities (RH) in the several greenhouses, in the order of decreasing humidity levels. Again values obtained by means of the model including and by means of the one neglecting condensation and evaporation are given.

Table 4 Resulting yearly average daytime and nighttime RH for the several greenhouses, simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation [%]

		day			night		
	ε (IR)	+	-	error	+	-	error
IM	0.00	83	93	10	85	96	11
LEG	0.20	84	92	8	84	93	9
PP	0.45	84	91	7	83	88	6
EVA	0.59	83	91	7	82	89	8
PVCf	0.62	83	91	8	82	90	8
PVCr	0.69	83	91	8	81	91	10
PEth	0.79	83	91	8	81	91	10
PCt	0.81	83	91	9	81	91	11
PVCp	0.85	83	91	9	81	92	11
SG	0.90	83	92	9	80	92	12
PC	0.91	83	92	9	80	92	12
PMMA	0.93	83	92	9	80	92	12

From this table, it can be seen that neglection of condensation leads to an overestimation of the RH by on average 10 %, since in that case no water vapour is removed from the inside air by condensation. Since condensation fluxes are somewhat higher during nighttime, the corresponding errors are also higher. From Fig. 3, giving the average values for each week since the start of the culture period (starting on 1 December) for the LEG covered greenhouse, it follows that the differences are almost negligible during summer, while they are highest during winter and mainly during the growth phase of the crop.

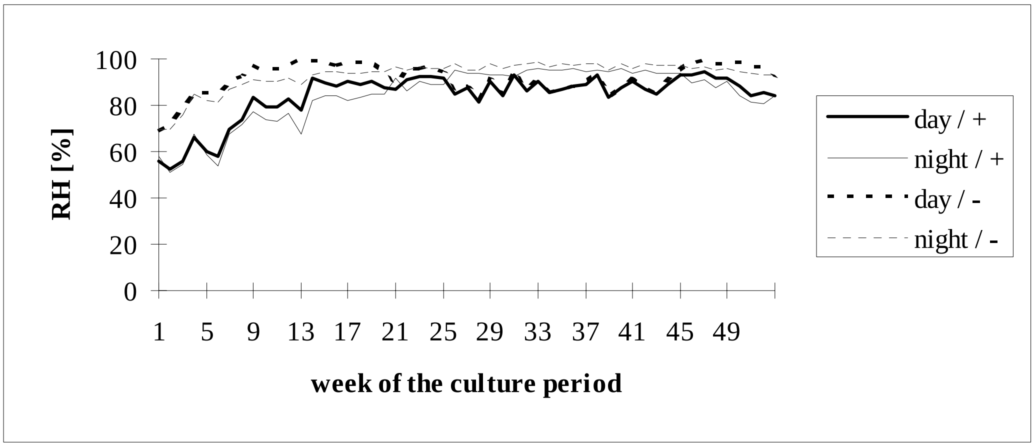

Fig. 3 Weekly average RH values for a LEG covered greenhouse, simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation

From Table 4, it can also be concluded that for the claddings considered here, there are nearly no differences between the respective yearly average daytime RH, whereas for nighttime values, differences can be as large as 5 %. It is found that the order of decreasing humidity in the greenhouse exactly matches the order of increasing far infrared radiation emittance. This was to be expected, since in the case of condensation, higher emittances give rise to higher heat losses from the cover and consequently to higher condensation fluxes and lower RH in the greenhouse. This complies with the experiences of growers using low emissivity claddings. It is also illustrated by Table 5, where yearly total latent heat flux densities are listed together with the relative contribution of condensation to the water vapour removal from the inside air for the several greenhouses.

Table 5 Total yearly latent heat flux densities to and from the cover and the floor and relative contribution of condensation to the water vapour removal from the inside air

	ε (IR)	cond. flux dens. cover [MJ/(m^2·yr)]	evap. flux dens. cover [MJ/(m^2·yr)]	cond. flux dens. floor [MJ/(m^2·yr)]	contribution to vapour removal [%]
IM	0.00	410	-21	1.3	79
LEG	0.20	408	-12	4.7	83
PP	0.45	449	-11	5.0	87
EVA	0.59	477	-24	4.3	88
PVCf	0.62	482	-24	4.2	88
PVCr	0.69	494	-24	3.5	88
PEth	0.79	512	-23	3.5	89
PCt	0.81	510	-11	4.3	89
PVCp	0.85	516	-11	4.2	89
SG	0.90	524	-11	3.6	89
PC	0.91	526	-11	4.0	89
PMMA	0.93	531	-11	3.6	89

In Table 5, materials are given in the sequence of increasing net total yearly latent heat flux density to the cover, i.e., the sum of columns 3 and 4. It can indeed be seen that this sequence is exactly the same as the one of increasing emittance for far infrared radiation. As a result, the yearly total condensation flux density in the LEG covered greenhouse (158 l/m^2) is about 30 % lower than in the greenhouse covered with a single PMMA plate (208 l/m^2).

For the cover, the evaporation fluxes are about an order of magnitude lower than the condensation fluxes. This means that nearly all water that condenses onto the cover is evacuated via the condensation gutters, while only a small fraction reevaporates. It is seen that for most materials, a higher emittance in the spectrum of far infrared radiation gives rise to a lower evaporation flux, as was to be expected, since evaporation is most likely to occur in the most insulating greenhouses. As an example, monthly total condensation and evaporation flux densities are given for EVA in Fig. 4. Evaporation is only observed during summer, while condensation flux densities are highest during the early spring, since in winter the young and little plants do not bring much water in the air.

The results of Table 5 point out that condensation and consequently evaporation flux densities to the floor are always negligible. Condensation fluxes are only about 1 % of the corresponding values for the cover. Condensation on the floor is mainly observed during spring when the soil, having a very high thermal inertia, is relatively cool with respect to the surroundings. For the simulation circumstances and for the materials investigated in this study, no condensation on the vegetation was observed.

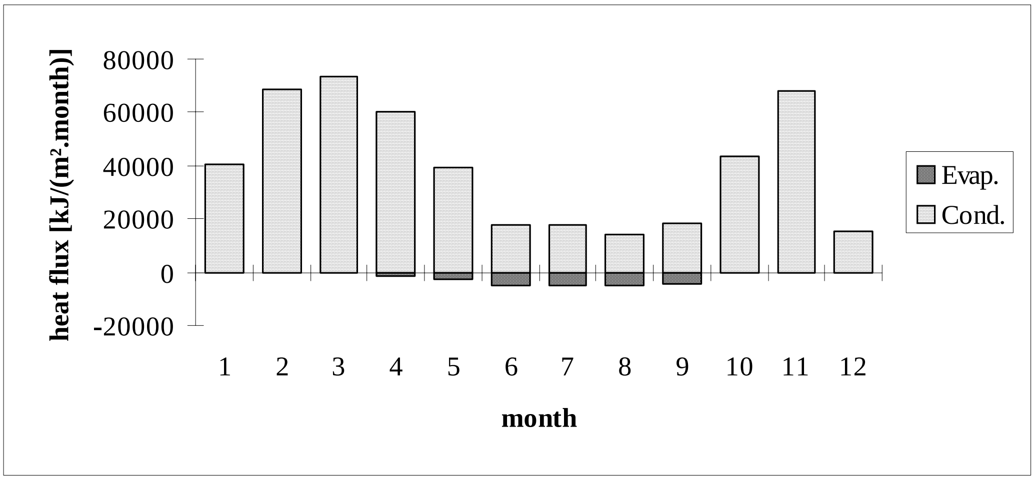

Fig. 4 Monthly latent heat flux densities to or from the cover for an EVA covered greenhouse

Humidity in the greenhouse is mostly not actively controlled. However, an appropriate humidity level is very important. When the inside air is too dry, the plants will of course wilt. In greenhouses, problems with humidity levels are mostly related to air that is too moist, slowing down the growth of plants and fruits. Excess water vapour is normally evacuated by ventilation. However, since energy prices have increased, ventilation systems mainly aim at keeping the inside air temperature within some predefined optimum zone. Control of humidity is mostly a secondary task of the ventilation system, for which only smaller modifications in the ventilation rates are allowed. Values in the last column of Table 5 allow to assess to what extent ventilation and condensation contribute to the nighttime water vapour removal from the greenhouse. It is seen that condensation is the far most important sink of water vapour; for nearly all greenhouses, it is responsable for 88 to 89 % of the nocturnal dehumidification of the greenhouse air. Only for the IM and the LEG covered greenhouses, the role of condensation is slightly less important. This implies that activally controlling the humidity by ventilation is indeed very difficult during nighttime, since increasing the air renewal rate will not only increase the direct water vapour removal to the outside air, but also decrease the water vapour removal by condensation. Of course, since the relative contribution of ventilation is higher in summer (up to 30 %), the efficiency of ventilation for removing water vapour will also be higher during this period.

5.3. Inside air and vegetation temperatures

Although neglection of condensation and evaporation was seen to give rise to relatively important errors of between 0.5 and 1°C on the yearly average cover temperature, this case will not be treated here. The discussion will be restricted to the inside air temperature, the vegetation temperature and the temperature difference between plants and air, because of the importance of the first in current climate control strategies and because of the physiologycal importance of the other two parameters.

5.3.1. Inside air temperature

Since active greenhouses were assumed for these simulations, neglection of condensation did not lead to significant errors in simulating the inside air temperature. Fig. 5 gives the example of the PP covered greenhouse.

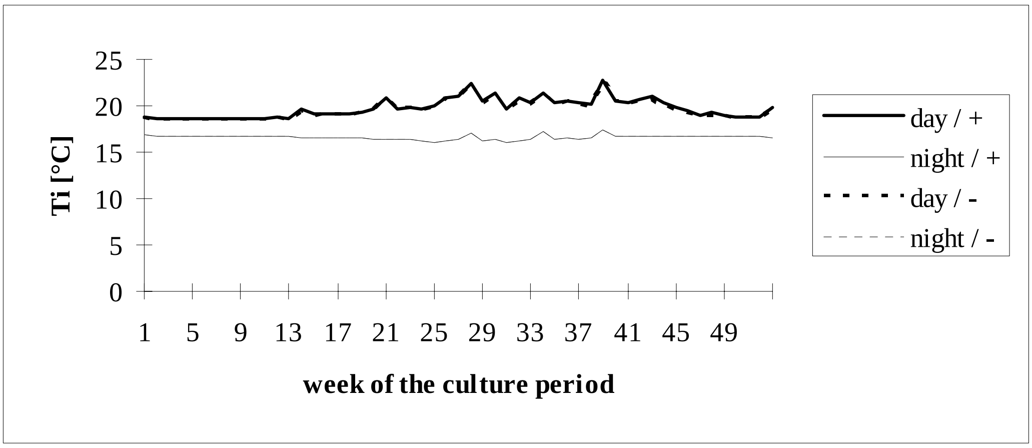

Fig. 5 Weekly average inside air temperature (Ti) values for a PP covered greenhouse, simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation

The inside air temperature is probably the main parameter in validating (greenhouse) climate simulation programs. This might explain why models, neglecting the condensation and evaporation phenomena or treating them only in an approximative way, are so widely used, although they lead to important errors in estimating the AHR or the RH, as demonstrated above.

Differences in yearly mean inside air temperatures were of course also insignificant, since the same setpoints were imposed to all greenhouses.

5.3.2. Vegetation temperature and temperature difference

Since photosynthesis by leaves is a temperature dependent process, the vegetation temperature is very important with respect to plant growth and fruit setting. In this view, it is not important to control the inside air temperature, but the vegetation temperature. Of course, it can be expected that the vegetation temperature will be closely related to the inside air temperature, so that for climate control systems, the inside air temperature is nowadays still the parameter of interest.

Since plants need energy for transpiration, the leaf temperature is mostly somewhat lower than the surrounding air temperature. But when exposed to high radiation levels, their temperature on sunshiny summer days might also be higher. This can be seen in Figs. 6 and 7, giving the weekly average temperature differences between the vegetation and the inside air for a SG and a PP covered greenhouse.

Fig. 6 clearly shows that for glass products, neglection of condensation leads to an important underestimation of the temperature difference and thus also to an overestimation of the vegetation temperature. The largest errors are found for wintertime. This can be simply explained by the fact that condensation (which is most important during winter) withdraws a lot of water vapour from the air. As already discussed in section 5.2., this leads to an important decrease of the RH of about 10 %. Since the air becomes dryer when condensation goes on, the evaporation of the plants is stimulated, so that part of their sensible heat is converted into latent heat, resulting in a lower vegetation temperature.

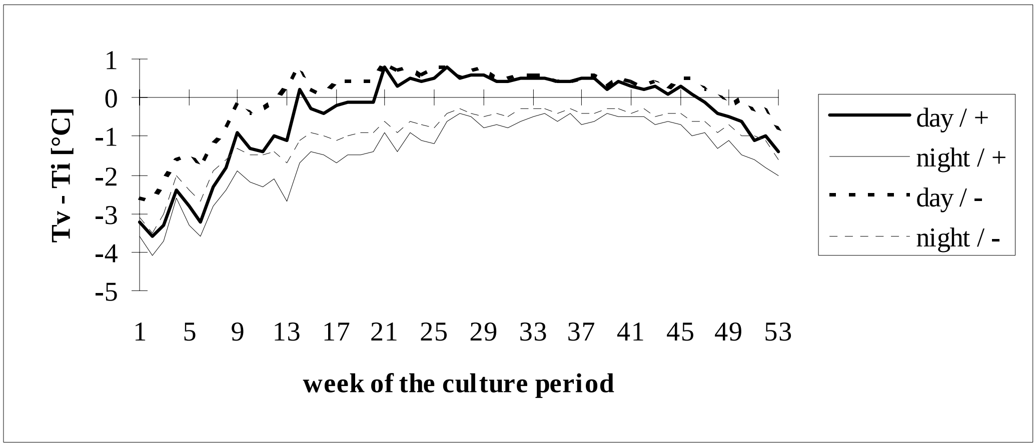

Fig. 6 Weekly average temperature differences between the vegetation and the inside air (Tv - Ti) for a SG covered greenhouse, simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation

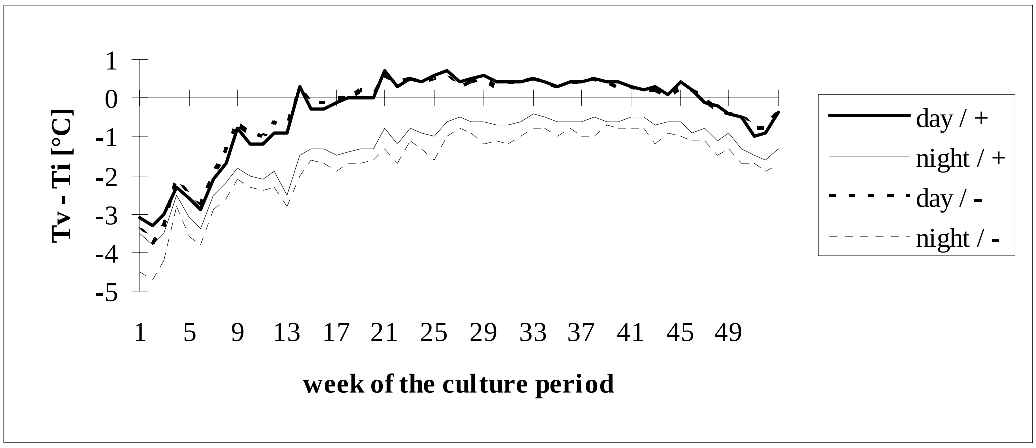

Fig. 7 Weekly average temperature difference between the vegetation and the inside air (Tv - Ti) for a PP covered greenhouse, simulated by (+) the complete model and by (-) the model neglecting condensation and evaporation

From Fig. 7, it can be concluded that daytime values obtained for the PP covered greenhouse by means of the complete model on the one hand and by means of the model neglecting condensation and evaporation on the other hand, do not differ much. For nighttime values, however, the model neglecting condensation is seen to give rise to an overestimation of the temperature difference, in contrast to what was found for glass. For materials that are highly transparent to far infrared radiation, the heat loss of the plants due to enhanced transpiration during condensation is more than compensated for by the fact that at the same time less sensible heat is lost since the wet cover annules the direct far infrared radiative heat loss from the vegetation to the sky. As a consequence, overestimation of the vegetation temperature and consequent underestimation of the temperature difference between the vegetation and the inside air are found to become smaller or even inversed for increasing values of the far infrared radiative transmittance of the cladding material.

As already stated, the vegetation temperature is a very important parameter with respect to plant growth, while the temperature difference between the vegetation and the inside air determines the vapour pressure deficit and consequently the transpiration flux density. The fact that the temperature difference between vegetation and inside air varies not only according to the greenhouse cladding, but also according to the weather circumstances, makes clear that the use of the inside air temperature as the controlled parameter in current climate regulation systems is not sufficient. As already argued, the vegetation temperature should be considered too. To this end, feedback systems could be used, measuring the leaf temperature by e.g. needle thermocouples. However, as this kind of thermocouples must be treated very carefully, they cannot be used in actual greenhouses, where plants are handled quite often. Another solution is the use of computer models, such as the U.D.G.C.M. for use as feedforward mechanisms in existing climate regulation systems. As has been shown here, such models will have to contain thorough descriptions of the condensation and evaporation phenomena in the greenhouse to be reliable.

6. SUMMARY AND CONCLUSIONS

The Universal Dynamic Greenhouse Climate Model (U.D.G.C.M.) was used to simulate the effect of condensation and evaporation on the auxiliary heating requirements, on the inside air humidity and temperature and on the vegetation temperature in greenhouses covered with 12 different cladding materials.

For the circumstances of the simulations, condensation was shown to increase the auxiliary heating requirements for materials having a far infrared radiation transmittance lower than 0.18, and to reduce them for all other materials. For the materials investigated in this study, the savings ranged between +25 % for PP and -17 % for standard glass. Thermal insulation properties were shown to depend entirely on the far infared radiation transmittance in the absence of condensation, while in the presence of condensation, the outside surface emittance was found to be predominant, implying that the status of the cover (dry / wet) completely changes the classical cladding sequence from poorly to highly insulating materials. Materials completely reflecting all far infrared radiation could be shown to be best insulating under both wet and dry conditions.

It was also demonstrated that neglecting condensation and evaporation gives rise to an overestimation of the yearly average inside air relative humidity of about 10 % for most materials. Since condensation fluxes were found to be lowest in greenhouses cladded with low emissivity materials, yearly average relative humidities were somewhat lower in this kind of greenhouses. This also explains why the relative contribution of condensation to the nighttime water vapour removal from the inside air was found to be lower for low emissivity cladded greenhouses (79-83 %) when compared to the other greenhouses (88-89 %). Evaporation fluxes from the cover as well as condensation fluxes to the floor were shown to be negligible when compared to condensation fluxes to the cover.

Neglection of condensation was shown to have nearly no effect on the simulated temperature of an active greenhouse, whereas it can result in an overestimation or an underestimation of the vegetation temperature, according to the outside climate conditions and to the cladding's far infrared radiation transmittance, high transmittances giving rise to underestimates, underlining the necessity of considering the vegetation temperature in greenhouse climate control systems.

As a general conclusion, it might be stated that greenhouse climate models for use in climate control systems cannot do without a detailed description of condensation and evaporation phenomea inside the greenhouse.

7. REFERENCES

Ahmadi, G. & Glockner, P.G. (1982). Dynamic simulation of the performance of an inflatable greenhouse in the southern part of Alberta. I. Analysis and average winter conditions. Agricultural Meteorology, **27**, 155-180. Cited in de Halleux (1989).

Arinze, E.A., Schoenau, G.J. & Besant, R.W. (1984). A dynamic thermal performance simulation model of an energy conserving greenhouse with thermal storage. Transactions of the ASAE, **27**, 508-519. Cited in de Halleux (1989).

Avissar, R. & Mahrer, Y. (1982). Verification study of a numerical greenhouse microclimate model. Transactions of the ASAE, **25**, 1711-1720.

Bot, G.P.A. (1983). Greenhouse climate : from physical processes to a dynamic model. Ph.D. thesis, Wageningen, The Netherlands, Landbouwhogeschool, 240 p.

Cooper, P.I. & Fuller, R.J. (1983). A transient model of interaction between crop, environment and greenhouse structure for predicting crop yield and energy consumption. Journal of agricultural Engineering Research, **28**, 401-417. Cited in de Halleux (1989).

Cormary, Y. & Nicolas, C. (1985). La thermique des serres. Coll. de la Direction des Etudes et Recherches d'Electricité de France. Paris, France, Vol. **58**, 357 p. Cited in de Halleux (1989).

de Halleux, D. (1989). Modèle dynamique des échanges énergétiques des serres : étude théorique et expérimentale. Ph.D. thesis, Gembloux, Belgium, Faculté des Sciences Agronomiques de Gembloux, 278 p.

de Halleux, D., Deltour, J., Nijskens, J., Nisen, A. & Coutisse, S. (1985a). Dynamic simulation of heat fluxes and temperatures in horticultural and low-emissivity glass-covered greenhouses. Acta Horticulturae, 170, 91-96.

de Halleux, D., Nijskens, J., Deltour, J., Coutisse, S. & Nisen A. (1985b). Effet de la condensation sur les transferts thermiques des couvertures de serres : cas du verre et du polyéthylène. Plasticulture, 66, 19-26.

Deltour, J., de Halleux, D., Nijskens, J., Coutisse, S. & Nisen, A. (1985). Dynamic modelling of heat and mass transfer in greenhouses. Acta Horticulturae, 174, 119-126.

Dogniaux, R., Lemoine, M. & Sneyers, R. (1978). Année-type moyenne pour le traitement de problèmes de captation d'énergie solaire. Misc. sér. B, n^{o} 45. Institut Royal Météorologique de Belgique, Bruxelles, 48 p.

Feuilloley, P., Issanchou, G., Jacques, J.-C., Guillaume, S., Mekikdjian, C., Mirabella, J.-F. & Merlot, A. (1994). Films plastique de couverture de serre. Condensations et propriétés thermiques. Résultats de mesure. Plasticulture, 103, 2-10.

Garzoli, K.V. & Blackwell, J. (1981). An analysis of the nocturnal heat loss from a single skin plastic greenhouse. Journal of agricultural Engineering Research, **26**, 203-214.

Glaub, J.C. & Trezek, G.J. (1981). Heat and mass transfer analysis of greenhouses. ASAE paper 81-4031. Cited in de Halleux (1989).

Jolliet, O. & Bailey, B.J. (1994). The effect of climate on tomato transpiration in greenhouses : measurements and models comparison. Agricultural and Forest Meteorology, **58**, 43-62.

Kimball, B.A. (1986). A molecular energy balance program including subroutines for greenhouses and other latent heat devices. ARS 33, Agricultural Research Service, United States Department of Agriculture, United States of America, 356 p. Cited in de Halleux (1989).

Kindelan, M. (1980). Dynamic modeling of greenhouse environment. Transactions of the ASAE, **23**, 1232-1236.

Klein, S.A., Beckman, W.A., Cooper, P.I., Duffie, N.A., Freeman, T.L., Mitchell, J.C., Beekman, D.M., Oonk, R.L., Hughes, P.J., Eberlein, M.E., Karman, V.D., Pawelski, M.J., Utzinger, D.M., Duffie, J.A., Brandemuehl, M.J., Arny, M.D., Theilacker, J.C., Morrison, G.L., Clark, D.A., Braun, J.E., Evans, B.L. & J.P. Kummer. (1988). TRNSYS. A transient system simulation program. Engineering experiment station report 38-12, Solar Energy Laboratory, University of Wisconsin-Madison, USA.

Lacroix, R. (1987). La condensation sur divers matériaux de recouvrement de serre. Rapport de recherche présenté au Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, Université du Québec, Canada, 51 p.

Lacroix, R. (1988). Etude comparative de la structure des modèles de transfert d'énergie et de masse dans les serres de production. Rapport de recherche (Maîtrise en sciences de l'environnement). Université du Québec à Montréal, Montréal, Canada, 118 p. Cited in de Halleux (1989).

Nijskens, J., de Halleux, D. & Deltour, J. (1991). Sensitivity study of a greenhouse climate dynamic model. Bulletin des Recherches Agronomiques de Gembloux, **26**, 389-410.

Nijskens, J., Deltour, J., Coutisse, S. & Nisen, A. (1984). Heat transfer through covering materials of greenhouses. Agricultural and Forest Meteorology, **33**, 193-214.

Nijskens, J., Deltour, J., Coutisse, S. & Nisen, A. (1985). Radiation transfer through covering materials, solar and thermal screens of greenhouses. Agricultural and Forest Meteorology, **35**, 229-242.

Pieters, J. (1996). Influence of condensation and rain on the heat transfer coefficient of greenhouse claddings. Agricultural Engineering Journal, **5**, 1-17.

Pieters, J. & Deltour, M. (1997). Greenhouse climate modelling. From Fundamental thermodynamics to detailed climate mechanism. In preparation.

Pieters, J.G., Deltour, J.M. & Debruyckere, M.J. (1994). Influence of condensation on static heat transfer through greenhouse covers during night. Transactions of the ASAE, **37**, 1965-1972.

Pieters, J.G., Deltour, J.M. & Debruyckere, M.J. (1995). Onset of condensation on the inner and outer surface of greenhouse covers during night. Journal of agricultural Engineering Research **61**, 165-171.

Pieters, J., Deltour, J. & Debruyckere M. (1996a). Numerical method for the determination of the geometry and light transmittance of real drops on transparent materials. Journal de Physique III, **6**, 975-989.

Pieters, J., Deltour, J. & Debruyckere, M. (1996b). Condensation and dynamic heat transfer in greenhouses. Part I : Theoretical model. Agricultural Engineering Journal, **5**, 119-133.

Pieters, J., Deltour, J. & Debruyckere, M. (1996b). Condensation and dynamic heat transfer in greenhouses. Part II : Results for a standard glasshouse. Agricultural Engineering Journal, **5**, 135-148.

Pieters, J., Deltour, J. & Debruyckere, M. (1997). Simulation of light transmission through condensation drops on glass and polyethylene. Accepted for publication in “Agricultural and Forest Meteorology”.

Pirard, G., Vancayemberg, F. & Deltour, J. (1992). Rapport d'activités d'août 1992. Centre d'Etude de la Régulation Climatique des Serres (I.R.S.I.A.), Gembloux, Belgium, 125 p.

Pirard, G., Vancayemberg, F. & Deltour, J. (1993). Rapport d'activités de décembre 1993. Centre d'Etude de la Régulation Climatique des Serres (I.R.S.I.A.), Gembloux, Belgium, 71 p.

Pirard, G., Vancayemberg, F. & Deltour, J. (1994). Rapport d'activités de décembre 1994. Centre d'Etude de la Régulation Climatique des Serres (I.R.S.I.A.), Gembloux, Belgium, 143 p.

Seginer, I. & Kantz, D. (1989). Nighttime use of dehumidifiers in greenhouses : an analysis. Journal of Agricultural Engineering Research, **44**, 141-158.

Selcuk, M.K. (1970). Use of digital computers for the heat and mass transfer analysis of controlled environment greenhouses. Proceedings, First symposium on the use of computers for engineering related to buildings. National bureau of standards. Gaithersburg. Md. 557-577. Cited in de HALLEUX (1989).

Silveston, P.L., Costigane, W.D., Tiessen, H. & Hudgins, R.R. (1980). Energy conservation through control of greenhouse humidity. I. Condensation heat losses. Canadian Agricultural Engineering, **22**, 125-132.

Soribe, F.I. & Curry, R.B. (1973). Simulation of lettuce growth in an air-supported plastic greenhouse. Journal of agricultural Engineering Research, **18**, 133-140. Cited in de Halleux (1989).

Stoffers, J.A. (1990). Influence of material properties on greenhouse climate. Acta Horticulturae, 281, 231-245.

Takakura, T., Jordan, K.A., & Boyd, L.L. (1971). Dynamic simulation of plant growth and environment in the greenhouse. Transactions of the ASAE, **14**, 964-971.

Van Bavel, C.H.M. & Sadler, E.J. (1979). A computer simulation program for analysing energy transformations in a solar greenhouse. Mimeographed report. Texas A&M University, SG79, Texas, United States, 75 p. Cited in de Halleux (1989).

Walker, J.N. & Walton, L.R. (1971). Effect of condensation on greenhouse heat requirement. Transactions of the ASAE, **14**, 282-284.

Yang, X., Short, T.H., Fox, R.D. & Bauerle, W.L. (1990). Dynamic modeling of the microclimate of a greenhouse cucumber row crop part I. Theoretical Model. Transactions of the ASAE, **33**, 1701-1709.