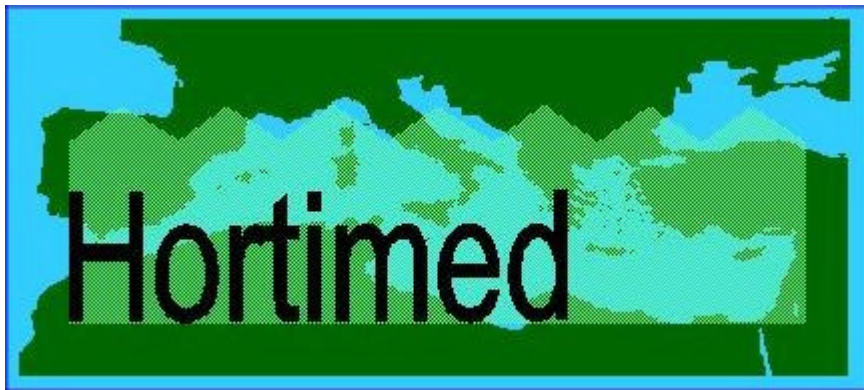


**SUSTAINABLE WATER USE IN PROTECTED  
MEDITERRANEAN HORTICULTURE**

**Project Number ICA3-1999-10027**



**DELIVERABLE 5**

**ARO-ISWES**  
**Agricultural Research Organization**  
**Bet Dagan, ISRAEL**

Prepared and written by Marcel Fuchs

## MULTIVARIATE ANALYSIS OF CLIMATIC AND PHYSIOLOGICAL FACTORS AFFECTING TRANSPIRATION IN RELATION TO WATER OR OSMOTIC STRESS ON GREENHOUSE CROPS.

### Executive summary

Deliverable 5 presents a procedure for evaluating the effect of independently varying external climatic factors on the transpiration of greenhouse crops under summer conditions. It predicts the crop canopy temperature, air temperature and humidity inside the greenhouse. It uses greenhouse construction characteristics as input parameters, and takes into consideration ventilation rate and plant water stress. The analysis also examines the effect of evaporative cooling for a greenhouse fitted with an evaporative wet pad. For any given cooling efficiency, the procedure evaluates the temperature and humidity of the air leaving the wet pad and evaporation rate from the wet pad.

### Introduction

Irrigation is always the water provider of plants grown in greenhouses. Proper management of the water input requires knowledge of the water consumption by plant transpiration. In modern greenhouses, nutrients are added to the irrigation water. Through this practice, water application entails also nutrient application associating water and mineral dosage. In the case of closed-loop irrigation systems, transpiration concentrates non-nutrient ions like  $\text{Na}^+$  and  $\text{Cl}^-$  in the irrigation solution. The raised osmotic potential of the root medium or by toxicity of the ions may harm the crop. Therefore, transpiration is an essential process determining the hydraulic and chemical environment of crop grown on artificial substrates in closed-loop systems. The purpose of this deliverable is to establish the relations between climatic, physiological factors and transpiration. A special effort is made to identify independent variables, and parameterize climate control operations to quantify their effect on transpiration and the internal microclimate in the greenhouse. An EXCEL workbook presents the results of the analysis in an interactive multivariate format that allows the user to manipulate the relevant independent inputs and the climate control operations like ventilation, shading and evaporative wet pad.

### Energy balance model

The energy balance is the scientific tool that establishes the relation between microclimate and transpiration of plants. For plant in greenhouses, the reduction of the solar radiation and spatial confinement caused by the cover material modify the plant aerial environment. Transpiration involves the endothermic transformation of water from liquid to vapor form. As such it is a physical process. Still, it depends on the plant ability to conduct water to the leaves where the transformation of liquid to vapor takes place. As plants have adapted to prevent the desiccation of their vital tissues, theory must include a physiological function of the plant that controls its vapor loss..

A model always gives an approximate image of reality. In the present case, we deal with the daytime energy balance of a greenhouse in a region with mild climate. The implications are:

1. There is no artificial heating
2. The ventilation is good, either by side and/or roof vents or exhaust fans.
3. The vegetation cover in the greenhouse is high (leaf area index > 3)

### *Solar radiation balance*

The solar radiation intercepted by the canopy of the crop  $S_i$  is:

$$S_i = s \frac{t_r S_o}{1 - r_r r_c} \quad (1)$$

$S_o$  solar radiation outside (0 to 1000 Wm<sup>-2</sup>)

$r_c$  solar reflection coefficient of the canopy ( $\sim 0.25$ ), constraint:  $r_c = 1$

$t_r$  solar transmission coefficient of the roof cover ( $\sim 0.6$ ), constraint:  $t_r + r_r = 1$

$r_r$  solar reflection coefficient of the roof cover ( $\sim 0.2$ )

$s$  empirical shading factor. If the greenhouse is fitted with a shading device, transmission and reflection coefficients of the roof are modified by the properties of the screen. A specific factor can be established for every shading configuration, but the empirical factor  $s < 1$  provide a simple way to account for the reduction in radiation transmission.

### Terrestrial radiation balance

The terrestrial radiation (radiation emitted by atmosphere, roof, crop or soil) in the greenhouse is approximately given by (for daytime):

$$\begin{aligned} R_i &= R_d + T_o + R_u + T_c \\ R_d + T_o &= 5.67 \cdot 10^{-8} \cdot 0.88 t_R + \epsilon_R T_o + 273.2^4 \\ R_u + T_c &= 5.67 \cdot 10^{-8} \cdot (t_R + \epsilon_R) T_c + 273.2^4 \end{aligned} \quad (2)$$

$T_o$  outside air temperature (°C)

$T_c$  crop canopy surface temperature (°C)

$t_R$  transmission coefficient for terrestrial radiation of the roof cover

(IR polyethylene  $\sim 0.3$ ; Glass  $\sim 0$ )

$\epsilon_R$  emission coefficient for terrestrial radiation of the roof cover

(IR polyethylene  $\sim 0.55$ ; Glass  $\sim 0.95$ )

Shading devices modify the effective  $t_R$  and  $\epsilon_R$ . Internal shading introduces a term depending on  $T_i$ , the temperature inside the greenhouse. Yet, the magnitude of this contribution to daytime radiation balance is minor and does not justify the additional complexity of the equations.

### Net radiation

As part of the solar radiation intercepted by the crop is reflected, the net radiation  $R_n$  is:

$$\begin{aligned} R_n &= S_a - R_i \\ S_a &= (1 - r_c) S_i \end{aligned} \quad (3)$$

where  $S_a$  is the solar radiation absorbed by the crop canopy.

### Sensible heat

The sensible heat  $H$ , is the heat exchange between the inside of the greenhouse and outside. It is also equal to the heat exchange between the crop canopy surface and the air inside the greenhouse through the air boundary layer of the leaves. As we deal with a well-ventilated greenhouse, we assume that the in-out heat exchange is only by air convection:

$$H = \rho c_p \frac{T_i - T_o}{r_x} = \rho c_p \frac{T_c - T_i}{r_b / LAI} \quad (4)$$

$\rho$  air density =  $1.293 \frac{273.2}{T_o + 273.2} \frac{P}{101.3}$  kg m<sup>-3</sup>, depends on air temperature T in

°C and barometric pressure in kPa

$c_p$  specific heat of air at constant pressure ( $\sim 1005$  J kg<sup>-1</sup>°C<sup>-1</sup>)

$T_c$  temperature of the crop (°C)

$T_i$  temperature of the air in the greenhouse ( $^{\circ}\text{C}$ )

$T_o$  temperature of the air outside ( $^{\circ}\text{C}$ )

$r_X$  ventilation resistance ( $\text{s m}^{-1}$ )

$r_b$  boundary layer resistance ( $\text{s m}^{-1}$ )

$$r_X = \frac{3600}{XZ} \quad (5)$$

X number of volume exchange per hour by ventilation ( $\text{h}^{-1}$ )

Z mean height of the greenhouse (m)

To illustrate  $r_X$ , we calculate it for a typical polyethylene greenhouse with a ventilation rate of 40 volume exchanges per hour ( $= X$ ), and a height of 4.5 m ( $= Z$ ):

$r_X = 20 \text{ s m}^{-1}$ . Taking into account a typical conductive heat loss of  $6 \text{ W m}^{-2} \text{ K}^{-1}$  would decrease this value to  $r_X = 18.3 \text{ s m}^{-1}$ .

The boundary layer resistance  $r_b$  is related to pressure driven air flow in the greenhouse:

$$r_b = 300 \left( \frac{p}{U} \right)^{0.5} \quad (6)$$

LAI leaf area index

$l$  leaf diameter (m)

$U$  airflow in greenhouse ( $\text{m s}^{-1}$ )

$$U = \frac{A^{0.5}}{r_X Z} \quad \text{for natural ventilation} \quad (7)$$

$$U = \frac{Y}{r_X Z} \quad \text{for forced ventilation}$$

A area of the greenhouse ( $\text{m}^2$ )

Y distance between entry vent and exhaust fan (m)

Thermal induced buoyancy proportional to  $|T_c - T_i|^{0.25}$  lowers the boundary layer resistance, but this effect is minor in well-ventilated greenhouses.

### Latent heat

The latent heat flux  $E$  is carried out by the air exchange between inside and outside the greenhouse, expressed by the air exchange resistance  $r_X$  defined in Eq. (5). If transpiration is the only source of water vapor (non-condensation condition), it is also the vapor transfer from the leaf to the air inside the greenhouse:

$$E = \frac{c_p (e_i - e_o)}{r_X} = \frac{c_p (e(T_c) - e_i)}{r_b + r_c + LAI} \quad (8)$$

$e_i$  water vapor pressure in the greenhouse (kPa)

$e_o$  water vapor pressure outside (kPa)

$\gamma$  psychrometric constant  $\sim 0.0667 \text{ kPa K}^{-1}$ , depends on temperature and pressure. This near constant  $\gamma = c_p p / 0.622 L$ , where  $p$  is the barometric pressure ( $\sim 101.3 \text{ kPa}$ ) and the latent heat of water vaporization at temperature  $T$  in  $^{\circ}\text{C}$ ,

$L = 2.498 \times 10^6 + 3.369 \times 10^3 T \text{ J kg}^{-1}$ .  $\gamma$  indicates how much vapor evaporation adds to a parcel of air per degree of cooling if the heat content of the air is the only source of energy.

$e(T_c)$  saturated water vapor pressure at the temperature of the crop (kPa) commonly calculated by the following empirical formula:

$$e(T_c) = 0.6108 \exp \left( \frac{17.27 T_c}{T_c + 237.3} \right) \quad (9)$$

Equation (9) applies to the computation of saturated water vapor pressure at any temperature. As water vapor has to pass through both the stomates in the epidermis of the leaves and the boundary layer, the resistance of the water pathway includes  $r_c$  the stomatal resistance of the leaf in addition to  $r_b$  defined in Eq. (6). Stomatal resistance is a physiological characteristic of the crop. It is referenced in the literature as leaf or stomatal conductance  $g_c \approx r_c^{-1}$ , expressed in  $\text{m s}^{-1}$ , which is the reciprocal of the resistance. This expression of the conductance is for the volumetric flow of water vapor but because the mass of water carried in a unit volume of gas is a function of the temperature and the pressure, the literature often gives conductance in mass flow units as  $\text{mol m}^{-2} \text{s}^{-1}$  labeled here as  $g_{cM}$ . Therefore, the conversion from conductance to resistance has two forms depending on the units used for the conductance.

$$\begin{aligned} r_c &\approx \frac{1}{g_c} && g_c \text{ in } \text{m s}^{-1} \\ r_c &\approx \frac{0.029}{g_{cM}} && g_{cM} \text{ in } \text{mol m}^{-2} \text{s}^{-1} \end{aligned} \quad (10)$$

0.029  $\text{kg mol}^{-1}$  is the equivalent molar mass of air.

The stomatal or leaf conductance of many greenhouse crops is a function of the photosynthetic photon flux density (*PPFD* expressed in units of  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) reaching the surface of the leaves. The literature gives information for many crops. Stomatal conductance depends also on other environmental factors as  $\text{CO}_2$ , humidity and temperature, but *PPFD* is the main controlling factor. As this quantity is related to  $S_i$  calculated in Eq. (1) it can be calculated. Leaf conductance is also related on the water status of the plant and on the osmotic potential of the nutrient solution. Stomatal closure is the first physiological response to water stress. In greenhouses, we try to optimize water supply to avoid water stress. Still water stress may occur. It is parameterized by a stress factor  $0 = f < 1$ . One of HORTIMED's research objectives is to seek the osmotic effect of the nutrient solution on the stomatal conductance. The accepted form of the conductance function is:

$$g_{c(M)} \approx \frac{f \cdot g_{c(M)MAX}}{1 + \frac{f \cdot P}{PPFD}} \approx \frac{f \cdot g_{c(M)MAX}}{1 + \frac{f \cdot P}{2.02 S_i}} \quad (11)$$

where  $g_{cMAX}$  ( $\text{m s}^{-1}$ ) is the maximum stomatal conductance a light saturation. The second part of the equation establishes the relation to  $S_i$ , to be used if the *PPFD* balance is not measured. The factor 2.02 transforms the global radiation in  $\text{W m}^{-2}$  to photon flux density in  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in the photosynthetic active radiation waveband. It assumes that the transmission of the cover material is not spectrally selective. The parameter  $P$  is the photon response of the stomates; the smaller this number, the faster stomates reach maximum aperture.

Table 1 gives values for the major greenhouse crops included in HORTIMED.

#### Energy balance closure

As photosynthesis represents less than 2% of radiant energy absorbed by the foliage of the greenhouse net radiation  $R_n$  in Eq.(3) is dissipated as sensible heat  $H$  defined by (4) and latent heat  $E$  defined by (8):

$$R_n \approx H + E \quad (12)$$

Table 1. Numerical values of leaf conductance characteristics for use in greenhouse climate models.

Crop	Units	$g_{c-MAX}$ m s <sup>-1</sup>	$P$ $\mu\text{mol m}^{-2}$ s <sup>-1</sup>	Source
Roses at EC= 2.0 dSm <sup>-1</sup>		0.016	88	HORTIMED
Roses at EC = 3.4 dSm <sup>-1</sup>		0.012	56	HORTIMED
Roses at EC = 4.4 dSm <sup>-1</sup>		0.011	56	HORTIMED
Tomato		0.011	216	(Fuchs, Segal,
Sweet pepper		0.020	300	Dayan and Jordan, 1995)

### Computations

In the set of 12 equations shown here above we can identify four types of parameters:

1. Parameters characterizing the construction like greenhouse area or roof transmission coefficient
2. Outside climate parameters, solar radiation, air temperature and humidity
3. Climate control operation, ventilation rate
4. Plant characteristics, LAI, leaf diameter, and stomatal conductance function.

Parameters of type 1, including the shading factor, LAI and leaf diameter, for any given day are fixed and treated in the computations are adjustable constants. Parameters of type 2 are uncontrollable independent variables. Parameters of type 3 and stomatal conductance are controllable independent variables.

The equation set introduces several state variables. These variables result from the computations and are therefore dependent variables. Among these variables the analysis focuses on transpiration, crop canopy temperature, air temperature and humidity in the greenhouse.

The first step is to find the crop canopy temperature  $T_c$ :

$$T_c - T_o - \frac{r_a}{c_p} (S_a - R_d - T_o) - R_u - T_c - \frac{r_a}{r_a + r_s} (e_o - e(T_c)) \quad (13)$$

where  $r_a = r_x + r_b/LAI$  and  $r_s = r_c/LAI$ .

Eq. (13) is implicit because  $T_c$  figures on both sides of the equal sign. Its numerical solution is by an iterative Newton-Raphson procedure (see Appendix 2). The solution yields also  $e(T_c)$  from Eq. (9). The next step calculates transpiration  $E$ :

$$E = \frac{c_p (e(T_c) - e_o)}{r_a + r_s} \quad (14)$$

Air temperature inside the greenhouse  $T_i$  derives from:

$$T_i - T_o = \frac{r_x (R_n - E)}{c_p} \quad (15)$$

and internal water vapor pressure  $e_i$  from:

$$e_i - e_o = \frac{r_x E}{c_p} \quad (16)$$

Additional forms of internal humidity can be calculated as vapor pressure deficit  $e(T_i) - e_i$  or relative humidity %  $100 e_i / e(T_i)$ .

## The wet pad model

The theoretical wet pad model assumes that the air flow entering the greenhouse passes exclusively through the evaporative pad and equilibrates with the psychrometric wet bulb temperature  $T_w$  and consequently contains vapor at a partial pressure equal to the saturated vapor pressure at  $T_w$ ,  $e(T_w)$ :

$$T_w = T_o + \frac{e(T_w) - e_o}{\gamma} \quad (17)$$

The solution of Eq. (17) entails an iterative Newton-Raphson numerical procedure that yields both  $T_w$  and  $e(T_w)$ , (see Appendix 3).

In practice the evaporative pad operates below full efficiency  $\eta$ :

$$\eta = \frac{T_o - T_p}{T_o - T_w}; \quad T_p = T_w + \eta(T_o - T_w) \quad (18)$$

where  $T_w = T_p < T_o$  is the actual temperature of the air leaving the wet pad. This temperature is the value resulting from volumetric air flow in equilibrium with the wet pad  $v_w$  having reached  $T_w$  mixed with air flow  $v_X - v_w$  still at  $T_o$ , the outside temperature. The total volumetric airflow  $v_X$  is  $AZ\bar{X}$ . The value of  $v_w$  derives from the sensible heat balance of the air flowing into the greenhouse:  $T_p v_X = T_w v_w + T_o (v_X - v_w)$  yielding  $v_w = \eta v_X$ . The water vapor pressure in the air off the wet pad  $e_p < e(T_w)$  is the result of the mixture of the volumetric air flow at  $e(T_w)$  and volumetric air flow at  $e_o$ :

$$e_p = \eta e(T_w) + (1 - \eta) e_o \quad (19)$$

The energy balance of the greenhouse is obtained by using  $T_p$  as the temperature of the air entering the greenhouse and  $e_p$  as its water vapor pressure:

$$H = c_p \frac{T_i - T_p}{r_x} + c_p \frac{T_c - T_i}{r_b / LAI} \quad (20)$$

$$E = \frac{c_p (e_i - e_p)}{r_x} + \frac{c_p (e(T_w) - e_i)}{r_b + r_c / LAI} \quad (21)$$

The evaporation from the wet pad as latent heat flux density (per unit area of the greenhouse)  $E_p$  is:

$$E_p = \frac{c_p (e_p - e_o)}{r_x} \quad (22)$$

## Implementation

The implementation of the multivariate model is presented in the form of an EXCEL workbook. Instructions describing the inputs and operations of the various worksheets are imbedded in the EXCEL worksheets.

To facilitate the use of Deliverable 5 for the decision support software developed in work package 4 the following list cross references between input characteristics used in the equations here above and their locations in the EXCEL workbook.

## Symbol locator table

	Equation references	XLS file location
<b>Input parameters</b>		
<b>Solar (short wave) radiation</b>		
$r_c$ solar reflection coefficient of the canopy ( $\sim 0.25$ ), constraint: $0 < r_c = 1$	(1), (3)	Input!D11
$t_r$ solar transmission coefficient of the roof cover ( $\sim 0.6$ ), constraint: $0 < t_r + r_r = 1$	(1)	Input!C5
$r_r$ solar reflection coefficient of the roof cover ( $\sim 0.2$ )	(1)	Input!D5
<b>Terrestrial (long wave) radiation</b>		
$t_R$ transmission coefficient for terrestrial radiation of the roof cover, constraint: $0 < t_R + e_R = 1$ (IR polyethylene $\sim$ 0.3; Glass $\sim 0$ )	(2)	Input!C8
$e_R$ terrestrial radiation emission coefficient of the roof cover. (IR polyethylene $\sim 0.55$ ; Glass $\sim 0.95$ )	(2)	Input!D8
<b>Construction</b>		
$Z$ mean height of the greenhouse (m)	(5), (7)	Input!D22
$A$ area of the greenhouse ( $m^2$ )	(7)	Input!C22
$Y$ distance between entry vent and exhaust fan (m)	(7)	Input!E22
$L_{vent}$ vent opening width (m)	Table A1 or (25)	Input!C33-5
$H_{vent}$ vent opening height (m)		Input!D33-5
$A_{vent}$ Greenhouse ground area associated to a vent ( $m^2$ )	(23)	Input!E33-5
Single or multispan	Table A1	Input!F33-5
? porosity of insect proof net (mesh and free pore)	(24)	Input!I33-5 C39,E40
<b>Crop characteristics</b>		
$LAI$ leaf area index	(4), (8)	Input!C13
$l$ leaf diameter (m)	(6)	Input!C14
$g_{c-MAX}$ maximum stomatal conductance ( $m\ s^{-1}$ )	(11)	Input!C28
$g_{cM-MAX}$ maximum stomatal conductance ( $mol\ m^{-2}\ s^{-1}$ )	(11)	
$P$ stomatal response to photons	(11)	Input!D28
<b>Operation parameters</b>		
$X$ ventilation, air exchange rate ( $h^{-1}$ )	(5)	Any <sup>1</sup> !P4,WPAny!R4
$s$ shading	(1)	Input!E5
? wet pad efficiency	(18)	WPAny!M4
$f$ water stress factor	(11)	Any!L4,WPAny!M4
<b>Outside climate variables</b>		
$T_o$ air temperature ( $^{\circ}C$ )	(4)	Any!N4,WPAny!P4
Relative humidity ( $\% = 100 \times e_o/e(T_o)$ )	(8)	Any!O4,WPAny!Q4
$S_o$ Solar radiation ( $W\ m^{-2}$ )	(1)	Any!M4,WPAny!O4
$u$ wind speed $m\ s^{-1}$	(23)	Input!G33-5

<sup>1</sup>Any stands for Radiat, T-out, RH-out, Stress, Air Exch or Eff

## Appendix 1: The IRTA-CIFA tested natural ventilation model

In deliverable 4, IRTA-CIFA tested a natural ventilation model. This appendix explains the integration of ventilation input parameters into the EXCEL workbook. Only the essential parts of the ventilation model are used here. The complete model is in deliverable 4. Symbols used in deliverable 4 are modified to fit the pattern set in the present deliverable as given in the symbol locator table.

$$r_x = \frac{2A_{vent}}{S_{vent} C_k C_n C_d C_w^{0.5} u} \quad (23)$$

$A_{vent}$  is the ground area of the greenhouse affected by a particular vent. It is the total area of the greenhouse divided by either the number of roof vents or side vents.

$S_{vent}$  is the area of the opening of the vent.

$C_k$  is a temporary adjustment factor =0.667 to adjust the calculations with the ventilation rates measured in the Besor experimental greenhouses.

$u$  is the outside wind speed in  $m s^{-1}$ .

$C_n$  is the drag coefficient due to the obstruction of vents by insect proof nets:

$$C_n = \frac{1}{\rho^2} \quad (24)$$

$\rho$  is the porosity of the net porosity, the ratio of the opening length over the mesh length raised to the power 2. Without nets  $\rho = 1$ , and  $C_n = 1$ .

$C_d$  is a drag coefficient affected by the vent shape taken from the following table:

Table A1. Drag coefficient for vents.

$L_{span}/H_{span}$	13.3	16	20	26.6	40	60	80
Single span	0.681	0.698	0.78	0.815	0.815	0.815	0.815
Multi span	0.518	0.551	0.57	0.621	0.621	0.621	0.621

For  $L_{span}/H_{span} < 13.3$  the following extrapolation is used

$$C_d = \frac{M L_{vent} / H_{vent}}{3.2 L_{vent} / H_{vent}} \quad (25)$$

$M = 0.815$  for single span  
 $M = 0.621$  for multi span

$C_w$  for roof vents is either 0.43 when the wind direction is windward or 0.079 for a leeward direction. For side vents  $C_w = 0.221 u^{1.6}$

## Appendix 2: Numerical solution of Eq. (13)

Eq (13) establishes that the function  $F(x)$  defined below equals 0 when  $x = T_c$ .

$$F(x) = T_o \frac{r_a}{c_p} S_a R_d T_o R_u x \frac{r_a}{r_a r_s} e(x) x$$

The Newton-Raphson iteration for approaching  $T_c$  is:

$$x_{n+1} = x_n + \frac{F(x_n)}{F'(x_n)}$$

$$F'(x_n) = \frac{r_a}{c_p} R_u'(x_n) - \frac{r_a}{r_a + r_s} e^{x_n} - 1$$

$$R_u'(x_n) = 4 \times 5.67 \times 10^{-8} (T_R + x_n)^3$$

$$e^{x_n} = \frac{17.27 \times 237.3}{x_n + 237.3}$$

The iteration start at  $n = 1$  with  $x_1$  set equal to  $T_o$ . The practice shows that for  $n = 4$ ,  $|x - T_c| < 0.0001$  °C.

### Appendix 3: Numerical solution of Eq. (17)

Eq. (17) establishes that the function  $G(x)$  defined below equals zero when  $x = T_w$ .

$$G(x) = T_o - \frac{e^{x} + e_o}{x}$$

The Newton-Raphson iteration for approaching  $T_w$  is:

$$x_{n+1} = x_n + \frac{G(x_n)}{G'(x_n)}$$

$$G'(x_n) = 1 - \frac{e^{x_n}}{x_n^2}$$

The iteration start at  $n = 1$  with  $x_1$  set equal to  $T_o$ . The practice shows that for  $n = 4$ ,  $|x - T_w| < 0.0001$  °C.

### Literature Cited

Fuchs, M., Segal, I., Dayan, E. and Jordan, K. A.1995. Improving greenhouse microclimate control with the help of plant temperature measurements. BARD project No. IS-1816-90r:62.