

10
11
12

Stamboeknr.: 372

09046 + 09063

1510 = 198666 *

153-6 EVAPORATION OF A GREENHOUSE CROP AND ITS RELATIONSHIP TO THE SUPPLY OF HEAT

Cecilia Stanghellini

ABSTRACT

A new combination formula to assess potential evaporation of greenhouse crops is proposed and shown to agree well with measured actual evaporation. The main peculiarity of the method here outlined is a new parametrization of the so-called aerodynamic resistance.

Vapour transfer has been considered to be the outcome of forced convection in the leaf boundary layer, with air movement being induced by free convection around the heating elements. Accordingly, vapour transfer at the evaporating surfaces can be completely determined when the free convective heat transfer of the heating system is known.

A formula for potential evaporation based on this principle is shown to give excellent agreement with measured evapotranspiration of a greenhouse tomato crop on 24 hour totals, and a good agreement on a few minutes time basis, even for nighttime data. Shortcomings and possible improvements of the method are discussed.

CENTRALE LANDBOUWCATALOGUS



0000 0935 5807

CONTENTS

1. Introduction	5
2. Theory	6
2.1. Potential evaporation	6
2.2. Combination method	7
2.3. Aerodynamic resistance	9
3. Materials and methods	11
3.1. Experimental set-up	11
3.2. Aerodynamic resistance in a greenhouse	13
3.3. Parametrization of potential evaporation in greenhouses	14
4. Results and discussion	17
4.1. Radiative part of potential evaporation	21
4.2. Storage of energy in the foliage	23
4.3. Aerodynamic resistance	25
5. Conclusion	27
Acknowledgements	29
References	30

SYMBOLS

A	= ground area fraction corresponding to a crop row	(-)
C	= concentration	kg m ⁻³
D	= apparent diffusion coefficient	m ² s ⁻¹
E	= vapour flux	kg m ⁻² s ⁻¹
G	= rate of change of stored heat per unit area	W m ⁻²
H	= sensible heat flux	W m ⁻²
L	= longwave radiation flux	W m ⁻²
LAI	= leaf area index	(-)
R	= radiation flux	W m ⁻²
S	= shortwave radiation flux	W m ⁻²
T	= temperature	K
c	= specific heat of air	J kg ⁻¹ K ⁻¹
d	= diameter	m
e	= vapour pressure	mbar
r	= resistance	s m ⁻¹
u	= wind speed	m s ⁻¹
z	= vertical coordinate	m
α	= heat transfer coefficient	W m ⁻² K ⁻¹
γ	= psychrometric constant	mbar K ⁻¹
δ	= slope of the saturated vapour curve	mbar K ⁻¹
ε	= emission coefficient	(-)
λ	= latent heat of vaporization of water	J kg ⁻¹
ρ	= density of air	kg m ⁻³
ρ'	= reflectance of the canopy	(-)
σ	= Stefan-Boltzmann constant	W m ⁻² K ⁻⁴
τ	= transmittance of the canopy	(-)

Subscripts:

a	= air	p	= pipes
abs	= absorbed	s	= surface
c	= convection	v	= vapour
H	= heat	z	= at height z
L	= longwave radiation		
l	= leaves		
n	= net		

Superscript:

*	= saturated
---	-------------

1. INTRODUCTION

In meteorology as well as in micrometeorology, vapour production is known to be a very efficient way of transferring energy, due to the large amount of energy needed for the phase change. It is, therefore, no wonder that over the centuries so many efforts have been devoted to improving man's knowledge about vapour production. Nevertheless, evaporation has proved to be a more elusive problem than could be expected since the way mass - as well as heat and momentum - is transferred in the atmosphere is still far from known.

The main object in all these efforts is to improve the management of water resources that are realized to be limited. The reason for devoting research to a quantitative knowledge of vapour production in greenhouses is even broader: what is at stake is the correct management not only of scarce - or expensive - water resources, but of even scarcer energy sources. In fact, the controlled climate of a greenhouse environment presents a challenge: vapour production could be controlled, in principle, if the physical laws governing it were known.

The underlying consideration is that it would cost far less energy to control vapour *production* than air humidity *afterwards*, as is normally done.

In the work described in this paper, an attempt was made to quantify the dependence of vapour production by a greenhouse crop on the relevant factors of the greenhouse climate.

2. THEORY

Vapour transfer from a surface to a height z can be described as a diffusion-type process:

$$E = D_v \frac{(C_s - C_z)}{z} \quad \text{kg m}^{-2} \text{s}^{-1} \quad (1)$$

where E is the vapour flux, D_v has the units of a diffusion coefficient, C_s and C_z are the vapour concentration at the surface and at height z , respectively. However, what makes this direct approach unworkable is that, in practical problems D_v is not known and can be orders of magnitude greater than the pure diffusion coefficient of vapour in air, since some turbulent transfer is present. Moreover, in most cases vapour concentration at the surface is not known, nor can it be easily measured.

2.1. Potential evaporation

Penman (1948) firstly showed that these shortcomings could be overcome by combining (hence the name "combination method") the energy balance equation with transfer functions for sensible heat and water vapour, to get - under circumstances characterized by some hypothesis - what he termed "potential evaporation", i.e. vapour production by a surface with unlimited water supply, exposed to a given climate.

Monteith (1965) and Rijtema (1965) extended the method, which in the original Penman formulation contained considerable empiricity, and Van Bavel (1966) firstly pointed out that "the fundamental condition that defines potential evaporation is that the surface vapour pressure can be found from the surface temperature".

It should be noted that potential evaporation thus defined can be interpreted as a characteristic parameter of a given climate, i.e. the amount of evaporative losses taking place from a surface *saturated at its temperature* exposed to such a climate. Actual evaporation differs from the potential one insofar as the condition of saturation is not met. In this context it is clear that the parametrization of potential evaporation does indeed have some relevance for research aimed at controlling vapour production through climate control procedures: climate completely defines only potential evaporation and not the actual one, which is likely to be influenced also by other factors such as the amount of

supplied water, water salinity, age and health of the crop, development of the roots, i.e. anything that could influence the extent to which the surface saturation condition is not met.

It is likely that, for greenhouse crops, water is normally available at the evaporating surface freely enough for actual evaporation to resemble the potential one. Results shown in Stanghellini (1981a) support this statement, although some of the results discussed in Stanghellini (1983b) show that there can be exceptions.

2.2. Combination method

An expression for the potential evaporation rate is derived below. A detailed discussion of the working assumptions needed for the following derivation can be found in Van Bavel (1966) and here only the relevant points will be given. The energy balance of an evaporating surface is:

$$R_n = \lambda E + H + G \quad \text{W m}^{-2} \quad (2)$$

which states explicitly that the net energy gained from radiation (R_n) must be equal to the energy released as latent (λE) and sensible (H) heat, plus the rate (G) at which energy is stored below the surface. However, sensible heat exchanged between the surface and the atmosphere is not better known than exchange of vapour, so that even if the absorbed radiation and storage rate were known, eq. (2) could not be directly applied to estimate vapour production. However, any flux can be formally written as a difference of potential across a resistance, so that it is possible to state

$$H = \frac{\rho c}{r_{aH}} (T_s - T_a) \quad \text{W m}^{-2} \quad (3)$$

where ρc is the thermal capacity of a unit volume of air (assumed not to depend on z), T_s and T_a are the temperatures of the surface and air at some height z , and r_{aH} is defined as the resistance to the transfer of heat offered by the air layer contained between the surface and the height z .

Eq. (1) can be written in a similar form when $r_{av} = z/D_v$ is defined and, after substitution of a difference in pressure instead of concentration, we get:

$$\lambda E = \frac{\rho c}{\gamma r_{av}} (e_s - e_a) \quad \text{W m}^{-2} \quad (4)$$

where e_s and e_a are the vapour pressure at the surface and at height z ,

respectively, γ is a psychrometric constant and r_{av} is the resistance offered to vapour transfer by the layer of air contained between the surface and z .

By considering

$$e_s = e^*(T_s) \quad \text{mbar (5)}$$

(vapour pressure at the surface is the saturated vapour pressure) as the defining condition for potential evaporation, and writing

$$e^*(T_s) = e^*(T_a) + \delta(T_a)(T_s - T_a) \quad \text{mbar (6)}$$

where $\delta(T_a)$ is the slope of the saturated vapour curve at temperature T_a , (4) can be written as:

$$\lambda E = \frac{\rho c}{\gamma r_{av}} (e^*(T_a) - e_a + \delta(T_a)(T_s - T_a)) \quad \text{W m}^{-2} \quad (7)$$

Substitution of (2) in (3) shows that:

$$T_s - T_a = \frac{r_{aH}}{\rho c} (R_n - \lambda E - G) \quad \text{K} \quad (8)$$

Substitution of (8) in (7) and rearrangement finally yield:

$$\left(1 + \frac{\delta(T_a)}{\gamma} \frac{r_{aH}}{r_{av}}\right) \lambda E = \frac{\rho c}{\gamma r_{av}} (e^*(T_a) - e_a) + \frac{\delta(T_a)}{\gamma} \frac{r_{aH}}{r_{av}} (R_n - G) \quad \text{W m}^{-2} \quad (9)$$

Eq.(9) can be further simplified by the assumption that $r_{aH} = r_{av}$ (similarity of heat and vapour transport, § 2.3), so that if the symbol r_a is used for both, we get:

$$\lambda E = \frac{\rho c}{r_a(\gamma + \delta(T_a))} (e^*(T_a) - e_a) + \frac{\delta(T_a)}{\gamma + \delta(T_a)} (R_n - G) \quad \text{W m}^{-2} \quad (10)$$

The fundamental advantage of the combination method is that a vapour transfer coefficient is far less critical in (10) than in (1).

Moreover, since no state function needs to be known for the surface, the variables to be used in (10) may be measured at only one level in the air.

Eq.(10) is built up from two terms, the first being dependent on the ability of the air to accept the vapour produced and to carry it away from the surface, whereas the second is solely dependent on the net supply of energy at the evaporating surface. This is the reason for the widely used definitions of an "aerodynamic" and "radiative" term for the first and second terms of eq.(10), respectively.

It should be noted that in principle eq.(10) represents an instantaneous evaporation rate and its use is, therefore, by no means restricted to time averages over periods of days or longer, although this impression is fairly widespread. In practice, however, the use of eq.(10) for short time intervals is limited by the fact that the storage term G is seldom known with sufficient accuracy (§ 4.2).

2.3. Aerodynamic resistance

The assumption of similarity between the transport of vapour and heat made implies that both are passive components of the air mixture (i.e. not influencing its dynamic properties), which neither is.

Moreover their "pure" diffusion coefficients are different, being $D_v = 2.12 \cdot 10^{-5}$ and $D_H = 1.81 \cdot 10^{-5} \text{ m}^2 \text{ s}^{-1}$ (in air at 0 °C).

However, a "turbulent" diffusion coefficient, being typically in the order of magnitude of $10^{-2} \text{ m}^2 \text{ s}^{-1}$ or more, seems unlikely to be affected by differences on such a small scale. A hydrodynamic analogy makes this point clearer: small particles of different shapes or weights are transported similarly in a strong current, since the effect of their different properties on the flow is negligible. Thus, eq.(10) can suffice for the present purpose. Observe that the hypothesis of similarity, although representing a simplification, is not needed for the validity of the combination method (eq.(9) is valid in any case) as is, on the other hand, the condition of saturation.

The resistance r_a , sometimes called the aerodynamic resistance, is some combination of the resistances offered to vapour on its path from the leaf surface through the leaf boundary layer to the air. In fact, vapour production on the leaf surface takes place both through stomatal pores whose opening and closing is controlled by the hydraulic behaviour of guard cells acting as valves and through a thin cuticle.

A common way of describing this water mass flow is to use its analogy with the flow of current through a circuit, stating that stomatal and cuticular resistances are wired in parallel, and then in series to the boundary layer resistance. However, calculating the total resistance r_a from this wiring is a forbidding job, since the individual resistances are not known, nor easily measured separately, neither is there any good reason to assume that they should be the same on both sides of a leaf. It thus makes some sense to pack everything together in a total resistance r_a and try to make some assumptions about it.

Indeed, many different equations have been provided in the literature for the aerodynamic resistance, which can be grouped into two categories: empirical ones (e.g. Penman, 1948; Rijtema, 1965) containing some empirical function of wind speed, and "theoretical" ones derived from the theory of convective transfer in the boundary layer when a wind profile is established (e.g. Businger, 1956; Van Bavel, 1966). Both these approaches represent actually a parametrization of the boundary layer resistance and not of the resistance at the surface (stomatal and cuticular), so that they are adequate when the latter is much smaller than the former.

This statement is supported by the results of Van Bavel, 1966, whose formula for potential evaporation - clearly adequate in other conditions - constantly overestimated nighttime actual evaporation of alfalfa, while predicting well nighttime evaporation from open water or bare soil. The author concluded that while daytime stomatal effects are too small to be detected, a relevant superficial resistance develops at night, to which his parametrization of the aerodynamic resistance does not apply.

There is no physical ground for applying any of the functions given in the literature for r_a to greenhouse evaporation: the non-existence of a wind profile rules out the above theoretical approach, whereas the range of wind speeds for which most empirical formulae were developed (above 1 m s^{-1}) does not allow any extrapolation to the values normally experienced in greenhouses (0.1 m s^{-1}). However, on the basis of these findings, it can be safely stated that a higher boundary layer resistance is to be expected than in the field. In this respect indoor climate offers better opportunities for the validation of a formula for potential evaporation: the higher is the boundary layer resistance, the more likely are stomatal effects to be negligible.

3. MATERIALS AND METHODS

The results discussed hereafter concern data collected during a joint project between IMAG and the Department of Physics and Meteorology of the Dutch Agricultural University at Wageningen.

The project was aimed at establishing the energy balance of a greenhouse tomato crop. Central in the experimental set-up was the use of a prototype weighing lysimeter developed in the Twente Technical University (NL). The lysimeter is described by Bot et al., 1983; Dormans, 1983 and Stanghellini, 1983b, where a summary of the relevant relationships between transpiration and greenhouse climate, as appearing from the measurements, is also provided.

A detailed description of the complete instrumental set-up can be found in Stanghellini, 1981b, and van 't Ooster, 1983; here only the relevant parts for the present subject will be briefly repeated.

3.1. Experimental set-up

The greenhouse is a single-glass, Venlo-type, eight span, E-W oriented one. Heating is provided by hot water circulated in pipes (two pipes, a few centimetres above ground, for each crop row, and one at gutter level for each span); natural ventilation takes place through roof ventilators. Measurements were carried out, in two successive years, with tomato crops (cv. Sonatine and cv. Marathon) grown on rockwool mats 0.3 m wide, 1.6 m apart.

Both soil and rockwool were covered with white plastic sheets, and no evaporation could take place. Accordingly, when reference is made to measured values, only transpiration is considered. In the second year, a transparent-lamellae screen was set up in the house, and a climate control system was installed (Van Meurs, 1980).

Incoming shortwave radiation was measured above the house, directly below the roof (above the screen), at two points above a crop row and one below it. Reflected shortwave radiation was measured by a solarimeter placed in reverse just above a crop row (below one of the two solarimeters placed there). Net radiation was measured by sensors placed above, below and within another crop row. Temperature and humidity of the air were measured by Assmann aspirated psychrometers, outside, below the roof, above the canopy, at 1 m height and a few centimetres above the ground.

The temperature of the foliage was measured by a Heiman infrared thermometer,

pointing midway up in a crop row. Heat flux into the ground was measured with two heat flux plates at 0.05 m depth below a rockwool mat and in the middle of a path, respectively.

Most of the measuring devices were near the centre of the greenhouse, where transpiration was also measured.

The above-mentioned lysimeter has a maximum acceptable load of 100 kg and can measure weights with an accuracy of ± 0.1 g in a laboratory environment. In the greenhouse set-up actual accuracy did not exceed 0.3 g, due to some influence of air movement (Stanghellini, 1983b). It was working on the vent-out principle, in order to avoid temperature-related problems, as encountered in many previous experiments in greenhouses.

It was placed in a pit dug in the ground, carrying a portion of a crop row, that was thus in line with and at the same height as the rest of the row (Fig.1).



Fig. 1 - The lysimeter, as installed, supporting a tray with 4 plants. The plants were supported by a high frame, the lowest part of which can be seen on the photograph. In this way they were kept in line with and at the same height as the rest of the row. No relevant differences in growth were observed between the plants on the lysimeter and the others.

A micro-computer was also installed which apart from high frequency (>0.2 Hz) filtering of the lysimeter's direct output signal, checked for cumulative transpiration in order to automatically replenish the water consumed (Reinders, 1982).

The output provided by all the instruments was scanned by a data-logger at intervals of 1, 3 or 10 min and stored on disc for further processing.

Leaf area could be estimated from the mean length of leaves with the procedure developed by Van der Varst and Postel, 1972. The leaf area index (LAI) was calculated relating the estimated leaf area to the corresponding ground area with a plant density in the house of 2 per m².

3.2. Aerodynamic resistance in a greenhouse

As mentioned in § 2.3, there is not much use in developing an empirical relation for the aerodynamic resistance for greenhouse crops as a function of wind speed, since the meteorological conditions justifying such an approach are not met in a greenhouse climate. There is also a good practical reason; measurements of wind speed at levels as low as 0.05 - 0.15 m s⁻¹ are generally not accurate enough for such a purpose and can by no means be considered common practice, so that an evaporation formula based on such measurements would lose much of the attractive simplicity of the combination method.

Moreover, as Stanghellini, 1983a, showed, air movement in a greenhouse is largely due to free convection over the heating elements, so that a fairly well defined relationship could be established between indoor wind speed and the difference in temperature between the heating pipes and the air.

It is normal practice to state that the convective heat flow H_c from a surface is proportional to the difference in temperature between the surface and the air, i.e.

$$H_c = \alpha_c (T_s - T_a) \quad \text{W m}^{-2} \quad (11)$$

The convective heat transfer α_c , having the units of J s⁻¹ m⁻² K⁻¹, represents a volume density of specific energy times a speed, which can be thus interpreted as the net speed of heat transfer in a convective regime; let u_c be its symbol. Observe that u_c can be expected to bear some similarity with actual wind speed u only in a laminar flow, while becoming comparatively smaller with the onset and progress of turbulence.

If it is thus acknowledged that in most cases heating should be the driving force for transport in a greenhouse, there is a point in relating the aerody-

namic resistance to the convective heat transfer of the heating elements. The simplest assumption to be made is that the net speed u_c of transfer is uniform within the volume occupied by the heating system and the canopy. Accordingly, comparison of (11) with (3) shows that:

$$\frac{\rho c}{r_{aH}} = \alpha_c \quad \text{W m}^{-2} \text{K}^{-1} \quad (12)$$

so that we get $1/r_{aH} = u_c$.

In Stanghellini, 1983a, the convective heat transfer coefficient α_c of the heating pipes was derived, resulting - for the present set-up - in:

$$r_{aH} = 345 \cdot \left(\frac{T_a \cdot \bar{d}}{T_s - T_a} \right)^{\frac{1}{4}} \quad \text{W m}^{-2} \text{K}^{-1} \quad (13)$$

where \bar{d} is the pipe diameter in m, T_s is measured at the external surface of the pipes and temperatures are in K.

Eq.(13) can be used directly in (10), once the similarity between vapour and heat transfer is assumed. Anyhow, it is worthwhile to estimate the magnitude of u_c thus defined: if we assume $T_s \sim 40$ °C, $T_a \sim 15$ °C and $\bar{d} \sim 0.05$ m, we get $r_{aH} \sim 300 \text{ s m}^{-1}$ and $u_c \sim 3.5 \cdot 10^{-3} \text{ m s}^{-1}$.

It should be mentioned that extrapolation of relationships suggested in the literature (Rijtema, 1965; Van Bavel, 1966) would yield $u_c \sim u/30$ for comparable conditions. For wind speeds in the order of magnitude of 0.1 m s^{-1} , as measured in the present set-up, it would indeed result in a comparable value for the resistance r_a .

3.3. Parametrization of potential evaporation in greenhouses

When the radiative part of (10) (i.e. its second term) is considered, it is common experience that radiation absorbed by a greenhouse crop is not easily related to net radiation measured above it. A previous paper (Stanghellini, 1983c) dealt extensively with this subject, and here only the relevant equations will be repeated for completeness. It was shown that the radiation actually intercepted by such a canopy and not transmitted or re-emitted by it can be calculated from:

$$R_{abs} = A \cdot \left\{ (1 - \tau_L) R_n + \{ (1 - \rho') \tau_L - \tau \} S + 0.225 (1 - \tau_L^2) (L_p - L_l) \right\} \quad \text{W m}^{-2} \quad (14)$$

where R_n and S are the net and shortwave radiation fluxes, respectively, measured above a crop row; A is the fraction of ground area occupied by a crop row; τ_L and τ are the transmittance of a crop row for longwave and shortwave radiation, respectively; ρ' is the reflectance of a crop row for shortwave radiation; $L_p - L_z$ is the net longwave flux exchanged between the heating pipes and the canopy and 0.225 is a normalizing factor (ratio of pipe area to ground area).

The parameters are given by:

$$A = 0.83 (1 - e^{-0.87 \cdot LAI}) \quad (15)$$

$$\tau = e^{-0.75 \cdot LAI} \quad (16)$$

$$\tau_L = e^{-0.94 \cdot LAI} \quad (17)$$

$$\rho' = 0.45 \cdot e^{-0.68 \cdot LAI} \quad (18)$$

It should be stressed that eqs.(15) to (18) are empirical ones, valid only for the present set-up. However, they could be easily derived for any crop with the method outlined in Stanghellini, 1983c.

The net longwave flux $L_p - L_z$ can be calculated by the Stefan-Boltzmann law:

$$L_p - L_z = \epsilon \sigma (T_p^4 - T_z^4) \quad \text{W m}^{-2} \quad (19)$$

where σ is the constant of Stefan-Boltzmann, ϵ is the net emission coefficient ($\cong 1$) and T_p and T_z are the temperature of the pipe surface and of the leaves, respectively, in K.

In the combination method, however, it is assumed that no temperature of the leaf surface is known, and in (19) the use of air temperature in the place of T_z will suffice. In fact, large differences between air and leaf temperature are unlikely to be established in a greenhouse; moreover, the flux calculated in (19) is only a part of the flux represented in (14), which appears in (10) with a coefficient lower than one, so that it is not worthwhile to devote much attention to this point.

A last remark is due on a normalization problem: eq.(10), being derived from the energy balance at the evaporating surface, represents the latent heat flux per unit leaf area, so that when evaporation values for the ground area are requested, a factor LAI must be applied to eq.(10). On the other hand, eq.(14)

was already derived per unit ground area, so that a parametrization of potential vapour production for the above-mentioned greenhouse conditions, yields:

$$\lambda E = \frac{LAI \cdot \rho c}{(\gamma + \delta(T_a)) r_a} (e^*(T_a) - e_a) + \frac{\delta(T_a)}{\gamma + \delta(T_a)} \cdot R_{abs} \quad \text{W m}^{-2} \quad (20)$$

with r_a given by (13) and R_{abs} by (14).

4. RESULTS AND DISCUSSION

Potential evaporation was estimated applying eq.(20) to measured data covering a variety of climatic conditions and crop developments.

In Tab. 1 a summary is presented of 24-hour averages of measured and computed values at 3 or 10 min intervals (1982 and 1981, respectively). It may be concluded from Tab. 1 that the method described in this paper provides good estimates of daily evaporative losses. In fact, the 24-hour ratio of computed versus measured values varies from 0.83 to 1.18, with a mean of 0.95, i.e. the lack of agreement between actual and estimated evaporation would appear to be in the same order of magnitude as that of instrumental errors, on such a wide range of evaporative losses.

Tab. 1

Comparison of 24-h averages of 3 or 10 min (1982 and 1981, respectively) measured and computed evaporation. Values of LAI and shortwave incoming radiation at the top of the canopy (average over the daylight period) are given for reference. λE_m is the measured evaporation whereas λE_e is the estimated one. λE_r and λE_a are the radiative and aerodynamic terms of (20), respectively.

Day	LAI	R	λE_m	$\lambda E_e / \lambda E_m$	$\lambda E_r / \lambda E_a$
20 Febr. '81	0.97	196.9	16.0	1.18	0.36
13 Mar. '81	1.05	48.0	15.2	0.95	0.29
14 Mar. '81	1.09	107.8	20.9	0.89	0.45
8 Mar. '82	1.32	91.7	25.9	0.88	1.96
22 Mar. '82	2.03	130.4	35.9	0.93	4.83
23 Mar. '82	2.05	94.3	31.3	1.06	2.82
24 Mar. '82	2.16	210.2	49.5	1.01	5.26
25 Mar. '82	2.16	200.3	64.2	0.83	4.55
13 May '82	2.26	340.7	124.2	0.94	4.38
28 May '82	1.95	250.6	76.8	0.89	4.49
29 May '82	1.95	220.8	74.3	0.86	4.05

However, only a short-term evaluation of eq.(20) can be considered adequate, since the agreement between measured and computed values, as shown in Tab. 1, could result from a balancing of errors. Moreover, as stated earlier, the hope of controlling greenhouse vapour production rests on the short-term validity of a prediction method for it. To make this point clearer, transpiration during a cloudless spring day is shown in Fig. 2.

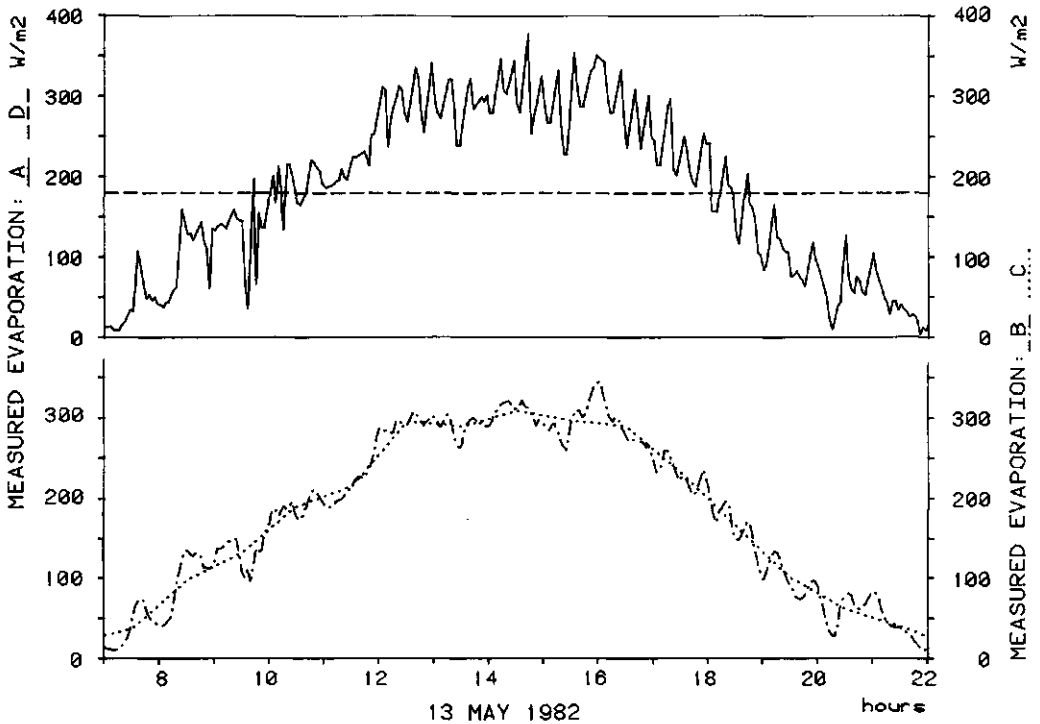


Fig. 2 - Transpiration during a cloudless spring day.

- a. as measured at 3 min intervals;
- b. filtered with a 15 min (5 values) progressive mean;
- c. its hourly averages;
- d. its daylight mean.

The fluctuations manifested in a. and b. were largely due to variations in the angle of opening of the windows, as set by the climate control system (§ 4.3).

It will be obvious that even hourly values are not adequate for the present purpose, and some useful information is lost even in the 15 min means. The value of the present parametrization for short-term estimates of evaporation and its limits will be discussed below, with the aid of some representative cases.

The measured and estimated evaporation for a late winter day and night are shown in Fig. 3, filtered with a 15 min (5 value) progressive mean, to improve

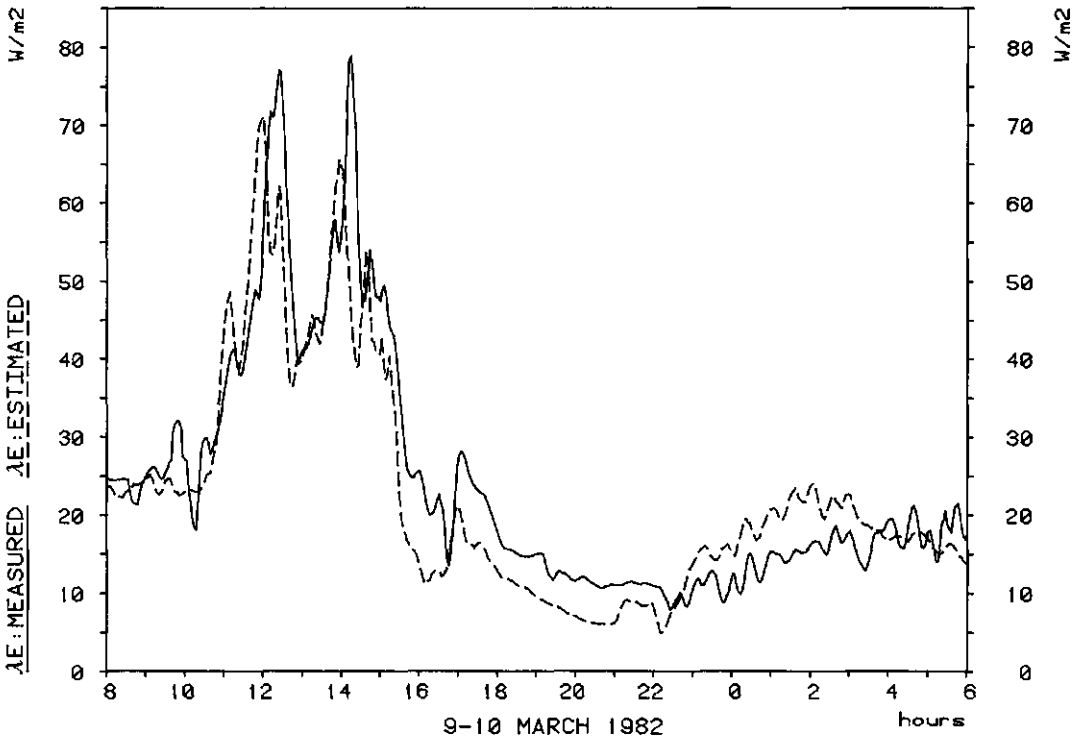


Fig. 3 - Measured and estimated evaporation (using eq.(20)). Both measurements and calculations were carried out at 3 min intervals, and here progressive means over 5 values (15 min) are shown (see text).

readability of the graphs. The day was characterized by scattered cloudiness, and some heating was provided until noon, between 16 00 and 18 00 hours, and after 21 00 hours. The peaks in evaporation at noon, 14 00 and 17 00 hours are largely attributable to corresponding peaks in incoming shortwave radiation. The transparent lamellae screen was closed during the whole day and open after 22 00 hours.

Another example of the adequacy of (20) is given in Fig. 4, representing values

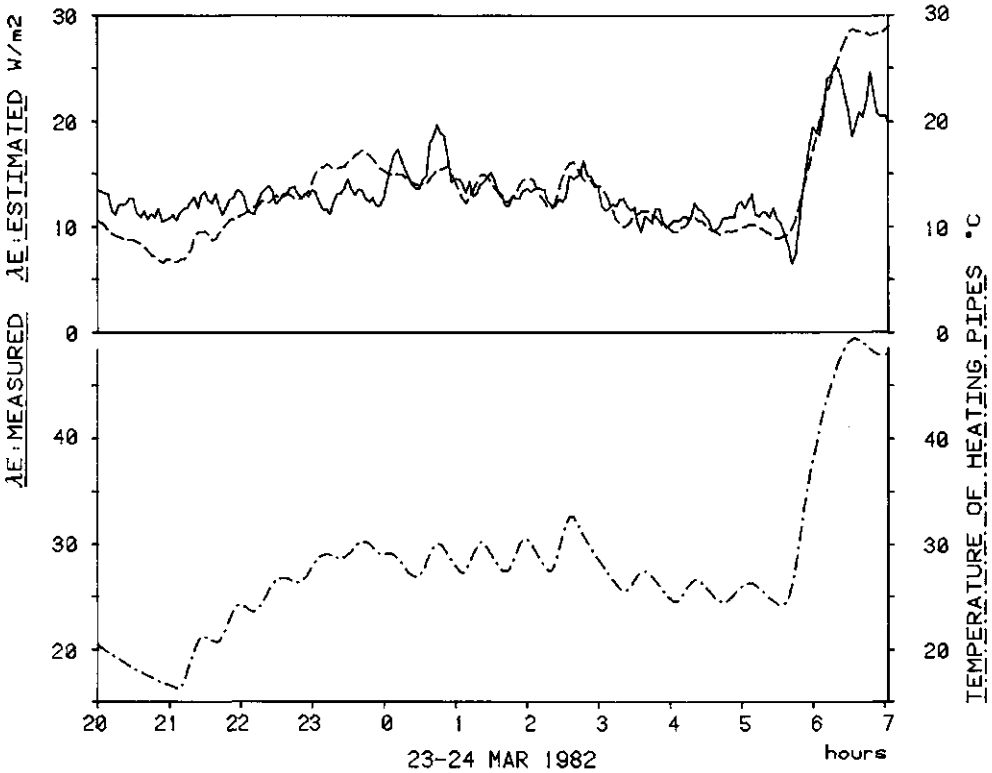


Fig. 4 - Measured and estimated evaporation for one night (top) and corresponding temperature of the heating pipes (bottom). Values indicated are as in Fig. 3, 5 value progressive means of 3 min data.

for one night a few weeks later. Five-value progressive means of 3-min measured and computed data are also given. As the trend of the corresponding temperature of the surface of heating pipes, plotted at the bottom of the figure shows, the roughly half-hourly fluctuations in both measured and computed evaporation are due to a corresponding period in the supply of energy.

To the present author's knowledge no estimates of potential evapotranspiration have been published, attaining such an accuracy for the small evaporative losses ($10 \text{ W m}^{-2} \cong 0.015 \text{ mm h}^{-1}$) and the short sampling intervals applying to Figs. 3 and 4.

There is room for improvement, however, as the following discussion will make clear.

4.1. Radiative part of potential evaporation

The ratio of the radiative to the aerodynamic part of computed evaporation, as given in Tab. 1 (i.e. the ratio of the 2nd to the 1st term of (20)), shows a definite increasing trend with time. It is fairly obvious that the eightfold increase in solar radiation as resulting from Tab. 1 must provide for a comparable growth in the radiation-dependent term of (20), there being no reason for this to be matched by a similar increase of the other term. Moreover, with daylight values, as in Fig. 5, the aerodynamic term is actually negligible, since the ratios as given in Tab. 1 account also for night time evaporation, which is largely aerodynamic. In these conditions almost any parametrization of the aerodynamic resistance would do; accordingly, daylight values for late spring and summer provide a good test of the radiative part of (20).

The measured and computed evaporation is shown in Fig. 5 (with 5-value progressive means of 3 min data) for such a day, characterized by high irradiation and scattered cloudiness. The corresponding values of the aerodynamic term of (20) are given as a reference. Apart from a definite phase shift, to be discussed in § 4.2, the amplitude of fluctuations in measured evaporation rates and their pattern is satisfactorily reproduced, in the computed values.

It can thus be stated safely that the present formulation for potential evaporation allows the effect of actions, such as the use of shading screens or infrared heating, on the irradiation of the crop to be estimated. Let us briefly discuss the effect of infrared heating, as an example.

The proposed parametrization of the aerodynamic resistance does not apply to

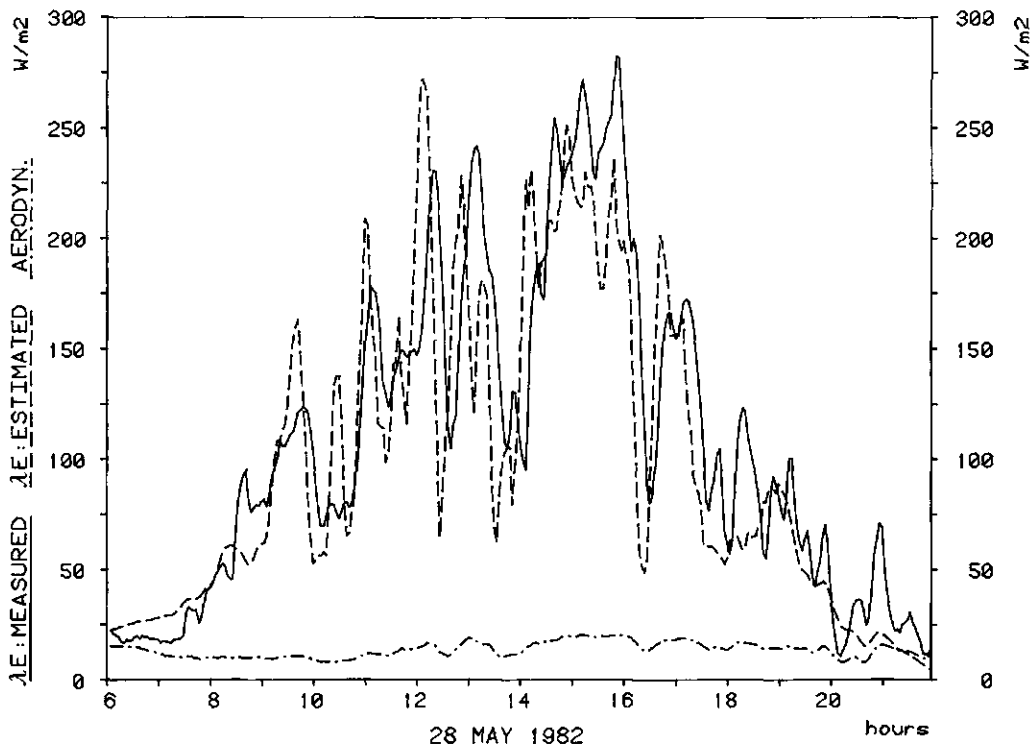


Fig. 5 - Measured and estimated evaporation for a late spring day characterized by scattered cloudiness. Here also, 15 min progressive means of 3 min values are shown. At the bottom of the figure the aerodynamic term (AERODYN) is also plotted (see text).

such a system, since it would ideally have no convective transfer. In real systems, of course, some convective transfer always takes place, but for the sake of simplicity let us assume that $r_a \sim \infty$, so that the resulting potential evapotranspiration is bound to be an underestimate of the actual one. A typical value for the ratio $\delta(T_a)/(\delta(T_a) + \gamma)$ is 0.6; measured nighttime net radiation above the crop can well go up to $100 - 150 \text{ W m}^{-2}$, of which, say half, is absorbed by the canopy. In this case eq.(20) yields $\lambda E = 30 - 45 \text{ W m}^{-2}$, which is double the highest nighttime evaporation rate measured in the present experiment. This result is confirmed by Van de Braak and Knies (1983), who observed that much more irrigation was needed in a greenhouse compartment infrared heated than in the control one, which was heated in a more conventional way.

4.2. Storage of energy in the foliage

In Fig. 3 and, more clearly, in Fig. 5 a phase shift between potential and actual evaporation is to be observed. The present author (Stanghellini, 1983c), already interpreted this time lag between the supply of energy and its dissipation in terms of storage of energy in the plant itself. Actually the term $R_n - G$ appears in (10) and R_{abs} in (20) to allow for this problem, its meaning being, in both cases, the difference in net radiation flux measured above the canopy and the flux of heat below it. However, the portion of the intercepted radiation that is stored in the foliage and not directly dissipated through both latent and sensible heat exchanges is not accounted for in this procedure. An order of magnitude for it can be easily calculated, since it must be equal to the time derivative of the temperature of the foliage times its thermal capacity, when energy used for photosynthesis is neglected.

Then, a temperature variation of $0.1\text{ }^\circ\text{C}$ in the interval between scans (180 s) of plants weighing 3 kg and having the thermal capacity of water ($4.2 \cdot 10^3\text{ J kg}^{-1}\text{ K}^{-1}$), with two plants per m^2 ground area, results in a thermal storage of 14 W m^{-2} . This problem has been overlooked in the literature, possibly for two reasons: one is that only short-term measurements of fluctuating evaporation rates could make it apparent, another is that most published studies deal with short field crops, such as alfalfa, whose thermal capacity per unit ground area may be too small to make the phase shift relevant.

In Stanghellini, 1983c, it was shown how this phase shift increases with the development of the canopy and how the presence of a thermal capacity comparable to the measured plant weights could explain it.

Results shown by Van Bavel, 1966, appear to support the point that such a delay does not need to be a stomatal effect: a relevant phase shift could be observed between hourly values of potential and actual evaporation of open water and wet bare soil, while not appearing in values concerning evapotranspiration from alfalfa.

Another effect attributable to this point is shown in Fig. 6, where 10-min measured and computed evaporation values are shown for a night characterized by far wider fluctuations of the surface temperature of the heating pipes (17 to $52\text{ }^\circ\text{C}$) around a comparable mean, as in Fig. 4, however, with a period of about 4 h. In the bottom of the figure, the radiative and aerodynamic parts of (20) are shown separately.

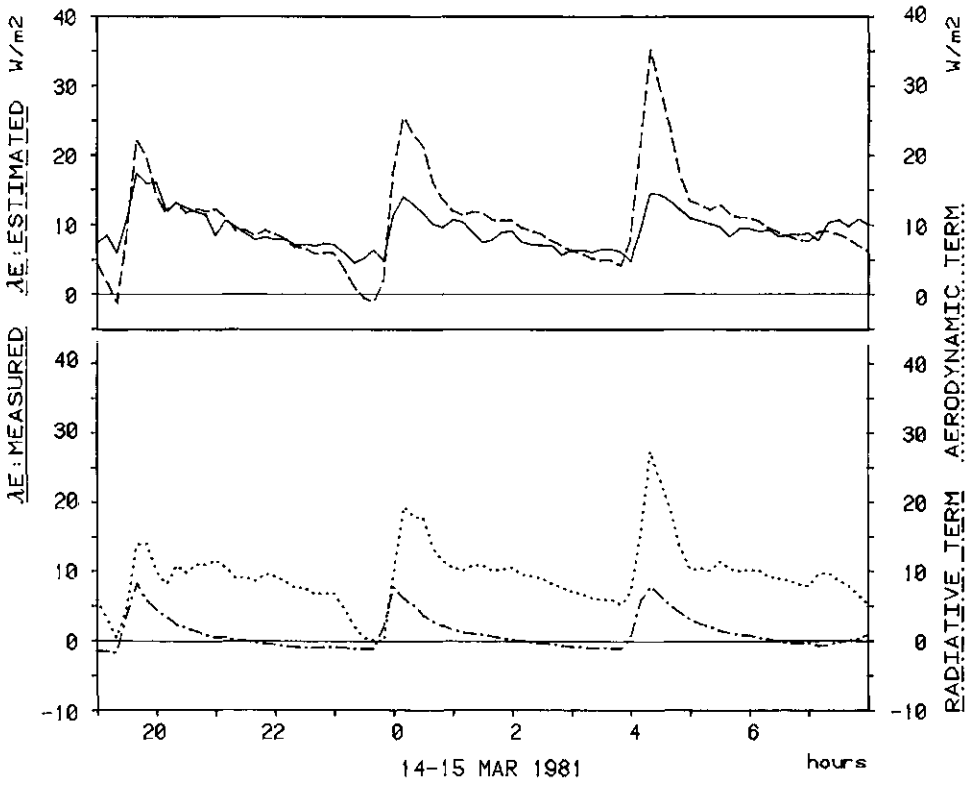


Fig. 6 - Measured and estimated nighttime evaporation of a still fairly undeveloped crop, at 10 min intervals (top). Heating was provided during three large fluctuations beginning respectively at 19 20, 23 40 and 4 00 hours. During warming up, which lasted about 20 min, the pipe temperature rose from 17 to 52 °C and air temperature from 12 to 17 °C. In the bottom of the figure the corresponding values of the radiative and aerodynamic terms are shown.

Notwithstanding a satisfactory performance of the method in general, the amplitude of oscillations in evaporation rates appears to be amplified. As far as the too low estimates at the end of the cooling periods are concerned, they have to be due to an underestimate of the radiative term, since the air was becoming more and more saturated while cooling, so that the aerodynamic

term had to become nil, for any value of the aerodynamic resistance. Some energy was thus contributed by the cooling of the foliage, which sustained evaporation rates in a way that is not accounted for in (20).

On the other hand, the reverse was happening during warming up: typically, the air was warming from 12 to 17 °C in 20 min; even if a smaller amplitude (3 °C) and a longer interval (30 min) are assumed for the warming up of the foliage, and a conservative estimate of 0.5 kg per plant is made for the relevant run, we get 7 W m^{-2} as the thermal energy stored during the time required for the foliage to warm up.

It will be clear at this point that the thermal storage of energy in the foliage is an unavoidable problem when short-term estimates of evaporation are needed, as here. However, the parametrization of both the phase shift and of the damping of the amplitude of oscillation of actual evaporation rates, require a knowledge of the temperature regime of the foliage, which is actually what the use of the combination method was meant to avoid.

Therefore, it has to be expected that no solution of the above-mentioned problems can be offered by a minor improvement of the method here outlined, but the whole procedure would have to be modified.

4.3. Aerodynamic resistance

Figs. 4 and 6 show that the proposed parametrization for the aerodynamic resistance is adequate since, the evaporation being mostly "aerodynamic" in those conditions (see Fig. 6), a wrong aerodynamic resistance would clearly affect the accuracy of the estimates.

On the other hand, there are circumstances in which pipe heating is by no means the driving force for vapour transfer (see Fig. 7 as an example). As was discussed in Stanghellini, 1983b, the large increase of actual evaporation taking place after 20 00 hours, was due to a sudden opening of the windows. The same applies to Fig. 5, and to many of the short-term fluctuations in evaporation rates seen in Fig. 2, the radiation pattern during that day being a clean, bell-shaped curve and no heating being then provided.

In Fig. 7, 3 min measured and estimated evaporation values are shown (top) for the late afternoon of a warm spring day, together with separate values for the radiative and aerodynamic terms. The underestimate of potential evapotranspiration is clearly due to an overestimate of the aerodynamic resistance, which, in its present formulation, does not account for the increase of air movement due to ventilation.

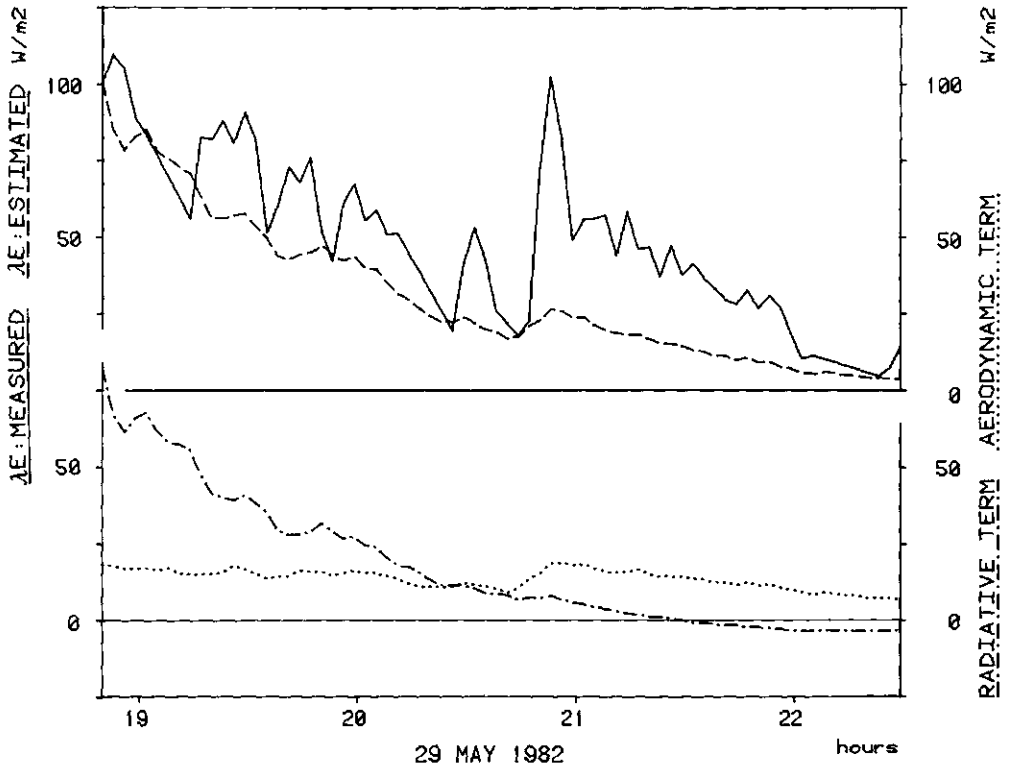


Fig. 7 - 3 min measured and estimated evaporation for the late afternoon of a spring day. Radiative and aerodynamic parts of (20) are shown separately at the bottom of the figure. Opening of the windows was continuously adapted by the climate control system, and at about 20 30 hours the windows were opened widely. The inadequacy of the aerodynamic term to account for the ensuing enhancement of vapour transfer is clear.

It should also be noted that the parametrization here suggested for the aerodynamic resistance, intended as the resulting resistance from the boundary layer, and the stomatal and cuticular ones, is acceptable only when the last two are negligible against the first one.

In this respect, although the agreement between nighttime predicted and measured values is far better in the present paper than in the one of Van Bavel, 1966, the problem of overestimating when the resistance at the surface becomes relevant has not been solved here: it is, however, less common in an indoor climate where the boundary layer resistance is likely to be greater than it is outdoors and stomatal resistance lower (Mansfield, 1965).

5. CONCLUSIONS

It has been shown how a combination method for potential evaporation in greenhouses gives excellent agreement with the measured actual vapour production of a tomato crop on a 24 h basis, and a fairly good one on a few minutes time basis. The method is based on simple measurements to be performed inside the house and on parameters of both the heating system and of the canopy, to be derived, once for all, with procedures described in previous publications (Stanghellini, 1983a, 1983c).

The physical basis of the combination method for estimating potential evaporation implies that eq.(20) can be applied successfully to any other greenhouse crop and conditions, provided that the absorbed radiation (R_{abs}) and aerodynamic resistance (r_a) are correctly evaluated.

The main difference between the method proposed here and similar methods developed for field crops resides in the parametrization of the so-called aerodynamic resistance. The theory for field crops is based on vapour (as well as heat) transfer due to forced convection in the presence of a well-established wind profile. Such theory obviously does not apply to greenhouse conditions, even though in most cases it is still possible to talk of forced convection at the leaf surface. The argument developed here was based on the consideration that in such circumstances there must be a subsystem for which free convection is established, so that air movement in the greenhouse can be completely attributed to such a free convection.

The choice of placing the origin of this free convection at the surface of the heating elements proved fairly adequate for nighttime winter conditions, which are, in fact, the most important as far as energy losses are concerned.

On the other hand, it is clear that this procedure is no longer justified when no heating is provided or when air movement in the greenhouse is forced by an external system (ventilation, warm air heating systems, etc.). In all these conditions a more flexible formulation of the aerodynamic resistance allowing for various causes of the forced convection at the evaporating surface would be more physically justified and would give better results.

Would an empirical formulation for the aerodynamic resistance based on measured indoor air movement give as good a result? Probably it would, but it would have two shortcomings. One is that adequate instruments for measuring air movement at the specified levels are expensive and delicate, and are by no means instruments to be installed in a commercial greenhouse, so that the practical

applicability of a formula based on such continuous measurements would be strongly reduced. The second is that the parameters of such an empirical formulation would have to be derived for all the possible combinations of crop and greenhouse structure to guarantee a general applicability of the method. It has also been shown how, to get better estimates of greenhouse evaporation on a time basis suitable for control systems, the energy stored or released during variations in the temperature of the foliage has to be accounted for. An extension of the method to allow for such a possibility would, however, severely affect its whole derivation, since a parametrization of the temperature of the evaporating surface would be needed, which has been avoided in the present study.

ACKNOWLEDGEMENTS

I wish to acknowledge the financial grant from the Dutch Ministry of Agriculture and Fisheries that allowed me to take part in this project and, in particular, Dr. Ir. G. Germing who always showed interest and appreciation for the work done.

The research was made possible by the collaboration with the Department of Physics and Meteorology of the Agricultural University and I am deeply indebted to Ir. G.P.A. Bot of that Department for his help.

I am grateful to Ir. W.P. Mulder, Head of the Climate Control Department of IMAG, for his stimulating support and to the staff members of that Department for the friendly working atmosphere. Much of the experimental work was done by F. Dormans, A. van 't Ooster and J. Reinders, students of the Agricultural University, to whom I am grateful for the pleasant collaboration.

My husband, Dr. M. Menenti, offered his help and advice in many circumstances throughout the whole study. Discussion with many colleagues was always fruitful for me, and I would like to thank here explicitly Ir. D. Bokhorst, Ing. A.M.G. v.d. Kieboom, Dipl.Phys. J.A. Stoffers and Ing. A.W.E. Weyerman for the time devoted to me.

F.J.M. Corver and the horticultural staff of IMAG kept the crop alive and healthy, notwithstanding the experiment, and D.H. Pasman and H. Schouwink gave much help with the experimental set-up.

REFERENCES

- VAN BAVEL, C.H.M., 1966. Potential evaporation: the combination concept and its experimental verification. *Water Resour. Res.*, 2(3), 455-467.
- BOT, G.P.A., J. MEIJERS, C. STANGHELLINI and A.J. UDINK TEN CATE, 1983. Development and application of a high precision weighing lysimeter. Submitted to *Jour. Agric. Engng. Res.*
- VAN DEN BRAAK, N.J. and P. KNIES, 1983. Personal communication.
- BUSINGER, J.A., 1956. Some remarks on Penman's equation for the evapotranspiration. *Neth. J. Agr. Sci.*, 4:77-80.
- DORMANS, F.J.S.M., 1983. Metingen aan en simulatie van de gewasverdamping in een geschermd kas. *Doctoral thesis, Agric. University, Wageningen. In preparation.*
- MANSFIELD, T.A., 1965. Studies in stomatal behaviour: XII. Opening in high temperature in darkness. *Jour. of Experimental Botany*, 16(49):721-731.
- VAN MEURS, W.Th.M., 1980. The climate control computer system at the IMAG, Wageningen. *Acta Horticulturae*, 106:77-83.
- MONTEITH, J.L., 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.*, XIX: 205-234.
- VAN 't OOSTER, A., 1983. Metingen aan en simulatie van het klimaat in een geschermd kas. *Doctoral thesis, Agric. University, Wageningen: 15-28.*
- PENMAN, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc.*, A193:120-145.
- REINDERS, J.E.M., 1982. De metingen van transpiratie en sapstroom in planten. *Doctoral thesis, Agric. University, Wageningen: 1-19.*
- RIJTEMA, P.E., 1965. An analysis of actual evapotranspiration. *Agric. Res. Rep. Wageningen*, 659:1-107.
- STANGHELLINI, C., 1981a. Estimation of energy requirement for evaporation in greenhouses. *Acta Horticulturae*, 115:693-699.
- STANGHELLINI, C., 1981b. Evapotranspiration and energy consumption in greenhouses. *Acta Horticulturae*, 119:273-279.
- STANGHELLINI, C., 1983a. Calculation of the amount of energy released by heating pipes in a greenhouse and its allocation between convection and radiation. IMAG, Wageningen, Research Report 83-3. 20 pp.
- STANGHELLINI, C., 1983b. Forcing functions in greenhouse climate and their effect on transpiration of crops. IMAG, Wageningen, Research Report 83-4, 55 pp.

- STANGHELLINI, C., 1983c. Radiation absorbed by a tomato crop in a greenhouse. IMAG, Wageningen, Research Report 83-5. In press.
- VARST, P.G.I. VAN DER and J.D.G. POSTEL, 1972. Bepaling bladoppervlak van tomatenplanten. ITT, Wageningen, Report 46, 36 pp.

