

# TRANSPIRATION OF GREENHOUSE CROPS

## an aid to climate management

This thesis is also available as publication of the Institute of Agricultural Engineering (IMAG), Postbus 43, 6700 AA Wageningen, The Netherlands.



BIBLIOTHEEK  
LANDBOUWUNIVERSITEIT  
WAGENINGEN

Promotor: dr. ir. J. Schenk, hoogleraar in de technische natuurkunde  
Co-promotor: dr. ir. G.P.A. Bot, universitair hoofddocent

NN 08201,1152

Cecilia Stanghellini

# TRANSPIRATION OF GREENHOUSE CROPS an aid to climate management

## Proefschrift

ter verkrijging van de graad van  
doctor in de landbouwwetenschappen,  
op gezag van de rector magnificus,  
dr. C.C. Oosterlee,  
in het openbaar te verdedigen  
op dinsdag 23 juni 1987  
des namiddags te vier uur in de aula  
van de Landbouwuniversiteit te Wageningen.



Instituut voor Mechanisatie, Arbeid en Gebouwen  
Wageningen, 1987.

BIBLIOTHEEK  
LANDBOUWUNIVERSITEIT  
WAGENINGEN

15N 488134

## CURRICULUM VITAE

Cecilia Stanghellini was born in Pistoia (Italy) on the 4th Augustus, 1953. She attended the local High School from 1967 to 1972. In 1977 she obtained her diploma in Physics (cum laude) at the University of Bologna with a thesis on the deposition rate of aerosols over evaporating surfaces, in partial fulfilment. From 1977 to 1978 she was with the Institute of Atmospheric Physics of the Italian Research Council (CNR), in Bologna, working on the corrosion of ancient buildings due to acid rain. She then joined Sogesta at Urbino, a state-owned engineering and training company, dealing with the management of energy and environment. There she participated in a number of projects including a climatological study on the efficiency of a focusing solar power plant, and a research on the influence of the local climate on the efficiency of various energy-saving techniques in the housing sector. In 1980-81 she received a grant from the International Agricultural Center in Wageningen, for an individual research program. This research – a study of the influence of artificial heating on the transpiration of greenhouse crops – was carried out at the Institute of Agricultural Engineering (IMAG) in Wageningen. The grant was later extended by the energy fund of the Dutch Ministry of Agriculture and Fisheries. From 1984 to 1986 she was a Ph.D. candidate with the Department of Physics and Meteorology of the University of Agriculture, in Wageningen, the contract being financed by the same fund. The work, of which this dissertation is the result, was carried out at the IMAG where she has been employed as a senior Scientist in the Process Engineering Division, since January 1987.

# STELLINGEN

- 1 Manipulation of the relative humidity in a greenhouse is no substitute for the manipulation of the transpiration rate.

This thesis, Chapter 4.

- 2 At least three parameters of the microclimate are needed for a reliable estimate of the actual transpiration rate of a greenhouse crop, in any condition.

This thesis, Chapter 4.

- 3 Stimulating air circulation in a greenhouse may have any effect (or no effect at all) on the transpiration rate of the crop.

This thesis, Chapter 2.

- 4 The active area for the exchange of energy of a greenhouse canopy can vary by two orders of magnitude, according to the modality of energy exchange.

This thesis, Chapter 3.

- 5 Aluminium coated heating pipes could attain a higher efficiency in greenhouse heating.

- 6 The total energy transfer coefficient of a greenhouse (better known as k-value) increases as the crop grows.

- 7 There is more scope for improving potential crop productivity through the manipulation of the geometrical properties of the canopy than through the manipulation of the optical properties of the leaves.

Menenti, M., 1984. Ph.D. Dissertation, Agricultural University, Wageningen: Stelling XI.

- 8 The establishment of simple relationships between plant properties and microclimate will improve current understanding of the impact of global climate on global vegetation patterns.

- 9 If measurement of the temperature of a field crop is to yield a tool for irrigation scheduling, it has to be coupled to more knowledge about the microclimate than the saturation deficit only.

Idso, S.B., 1982. *Agric. Meteorol.*, 27: 59-70.

- 10 Idso's conclusion that the stomatal conductance is proportional to the net radiation absorbed is invalid, since he ignored both the possibility that the stomatal resistance varies with the vapour pressure deficit and that the vapour pressure deficit varies with irradiation, in natural conditions.

Idso, S.B., 1983. *Agric. Meteorol.*, 29: 213-217.

- 11 Neither the available climatological data nor the current accuracy of forecasts on cost evolution allow for really sound decisions on the development of solar energy power plants to be taken.

- 12 Reverse discrimination (i.e. race-conscious hiring quotas) is a way of letting young whites pay the moral debts incurred by their forefathers.

- 13 Career opportunities for women would be more effectively improved by a wider availability of good child care than by an imposed sexual tailoring of the workforce at large.

*fatti non foste a viver come bruti  
ma per seguir virtute e conoscenza*

Dante Alighieri, 1307. La Divina Commedia.  
Inferno, Canto XXVI: 119-120.

THIS BOOK IS DEDICATED

to the memory of my father, Dr. Avv. Luciano Stangheli-  
lini, who was my most effective teacher

and to Laura and Anna Menenti, my daughters, both  
born during the time this research was carried out; and  
who may think they endured more than a fair share of it.

# ABSTRACT

Cecilia Stanghellini, 1987. Transpiration of greenhouse crops. An aid to climate management. Ph.D. Dissertation, Landbouwniversiteit, Wageningen. Also available as publication of the Inst. of Agric. Engng. (IMAG), Wageningen. 18 + 150 pp.; 134 eqs.; 57 figs.; 7 tables; 197 refs.; English, Dutch, Spanish, Italian summaries.

In this book some physical aspects of greenhouse climate are analyzed to show the direct interrelation between microclimate and crop transpiration. The energy balance of a greenhouse crop is shown to provide a sound physical framework to quantify the impact of microclimate on transpiration and to identify the constraints set on climate management by the thermodynamic behaviour of the canopy. Before the relationship among microclimate, canopy temperature and transpiration is rendered in mathematical terms, a good deal of experimental work is necessary to establish sub-models for the heat transfer of the foliage, for the radiative transfer within the canopy and for the canopy resistance to vapour transfer. The sub-models are merged in a combination-type equation to obtain the temperature of a greenhouse crop and its transpiration. The resulting estimates are shown to reproduce accurately the temperature and transpiration of a greenhouse tomato crop, as measured at time intervals of a few minutes.

To illustrate the practical application of the model thus developed a number of examples are presented. In particular, it is shown that defining the transpiration rate as the criterion for the control of air humidity within a greenhouse would deliver a quantitative framework for that control. That would largely enhance the efficiency of the (expensive) procedures applied at present for the control of humidity in greenhouses.

free descriptors: crop transpiration, greenhouses, humidity, climate control, heat transfer of leaves, radiation transfer in canopies.



# CONTENTS

<b>PREFACE</b>	<b>xi</b>
<b>LIST OF SYMBOLS</b>	<b>xv</b>
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Greenhouse management and vapour production	3
1.2 Energy balance, transpiration and temperature of greenhouse crops	3
1.3 Scope of the present research and organization of the book	5
<b>2. ENERGY EXCHANGE AT A LEAF SURFACE</b>	<b>7</b>
2.1 Definitions	8
2.1.1 Net radiation	8
2.1.2 Sensible heat flux	10
2.1.3 Latent heat flux	11
2.1.4 Photosynthesis rate	12
2.1.5 Thermal storage	13
2.2 Transpiration and temperature	13
2.2.1 Actual transpiration	13
2.2.2 Temperature of the external surface	19
2.3 External resistance at a leaf surface	20
2.3.1 General	20
2.3.2 Experimental determination of the external resistance	24
2.3.3 Results and discussion	28
2.4 Internal resistance	34
2.4.1 Response to environmental factors	35
2.5 Discussion	38
2.5.1 Net radiation as a function of surface temperature	39
2.5.2 Error due to the linearizations	41
2.5.3 Net radiation, saturation deficit and air temperature	42
2.5.4 External resistance	43
2.5.5 Internal resistance	50
2.6 Summary	53

<b>3.</b>	<b>ENERGY BALANCE OF A GREENHOUSE CANOPY</b>	<b>55</b>
3.1	Definitions	57
3.1.1	External resistance of a canopy	59
3.1.2	Internal resistance of a canopy	59
3.1.3	Transpiration and temperature of a canopy	61
3.2	Net radiation of a greenhouse canopy	62
3.2.1	Longwave transmittance of a stand	63
3.2.2	Shortwave transmittance of a stand	64
3.2.3	Reflectance (albedo) of a stand	66
3.2.4	Transfer of radiation in a greenhouse canopy	67
3.2.5	Experimental determination of the coefficients	68
3.2.6	Results and discussion	70
3.2.7	Radiation exchanged by a row crop	72
3.3	Thermal storage	74
3.4	Smoothing rules	76
3.4.1	Net radiation	76
3.4.2	Temperature of a canopy	79
3.4.3	Transpiration rate	82
3.5	Internal resistance of a canopy	83
3.5.1	Experimental determination of the internal resistance of a canopy	83
3.5.2	Results and discussion	89
3.6	Temperature and transpiration of a greenhouse canopy	94
<b>4.</b>	<b>TEMPERATURE AND TRANSPIRATION OF A GREENHOUSE CANOPY AS THE OUTCOME OF THE MICROCLIMATE</b>	<b>97</b>
4.1	Variation of canopy temperature and transpiration with the microclimate	98
4.1.1	Influence of the shortwave irradiation	98
4.1.2	Influence of the saturation deficit of the ambient air	99
4.1.3	Influence of the air temperature	100
4.1.4	Influence of the air velocity	102
4.1.5	Influence of the surface temperature of the heating system	103
4.1.6	Influence of the temperature of the cover and of the soil surface	104
4.1.7	Influence of the carbon dioxide concentration of the ambient air	105
4.1.8	Conclusion	106

4.2	Transpiration: a re-appraisal of current procedures of climate management	107
4.2.1	Manipulation of the ambient temperature	108
4.2.2	Manipulation of the humidity of the ambient	109
4.2.3	Manipulation of the shortwave irradiation of a canopy	110
4.2.4	Manipulation of the exitance of a canopy	110
4.2.5	Other manipulations of the microclimate	111
4.3	Examples	111
4.3.1	Optimal supply of heat at night	114
4.3.2	Making the best out of little irradiation	116
4.3.3	Containment of the transpiration rate	116
4.3.4	Cooling	117
4.4	Summary	119
5.	CONCLUSION	121
	SUMMARY	125
	SAMENVATTING	129
	RESUMEN	133
	SOMMARIO	137
	REFERENCES	141

## PREFACE

It cannot be denied that one is much relieved when setting about the task of writing this section, not least because the fatigue of writing the pages following these is completed. A no less important reason, however, is the pleasure of finally getting rid of the moral debt I contracted with so many people in the years I have been working on this research. I regard the publication of this book, therefore, as a most welcome chance to thank the people who contributed their kindness and their skills to it.

This dissertation is no more than I was meant to produce after three years devoted to the present subject as a Ph.D. candidate with the Department of Physics and Meteorology of the University of Agriculture at Wageningen, under a contract financed by the 'energy fund' of the Dutch Ministry of Agriculture and Fisheries. I wouldn't have succeeded in this time, however, were it not for the experience I had gained in the previous two years as a fellow with the Institute of Agricultural Engineering (IMAG) also at Wageningen, my grant being provided by the same fund. I therefore am greatly indebted to the manager of that fund, Ir. W.F.S. Duffhues and to Dr. Ir. G.H. Germing, coordinator of the research on energy aspects, for entrusting so much to me. However, this research would never have been performed, nor this book published, if not for the unyielding support granted to me by the directors of the IMAG. I feel therefore indebted in particular to Ir. J.J. Laurs, deputy director of the IMAG, and I do hope this book measures up to his confidence.

The experiments were shaped and this thesis was given its present form, thanks to what I learned from a number of people. I much enjoyed having to discuss each page of this book thoroughly with my promotor, Prof. Dr. Ir. J. Schenk. He made a far better product of my drafts, with his patient and careful reading. I am most grateful to my co-promotor, Dr. Ir. G.P.A. Bot for his availability. He contributed enormously to both the devising of the experiments and to getting my thoughts accurately expressed on paper. Dipl. Phys. J.A. Stoffers, Ir. D. Bokhorst and Ir. N.J. Van de Braak, all of IMAG, made time in their busy schedule to read the many drafts of this book and to comment keenly on them. They contributed by their various expertise an extremely stimulating environment, for which I am no less grateful than for the friendly atmosphere.

The work was carried out at the IMAG. The task of supervising my use of the remarkable facilities available there and of securing an ideal working environment rested upon the shoulders of Ir. W.P. Mulder and Ing. J. Maring, successive heads of the Process Engineering Division of the IMAG. I am quite grateful to them for making this interaction not only smooth and efficient, but also pleasant. I was lucky to be able to make use of the competence and kindness of D.H. Pasman for the cumbersome set up of the experiments. He also took care of the maintenance of the instruments, some of which were provided by the 'energy fund'. Two kinds of instruments (the artificial leaves and the thermocouple sets for the leaf temperature) however, were especially designed and produced, with remarkable ingenuity by P. Jansen, A.E. Jansen, T. Jansen and W.C.A.M. Hillen, all of the Department of Physics and Meteorology of the University of Agriculture. P. Jansen, moreover, took care of the data-logging installations.

The one reason I did enjoy such a boring task as performing the experimental runs was the collaboration I received from T. De Jong, F.J.S.M. Dormans and B. Van 't Ooster, then students of the University of Agriculture, now successfully graduated. T. De Jong, moreover, performed some analyses of the results of the experiments which have been used here, for the radiation model. For the experimental runs with the artificial leaves I was helped by F. Habraken and T. Sprokholz, during their practical experience trimester for the technical high school. Ing. T.H. Gieling of the IMAG kindly took care of a couple of experimental runs during a forced absence of mine. Ing. D. Van 't Akker of the Department of Physics and Meteorology rushed to the rescue the many times when something went wrong during the experimental runs. He, moreover, introduced me to the use of the program applied for the calculation of the parameters of the model for the internal resistance.

G.F. Van 't Sant, then head of the gardens of the IMAG, always succeeded in accommodating my wishes with regard to the experiments and the crops. F.J.M. Corver, C.J. Lammers, L.B.M. Romijnders and H.J.W. Scholten, provided extremely pleasant and successful assistance in solving a myriad of practical problems being, at the same time, able to keep the crop healthy, in spite of the experiments. F.J.M. Corver, in addition, kept track of the crop production and performed the statistical analysis of it. Ing. W.T.M. van Meurs, on the other hand, was extremely helpful with respect to my use (and misuse) of the climate control program of the IMAG greenhouses, as well as of the computer, originally meant to perform only that task. I am grateful to him for this, and for his critical reading and discussions of chapter four. I am also indebted to Ir. G.T. Bruggink of the department of Horticulture of the University, for discussing the model for the internal resistance with me, giving advices which proved extremely farsighted. Ing. A.M.G. van den Kieboom, then at the IMAG, determined the transmissivity of the glasshouse and measured the optical properties of many materials. Both he and Ing. A.W.E. Weijerman also helped in many ways during the experiments.

Ir. G.J.A. Nieuwenhuis of the Institute for Land and Water Management Research (ICW) kindly executed the thermography reproduced in fig. 2.6. To the staff of the library of the IMAG, i.e. Ir. G.D. Vermeulen, Miss A.F.C. Bonenberg and Miss H.M. De Stigter, I am grateful for their help in collecting a sizable amount of literature.

The many drawings of this book were patiently and skillfully completed by P. Van Espelo and C. Van Maanen and the photos were taken care of by J.C. Vierbergen. Marilyn Minderhoud-Jones and Ninette Smit-De Zylva suggested many improvements of my English text and Ing. H.J. Manting implemented the lay-out.

My husband, Dr. Massimo Menenti, despite his being abroad quite a fraction of the time, did contribute his deep understanding of evaporative events to some discussions on this matter. These brainstormings used to arouse my combative self, thereby contributing to shaping my own ideas. Our daughters Laura and Anna (unwillingly) accepted that some family meals were disrupted by the discussions just mentioned, to which they would eagerly contribute some noise. I was also lucky to get the help of members of my family in Italy. During the last few weeks of my tour-de-force to complete this book, which coincided with one of my husband's long spells abroad, my mother came to ensure a pleasant environment for the children. Lorenzo and Elena Stanghellini, my brother and sister, looked for rare editions of the Latin works which were not readily available in Wageningen, and which have been used in chapter one. With respect to the latter, my uncle, Dr. Ir. N. Rauty made useful suggestions.

Although I did draw on my background in the exact sciences, I realize that there are as many ways to represent a canopy, as there are leaves in it, and yet no representation is 'the exact one'. My aim has constantly been to make a compromise between realism and simplicity. However, it could be disputed to some length which compromise is the best. I wish to stress the point, therefore, that while many people contributed to this work, the responsibility for the approach, the methods, and the conclusions reported, are mine alone.

# LIST OF SYMBOLS

syml.	short explanation	units	defined by eq:
<b>A</b>	absorption coefficient for radiation	—	3.21
<b>B</b>	Planck's function	$W \cdot m^{-2} \cdot nm^{-1}$	2.2
<b>C</b>	any coefficient	—	
<b>c</b>	specific heat	$J \cdot kg^{-1} \cdot K^{-1}$	2.13
<b>c<sub>p</sub></b>	air specific heat at constant pressure	$J \cdot kg^{-1} \cdot K^{-1}$	2.8
<b>CO<sub>2</sub></b>	ambient carbon dioxide concentration	$m^3 \cdot m^{-3}$	2.54
<b>D</b>	diffusivity	$m^2 \cdot s^{-1}$	2.8
<b>d</b>	average leaf thickness	m	3.17
<b>E</b>	evaporation flux density	$kg \cdot m^{-2} \cdot s^{-1}$	2.1
<b>e</b>	vapour pressure	Pa	2.11
<b>F</b>	flux density of total available energy	$W \cdot m^{-2}$	3.35
<b>Gr</b>	Grashof number	—	2.32
<b>g</b>	acceleration due to earth gravity	$m \cdot s^{-2}$	2.32
<b>H</b>	flux density of sensible heat by convection	$W \cdot m^{-2}$	2.1
<b>h</b>	height of a row crop	m	3.15
<b>I</b>	irradiance	$W \cdot m^{-2}$	2.2
<b>J</b>	rate of thermal storage	$W \cdot m^{-2}$	2.1
<b>k</b>	radiation extinction coefficient	—	3.8
<b>L</b>	latent heat of vaporization of water	$J \cdot kg^{-1}$	2.1
<b>ℓ</b>	characteristic dimension	m	2.31
<b>LAI</b>	leaf area index	$m^2 \cdot m^{-2}$	3.2
<b>LE</b>	latent heat flux	$W \cdot m^{-2}$	2.1
<b>M</b>	photosynthesis rate	$W \cdot m^{-2}$	2.1
<b>Nu</b>	Nusselt number	—	2.33
<b>p</b>	inter row spacing (path width)	m	3.15
<b>Q</b>	electric power density in artificial leaf	$W \cdot m^{-2}$	2.39
<b>R</b>	radiation flux density	$W \cdot m^{-2}$	2.1
<b>Re</b>	Reynolds number	—	2.31
<b>RH</b>	relative humidity	—	
<b>r</b>	transfer resistance of heat or mass	$s \cdot m^{-1}$	2.10
<b>S</b>	flux density of sensible heat by conduction	$W \cdot m^{-2}$	2.14

syml.	short explanation	units	defined by eq:
T	temperature	K	2.7
t	time	s	2.13
u	wind speed	$\text{m}\cdot\text{s}^{-1}$	2.31
V	volume to area ratio	$\text{m}^3\cdot\text{m}^{-2}$	2.13
W	ratio of $R_n$ of a row crop to $R_n$ of a homogeneous crop	—	3.16
w	width of a row crop	m	3.15
z	vertical distance	m	2.8
$\beta$	thermal expansion coefficient of the air	$\text{K}^{-1}$	2.32
$\gamma$	thermodynamic psychrometric constant	$\text{Pa}\cdot\text{K}^{-1}$	2.11
$\delta$	slope of saturated vapour pressure curve	$\text{Pa}\cdot\text{K}^{-1}$	2.22
$\varepsilon$	surface emittance	—	2.2
$\lambda$	wavelength	nm	2.2
$\lambda$	thermal conductivity	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	2.19
$\nu$	kinematic viscosity of the air	$\text{m}^2\cdot\text{s}^{-1}$	2.31
$\rho$	surface reflectance	—	2.2
$\rho$	density	$\text{kg}\cdot\text{m}^{-3}$	2.8
$\sigma$	Stefan Boltzmann constant	$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$	2.7
$\tau$	transmittance	—	2.2
$\tau$	time constant	s	3.37

## SUBSCRIPTS

syml.	short explanation	defined by eq:
a	air	2.8
c	cold	2.40
E	at phase interface	2.15
e	external	2.28
g	of the soil surface	3.11
H	heat	2.10
h	of the environment	3.29
i	internal	2.28
l	longwave	2.6
m	which minimizes the resistance	3.48
min	minimal	2.54
n	net	2.1



symb.	short explanation	defined by eq:
$o$	at external surface	2.7
$p$	of the pipe system	3.14
$R$	radiation	2.65
$r$	range	2.3
$s$	shortwave	2.6
$t$	leaf tissue	2.13
$tot$	total	3.34
$u$	of the greenhouse cover	3.12
$V$	vapour	2.11
$w$	warm	2.39
$z$	at height/depth $z$	2.8
$\lambda$	spectral quantity	2.2
$\infty$	of a dense stand	3.11

## SUPERSCRIPTS

'	at a particular value	2.8
*	at saturation	2.12
-	dimensionless	2.54
-	mean	3.6

## LOGICAL RELATIONSHIP SYMBOLS

$=$	equal to
$\equiv$	by definition equal to
$\geq$	not smaller than
$>$	larger than
$>>$	much larger than
$\leq$	not larger than
$<$	smaller than
$<<$	much smaller than
$\approx$	roughly equal to
$\cong$	almost equal to
$\propto$	proportional to

# 1. INTRODUCTION

Mankind has long been aware of the fact that a wise modification of the environment could improve the productivity of crops. Indeed, as far back as 63 A.D. Seneca complained: 'Are not living against Nature, they who covet a rose in winter, and by means of the vapours of hot water and by an apt modification of the environment, breed in wintertime that spring flower?'. Indeed, the fact that light transmitting shelters could create a very suitable environment was certainly known to the Romans, as the Emperor Tiberius was able to eat cucumbers daily. These were 'grown in baskets fitted with wheels, so that they could easily be brought into the sun and on wintry days could be withdrawn into transparent shelters' (Plinius, 77 A.D.) – whence one might infer that the culture in movable benches also originated in Rome. However, though the mica used to cover those shelters was transparent enough for Martialis (93 A.D.) to assert: 'they admit the sun and the [light of] day without sun', it is probable that the (scarcity of) radiation was the factor which limited the productivity. In fact, at that time, it must have been easier to supply heat than light; a fact attested to by such a shelter unearthed in Pompeii which appears to have been fitted with hot-air flues (Lemmon, 1962).

In the course of time, the improvement in the techniques for producing flat glass panes enabled these shelters to evolve into ever more sunny 'orangeries' (Van den Muijzenberg, 1980). Clearly, the evolution of the use of glasshouses was based on some knowledge (albeit qualitative) of the relationship between plant growth and environment. Of course, no one could state that the production in those houses was efficient. It did not need to be, as their output was not normally meant to be sold. The purpose of such expensive cultivation was to appease the taste, or the curiosity, of the owner or (no less important) to impress his visitors. It is remarkable that already Plinius (77 A.D.) felt things had gone too far. He lamented: 'men are never satisfied with the things as Nature likes. Even [some] vegetables have to be grown only for the rich!'.

The use of greenhouses for commercial agricultural production had to wait until the technology was sufficiently advanced for the products to be sold, at competitive prices, on a market which had, in the meantime, become much richer. Today, the craft is such that in principle, it should be possible to let a climate control computer (coupled to quite a bit of gadgetry) to produce whatever microclimate

one wishes within a greenhouse. This would not necessarily result in competitive horticultural production however, as it might consume a lot of (supplied) energy. Moreover, people are now beginning to become aware that energy should not be wasted as its consumption has possibly far reaching consequences for the environment. Hence the aim of modern greenhouse management could be summarized thus: to let the greenhouse climate be determined by the weather (outside climate) to the extent to which it is useful and to produce a (partially) artificial climate whenever beneficial 'so that even during clear, cold days [the crop] can produce in the sun, undamaged' (Columella, 65 A.D.).

Although the development of computer technology could make expert systems for horticultural management possible, the present knowledge of the related physical, biological and economic processes is still insufficient. Challa (1985), summarizing a train of thought begun by Udink ten Cate et al. (1978), stated that the best way to achieve optimal greenhouse management was to define 'a hierarchical set of sub-systems, where each sub-system is optimized within the limits dictated by the higher levels'. Those three levels of the decision making process may be summarized thus:

1. Optimization of the long term return for the grower. In this stage a compromise between crop development and the market ability to absorb the product is effected. The output is a required trend of the crop processes or something like a sequence of 'process set-points';
2. The definition of the required microclimate. Here the microclimate necessary to attain the process set-points (with due consideration to the weather) is determined. Climate set-points are output to level 3;
3. Actuation of the climate set-points. Once the performance of the greenhouse in response to the weather and to any attempt to manipulate the microclimate is accounted for, the best control strategy to realize those climate set-points is decided upon.

Only this third level of decision making appears to be within reach of today's greenhouse management, thanks to a lot of research already performed in the fields of both greenhouse climate simulation (e.g. Takakura et al., 1971; Van Bavel et al., 1981, Von Elsner, 1982; Bot, 1983; Kimball, 1986) and climate control (e.g. Udink ten Cate, 1983; Kozai, 1985; Tantau, 1985; Verwaayen et al., 1985). On the other hand, the processes determining the crop production (i.e. the information required for level 1) are not sufficiently understood for their description in the form of equations to be available.

As climate control systems are used, the climate set-points have to be somehow assigned. They are most commonly fixed according to rules derived from substantial practical experience. The growing number (and complication) of those rules betray the shortcomings of the present state of the art, in relation to the knowl-

edge needed for a general approach to the second level, i.e. the transcription of the process set-points in terms of climate set-points. This work can make a contribution to the solution of this problem, although the whole book is devoted to only one of the many processes known to affect crop production, i.e. transpiration. The method developed here could well provide a blue-print for future research into other crop processes.

## **1.1 Greenhouse management and vapour production**

Production of vapour (transpiration) by a greenhouse crop is one of the processes one would much like to control. That is the consequence of two, quite different and sometimes contradictory, considerations. One is that crop production is long known to be related to water consumption, as a recent review by Van Keulen and Van Laar (1986) amply proves. The other has more to do with the saving of energy. In fact the application of energy saving devices (as double cover, thermal screens or reduced air exchanges), results in a lower rate of vapour removal, and a higher ambient humidity. Although 'initial concerns that this might increase the incidence of fungal diseases have not materialized' (Bailey, 1985), high humidity is often quoted as adversely affecting plant development, possibly as a consequence of reduced transpiration rates. Reduction of the ambient humidity by whatever means, is an expensive exercise and may dispose of the saving expected from applying better insulation (Breuer, 1987).

Therefore, whatever the rationale (thus the purpose) for either increasing or reducing the transpiration rate of a crop by means of manipulating the greenhouse climate, the relationship between the microclimate experienced by a canopy and its transpiration has to be accurately known. This relationship, moreover, has to be known on a time scale suitable for a climate control algorithm, i.e. of a few minutes. Hence, the scope of this work might be described as a means of providing some more insight into the way the microclimate determines the transpiration rate of a greenhouse canopy.

## **1.2 Energy balance, transpiration and temperature of greenhouse crops**

Although the main factors affecting the evaporation rate from a wet surface were known somewhere around two thousand years ago – as Greek and Latin philosophers were apparently aware of its being affected by both the Sun and the Winds – a comprehensive understanding of the process of evaporation still

seemed to elude scientists as recently as half a century ago. In 1926 Bowen provided for a theoretical description of the laws governing the simultaneous loss of heat and vapour from a surface. The practical application in agronomy of Bowen's findings, however, had to wait until 1948, when Penman contributed a sound theoretical basis for the understanding of the role played by radiation in determining evaporation from natural surfaces. He showed that the fundamental principles of thermodynamics (the energy balance equation) and of aerodynamics (the equations of transfer of heat and vapour) could be reconciled to yield the evaporation rate from an open water surface, if only the net radiation of the surface and the temperature, humidity and wind speed of the ambient air, were known.

In 1965, Monteith and Rijtema independently derived a variant of the Penman's method, valid for any wet surface (i.e. not necessarily open water). They stated that evaporation from such a surface is impeded by an additional transfer resistance, intrinsic to the surface. This surface resistance had also to be known for the appraisal of the evaporation rate. As this knowledge was seldom available, agrometeorologists used to assume the surface resistance to be small and stated that the Penman-Monteith-Rijtema method (also called the combination method) yielded, in this case, the 'potential' evapotranspiration of a crop. The fact that a crop transpiring at the 'potential' rate is not easily found in nature is plainly shown by the plethora of definitions of such a crop. Nor is this one the only conceptual limitation to the practical application of the combination method.

To begin with, most canopies cannot be regarded as a simple, flat surface. This implies that the assessment of the amount of radiation actually available is not as straightforward as it sounds. It also means that heat and vapour produced (or absorbed) at different depths within the canopy have to overcome transfer resistances of disparate magnitudes. A further implication is that the surface to which the intrinsic resistance for vapour transfer belongs is no longer easily identified. A canopy differs from a flat surface also in that its various parts are possibly exposed to a different microclimate, hence the specificity gradients appearing in the transfer equations may be non-uniform.

There is a practical problem too. The energy actually available for the transfer of sensible and latent heat is the difference between the net radiation and the thermal storage within the canopy. An assessment of the latter, however, requires the time course of the temperature of the canopy to be known, which is exactly the prerequisite the Penman method was meant to obviate. It is only when the thermal storage is small (over long time intervals or with stable weather) that knowledge of the net radiation may suffice for the successful application of the combination method. It is no coincidence, therefore, that these are also the conditions for which the method is acknowledged to be sufficiently accurate. Indeed, most of the afore-mentioned conceptual problems can also be solved by this means. Thus only long term averages of both the resistances and the net radiation

need to be known, and those may be incorporated in an empirical 'crop coefficient' (e.g. Doorenbos and Pruitt, 1977) whereby the ratio of the transpiration of a given crop to that of a crop transpiring at a 'potential' rate, exposed to the same weather, is estimated.

A greenhouse crop has peculiarities which rule out the simple transcription of experimental techniques developed for crops in a more natural environment. In fact, the resistance to the vertical exchange of heat for a field crop is normally estimated by the assumption that the canopy is immersed in a boundary layer, characterized by a well-defined (logarithmic) profile of the wind speed. This assumption is obviously untrue for a canopy enclosed in a greenhouse. Therefore, the need to appraise the boundary layer resistance within a greenhouse involves the development of an adapted experimental technique. Furthermore, the radiant energy available to a field crop is generally estimated as the difference between the net radiation measured on a surface above the canopy, and the heat transmitted below the soil surface. Of course, as sources of radiation are present within a greenhouse canopy, such an experimental method cannot be applied here.

Obviously, all these constraints make the combination method unsuitable, in this form, for the present purpose of determining the actual transpiration rate of a greenhouse crop for time intervals as short as a few minutes. On the other hand, the sound physical basis of it and its reliance on the knowledge of the microclimate exclusively, imply that the combination approach is quite attractive whenever the relationship between microclimate and transpiration is sought for, as it is here. Therefore, an adaptation of the Penman-Monteith-Rijtema method will be developed in this book, whilst trying to obviate the mentioned conceptual difficulties by a consistent set of definitions and a step-by-step approach.

### **1.3 Scope of the present research and organization of the book**

The scope of the present investigation can be described as the development of a method for the appraisal of the transpiration rate of a greenhouse canopy, as a physical process affected by the greenhouse climate (hereafter, microclimate). Once developed, such a method could be used within existing climate control systems in order to regulate the transpiration of a greenhouse crop in any way, suggested by both the present knowledge about crop welfare and the awareness of the need to keep the required energy to a minimum. Of course a model for the transpiration of the crop could also improve the accuracy of the greenhouse simulation models presently available, as the presence of a canopy exerts a non-negligible influence on the greenhouse environment.

After the outline provided in this chapter, the relationship between microclimate and vapour production will be analysed in chapter two. In the first place, this will be done for a simple wet surface like the one of an idealized leaf. It will

be shown how the system formed by the equations of balance and transport of energy and vapour to and from the surface, can be analytically solved, under some assumptions, to yield formulae for the temperature and vapour production of the surface. The parameters appearing in those formulae, namely the resistances to vapour and heat transfer, will be discussed. A method for the experimental determination of the resistance to heat transfer of leaves immersed in a greenhouse canopy will be described.

The equations deduced in chapter two will be applied in chapter three to a greenhouse canopy. First the impracticality of measuring the net radiation absorbed by such a canopy will be considered. In order to avoid this difficulty, a method will be developed, based on the theoretical equations of transfer of radiation in a turbid medium; such a method will be shown to yield fairly accurate results while requiring relatively simple measurements as input. Subsequently, the constraints imposed on the transpiration model by the fact that it is required to be accurate on a time scale of a few minutes, will be analysed. The resulting vapour production and surface temperature variations are then directly related to differentials in the surface temperature; the heat capacity of the foliage appearing as a parameter. A method based on experimental results, for the estimation of the heat capacity of the foliage will be described. Finally, the extension of the concept of resistance to a canopy will be discussed. An experimental determination of the canopy resistance to vapour transfer will be described, and the implications of the results reviewed.

In chapter four it will be considered if the model thus developed can be simplified (without considerable loss of accuracy). For this, a sensitivity analysis will be applied with respect to the various parameters previously introduced. On the other hand, the same analysis will reveal where the greatest scope lies, for an efficient control of vapour production, as well as of canopy temperature. A review of widely applied procedures to regulate air temperature and humidity in greenhouses will follow. It will be observed that quite often those procedures imply the unexpressed purpose of attempting to control the process of transpiration. The rest of the chapter, therefore, will be devoted to reconsider some typical climate control procedures from this point of view. It will be shown that the application of a 'transpiration set-point' could, indeed, improve the efficiency of the way the microclimate is controlled; it could even avoid the spilling of energy by unnecessary attempts to reduce the humidity in the greenhouse.

## 2. ENERGY EXCHANGE AT A LEAF SURFACE

The complexity of a canopy as a system of sources and sinks of heat and mass is such as to make an exact description of its physical behaviour almost impossible. While attempting to figure out a simpler representation (a model) of a canopy, one is facing two types of problems. The first one is the inherent spatial dishomogeneity of the foliage. This implies that, for an accurate description, the necessary variables have to be known for a good many points. The second one is the turbulent nature of the air stream within (and above) a canopy. Its consequence is that the direction and magnitude of the fluxes of energy and mass vary at any moment and cannot exactly be predicted.

In spite of this, in much of the literature concerned with the coupling of plants with their environment (e.g. Monteith, 1975; Jones, 1983), heat and mass transfer to and from a canopy are described as vertical fluxes along a concentration gradient, across some typical resistance. However, the assumption that transfer takes place along a vertical direction only, implies an averaging out of the variations along an horizontal plane. On the other hand, the known empirical relations between fluxes and gradients warrant the soundness of this approach only as far as time averages of fluxes and gradients are concerned. Therefore, the conditions for this approach to yield a sensible, albeit simplified representation of the behaviour of a real canopy, have to be thoroughly investigated. Certainly, things are no easier for greenhouse canopies, since the transfer of energy there cannot be figured out as taking place between the canopy and a (sufficiently distant) homogeneous air layer. Moreover, the presence of a heating system provides for some further complication, due to the additional energy (and buoyancy) sources within the canopy itself. To make up for these complications, a step-by-step approach will be adopted in the present work. The transport phenomena around a single leaf will be analyzed in the first place. Only afterwards will an attempt be made to describe the same phenomena in an ensemble of leaves, i.e. a canopy.

In fact, for a flat evaporating surface, such as the surface of an 'idealized' leaf, some of the conditions on which the assumption of one-dimensionality of the fluxes rests, are more intuitively met. Moreover, the existence of a boundary layer characterized by some resistance can be easily envisaged. In this chapter a method will be developed to determine vapour production and surface temperature of such an ideal leaf, on the basis of the energy balance of the surface. The conditions for such an approach to be of some value in relation to a greenhouse canopy, on the other hand, will be discussed in the next chapter.



## 2.1 Definitions

When radiation strikes the surface of a leaf, the energy thus absorbed is partly dissipated by evaporation of water and release of sensible heat, partly stored in the products of photosynthesis and as thermal energy in the leaf body. In fact, the temperature of the leaf continually adjusts to attain an equilibrium value such that the total consumption of energy would balance its gain. In agronomy and meteorology such a statement is commonly written as follows:

$$R_n = H + LE + M + J \quad W \cdot m^{-2} \quad (2.1)$$

where:

$R_n$  is the net flux density of radiation resulting from absorption and emission by the leaf ( $W \cdot m^{-2}$ )

$H$  is the flux density of sensible heat transferred to the air ( $W \cdot m^{-2}$ )

$LE$  is the flux density of latent heat due to evaporation of water ( $W \cdot m^{-2}$ ),  $L$  being the latent heat of vaporization of water ( $J \cdot kg^{-1}$ ), and  $E$  the vapour flux ( $kg \cdot m^{-2} \cdot s^{-1}$ )

$M$  is the rate at which energy is stored in the products of photosynthesis ( $W \cdot m^{-2}$ )

$J$  is the rate at which thermal energy is stored inside the leaf ( $W \cdot m^{-2}$ )

All the terms of eq(2.1) are written as averages for a unit surface area. It is convenient to define the surface area as the area from which sensible heat is lost, although this is not necessarily identical to the area from which energy is gained or lost by radiation or transpiration, as will be commented on later.

Certainly, all these energy fluxes may represent gains as well as losses of energy for the leaf. In fact, a leaf may well be a net radiator while gaining heat from warmer air or even from dew-fall at its surface. By writing eq(2.1) as such, the convention is made that the net radiation flux is positive when directed towards the leaf surface, while the fluxes on the right hand side are positive when leaving it. A reason for writing eq(2.1) in this (admittedly inconsistent) fashion, has probably been due to the use of regarding  $R_n$  as an easily measurable flux, largely independent from the temperature of the leaf, while both sensible and latent heat fluxes are acknowledged to be strong functions of the temperature of the surface.

### 2.1.1 Net radiation

A correct estimate of the net radiation flux of a leaf is far from straightforward. Since no natural leaf has a perfectly flat surface, the effective area exposed to the radiative flux may be difficult to estimate. Moreover, the radiative properties of the leaf tissue are dependent on wavelength. Therefore, when the radiation emitted by the leaf is also taken into account:

$$R_n = \int_0^\infty [(1 - \tau_\lambda - \rho_\lambda) I_\lambda - \varepsilon_\lambda B_\lambda] d\lambda \quad \text{W} \cdot \text{m}^{-2} \quad (2.2)$$

where:

- $\tau_\lambda$  is the spectral transmittance of the leaf
- $\rho_\lambda$  is the spectral reflectance of the leaf
- $I_\lambda$  is the spectral irradiance at the leaf surface ( $\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$ )
- $\varepsilon_\lambda$  is the spectral emittance of the leaf
- $B_\lambda$  is the Planck function, i.e. the spectral radiant exitance distribution of a black body at the same temperature as the leaf surface ( $\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$ )
- $\lambda$  is the wavelength (nm)

In this respect, it is worthwhile realizing that the spectral distribution of solar radiation below the earth's atmosphere is such that about 95% of the total energy is received in the range  $400 < \lambda < 2800$  nm (Coulson, 1975) while the exitance of a body at room temperature practically entirely falls between 2800 and 40000 nm. Thus it makes some sense to split eq(2.2) into two integrals, one for the solar radiation range and one for the thermal radiation. Total transmittance ( $\tau_r$ ), reflectance ( $\rho_r$ ) and emittance ( $\varepsilon_r$ ) over a given range (r), of extremes  $\lambda_1$  and  $\lambda_2$  are defined respectively as:

$$\tau_r \equiv \int_{\lambda_1}^{\lambda_2} \tau_\lambda I_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \equiv \int_{\lambda_1}^{\lambda_2} \tau_\lambda I_\lambda d\lambda / I_r \quad - \quad (2.3)$$

$$\rho_r \equiv \int_{\lambda_1}^{\lambda_2} \rho_\lambda I_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \equiv \int_{\lambda_1}^{\lambda_2} \rho_\lambda I_\lambda d\lambda / I_r \quad - \quad (2.4)$$

$$\varepsilon_r \equiv \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda B_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} B_\lambda d\lambda \quad - \quad (2.5)$$

Observe that the transmittance and reflectance are, by their definition, coupled to a radiation source. Therefore, strictly speaking, the values of  $\tau_r$  and  $\rho_r$  to be applied for a given radiation field should be determined experimentally – by means of eqs(2.3) and (2.4), respectively – in the presence of a similar radiation source. The indexes *s* and *l* may be respectively used for the shortwave (400 to 2800 nm) and longwave (2800 to 40000 nm) ranges. Then eq(2.2) can be written as:

$$R_n = (1 - \tau_s - \rho_s) I_s + (1 - \tau_l - \rho_l) I_l - \varepsilon_l \int_{2800}^{40000} B_\lambda d\lambda \quad \text{W} \cdot \text{m}^{-2} \quad (2.6)$$

For most leaves  $\tau_l$  and  $\rho_l$  are negligible and  $\varepsilon_l$  is accordingly almost one. Hence  $\tau_r = \rho_r = 0$  and  $\varepsilon_l = 1$  will be accepted in the present work. Moreover, it has been mentioned already that a body at room temperature emits a negligible amount of

radiation outside the longwave range. Therefore, the integration in the third term on the right hand side of eq(2.6) may be performed between the limits 0 to infinity without significant loss of accuracy. Such integration yields the function of Stefan-Boltzmann. When provision for all this is made, eq(2.6) reduces to:

$$R_n = (1 - \tau_s - \rho_s) I_s + I_t - \sigma T_0^4 \quad \text{W} \cdot \text{m}^{-2} \quad (2.7)$$

where  $T_0$  is the surface temperature of the leaf (K) and  $\sigma$  is the Stefan-Boltzmann constant ( $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ ).

### 2.1.2 Sensible heat flux

$H$  in eq(2.1) is the rate at which sensible heat is lost to the environment, per unit surface area. Such heat transfer can be represented as if it was depending on a diffusion process (either driven by molecular diffusion or by turbulence), so that its mean rate may formally be described as a density of flux along a concentration gradient. If the volumetric heat content is chosen as the relevant concentration and only vertical fluxes are considered, then the flux at height  $z$  above the surface is:

$$H(z) = -D' \frac{d(\rho_a c_p T_{a,z})}{dz} \quad \text{W} \cdot \text{m}^{-2} \quad (2.8)$$

where:

$\rho_a$  is the density of air ( $\text{kg} \cdot \text{m}^{-3}$ )

$c_p$  is the specific heat of air ( $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ) at constant pressure

$T_{a,z}$  is the temperature of the air at height  $z$  (K)

$D'$  is a coefficient having the dimensions of diffusivity ( $\text{m}^2 \cdot \text{s}^{-1}$ ).

The latter can be expected to be equal to the thermal diffusivity of air only for diffusion across a perfectly still air layer. It becomes several orders of magnitude larger with the onset of convection.

However, the profile of air temperature is seldom known with enough detail to allow the determination of  $H(z)$ , for any  $z$ . Moreover, what is of interest in most cases, is the heat exchanged between the leaf and the free air stream (bulk air), at such a distance that it is no longer influenced by the presence of the surface. Then, heat flow (as well as mass flow) does not pertain any more to the leaf sub-system, commonly identified as the leaf boundary layer. In the present work, the latter will be thought of as a sort of envelope of air, containing the leaf and disconnected from the sub-systems of the surrounding leaves. Let the thickness of such an envelope be  $z'$  and let us assume that  $\rho_a c_p$  is independent of height, then:

$$H(z') = D' \rho_a c_p \frac{T_0 - T_{a,z}}{z'} \quad \text{W} \cdot \text{m}^{-2} \quad (2.9)$$

It has to be realized, however, that the thickness of the leaf boundary layer is a rather elusive micrometeorological quantity: there is, in fact, much arbitrariness in all the formulae attempting to determine it as a function of the geometrical properties of the surface and of the dynamics of the air stream, as the comparison of theory and observations handily shows (§ 2.3.1). Arbitrariness is enhanced when those formulae are applied to a (sometimes fluttering and maybe hairy) leaf surface (Jones, 1983), immersed in such a peculiar air stream as within a canopy. However, if it is assumed that the bulk air beyond the boundary layer is perfectly mixed, so that no temperature differences exist, then the difference of temperature across the leaf boundary layer is equal to the temperature difference between the surface and the bulk air. On the other hand,  $D'$  cannot also be assigned a well defined value since the latter is much affected by the nature of the air flow. Hence, it makes some sense to group all problems together in a quantity  $D'/z'$  which may be regarded as a 'boundary layer conductance'. A corresponding 'boundary layer resistance'  $r_{aH}$  to heat transfer can be defined as its inverse, having the units of  $s \cdot m^{-1}$ . Accordingly, if the properties of bulk air are referred to by symbols with the subscript 'a' alone, one gets:

$$H = \frac{\rho_a c_p}{r_{aH}} (T_0 - T_a) \quad W \cdot m^{-2} \quad (2.10)$$

It will be clear by now that eq(2.10) is more a definition of the boundary layer resistance than a tool to estimate the flux of sensible heat lost by the surface. The usefulness of eq(2.10), however, will be shown in § 2.2.1, where an equation for the transpiration flux of the surface will be made independent of the state variables of the latter. On the other hand, it makes (in principle) no difference to have a conductance, and not a resistance, defined by eq(2.10); the formalism adopted here, however, allows for the fluxes of heat and mass to be proportional to concentrations, by the inverse of resistances having the same dimensions. This peculiarity allows for the resistance to vapour transfer to be written as the sum of two independent terms, as will be shown in § 2.2.1.

### 2.1.3 Latent heat flux

The latent heat flux (LE) is the rate at which energy is being consumed, per unit leaf area, to let water evaporate. If vapour pressure is chosen as appropriate potential, and the assumption of homogeneity outside the leaf boundary layer is repeated for the vapour pressure field, an argument analogous to the one developed in the previous section yields:

$$LE = \frac{\rho_a c_p}{\gamma r_{av}} (e_0 - e_a) \quad W \cdot m^{-2} \quad (2.11)$$

where:

$\gamma$  is the thermodynamic psychrometric constant ( $\text{Pa} \cdot \text{K}^{-1}$ )

$e_o$  and  $e_a$  are the vapour pressure at the external surface and of the bulk air, respectively (Pa)

$r_{av}$  is a boundary layer resistance to vapour transfer ( $\text{s} \cdot \text{m}^{-1}$ )

However, the vapour pressure at the external surface of a leaf is a quantity rather difficult to ascertain. Quite often in the relevant literature, the problem is circumvented by stating that the surface is saturated, i.e.:

$$e_o = e^*(T_o) \quad \text{Pa} \quad (2.12)$$

with the superscript \* meaning at saturation. Such a condition, however, definitely reduces the amount of naturally occurring surfaces whose transpiration rate might be determined. Indeed, eq(2.12) is often considered as the defining condition for potential evaporation (Van Bavel, 1966; Kreith and Sellers, 1975). In § 2.2 it will be shown that an equation for the vapour production rate of any surface may be derived after considering that eq(2.12) always holds true for a surface where the phase transition takes place. It will then be discussed how and to what extent fluxes measured at the external surface may be applied to the combination of eqs(2.1), (2.10), (2.11) and (2.12) to assess actual transpiration.

#### 2.1.4 Photosynthesis rate

An estimate of the magnitude of this energy rate can be made through the energy content of dry matter (about  $17.5 \cdot 10^6 \text{ J} \cdot \text{kg}^{-1}$ , according to Monteith, 1972) and the photosynthetic efficiency, i.e. the energy stored in dry matter expressed as a fraction of incoming radiant energy. This efficiency is by no means a constant, being affected by various factors such as leaf temperature,  $\text{CO}_2$  concentration of the air etc. Hence, it should be clear that the reasoning developed hereafter only provides for a rough appraisal. Typical efficiencies for single leaves (in terms of absorbed PAR – i.e. photosynthetically active radiation:  $400 < \lambda < 700 \text{ nm}$ ) range from 11 to 16% (Jones, 1983). These values may be converted into efficiencies in terms of incident solar radiation by multiplication by the leaf absorptance in the PAR ( $\cong 0.85$ ) and by the ratio PAR/total solar radiation ( $\cong 0.5$ ). A typical photosynthetic efficiency in terms of incident solar radiation is, therefore, between 4 and 7%. Such a value might be increased, to some extent, by the addition of  $\text{CO}_2$  to the greenhouse atmosphere or by the use of artificial light sources having a more favourable PAR/total radiation ratio: anyhow, it is unlikely that a value of 10% photosynthetic efficiency in terms of incident shortwave radiation ( $I_s$ ) is exceeded. Even more tricky is an estimate of the efficiency in terms of net absorbed radiation ( $R_n$ ). If a guesstimate of the maximum energy consumption for dry matter production as 10% of the net radiant energy is accepted, it should be

realized that such a fraction is comparable with the error in the appraisal of the latter, at least for a canopy (§ 3.2). Therefore, this energy flux will be overlooked hereafter, although it is acknowledged that it should be accounted for, in a more detailed analysis.

### 2.1.5 Thermal storage

The thermal storage –  $J$  in eq(2.1) – is the flux of energy per unit leaf area, used for heating (or released by the cooling of) leaf tissue. Namely, if  $\rho_l$  and  $c_l$  are the density ( $\text{kg}\cdot\text{m}^{-3}$ ) and specific heat ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ), respectively, of leaf tissue and  $V$  is a volume to area ratio ( $\text{m}^3\cdot\text{m}^{-2}$ ) – equal, for a flat leaf, to half the thickness, in our convention about the unit area –, then:

$$J = \rho_l c_l V dT_o/dt \quad \text{W}\cdot\text{m}^{-2} \quad (2.13)$$

whereby the following assumptions are implicitly made:

- $\rho_l c_l$  is constant in time and within the leaf
- spatial variations of temperature within the leaf are negligible.

A lamentable lack of clarity exists in the literature about this flux: sometimes it is omitted outright from energy balance considerations (e.g. Rosenberg, 1974); most of the time it is confused with the flux of heat into the soil underlying a canopy and, de facto, overlooked (e.g. Idso, 1983); finally, whenever it is explicitly recognized, it is dismissed altogether (e.g. Van Bavel, 1966). However, an appraisal of its magnitude can easily be done: usually between 80 and 90 % of tissue fresh weight is water, so that  $3.5\cdot 10^3 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$  looks as a reasonable guess for the specific heat of leaves; this yields  $\rho_l c_l V \sim 1.2\cdot 10^3 \text{ J}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ , when a leaf density of  $700 \text{ kg}\cdot\text{m}^{-3}$  (Jones, 1983) is taken, and a thickness of 1 mm. For a leaf temperature variation of, say, 15 K in 8 hours,  $J$  is then about  $0.5 \text{ W}\cdot\text{m}^{-2}$ , whereas for a variation of 1 K in a minute,  $J \sim 20 \text{ W}\cdot\text{m}^{-2}$ . It is true, therefore, that whenever daily, or even hourly averages are considered, eq(2.13) yields a neglectable energy flux; which makes more an academic question than a real one of the mentioned inconsistency about it. On the other hand, when eq(2.1) is applied to shorter time intervals, as with the present work, the magnitude of the thermal storage in relation to the other energy fluxes should be carefully considered.

## 2.2 Transpiration and temperature

### 2.2.1 Actual transpiration

The use of the vapour transfer equation (eq(2.11)) to appraise the transpiration flux of such an 'ideal leaf', as it has been defined in the previous section, requires the vapour pressure of its external surface to be known. This seldom happens. It

will hereafter be shown that an equation for the transpiration flux can be derived simply by assuming that there is somewhere beneath the external surface, a region (henceforth called the phase interface) being saturated at its temperature, i.e. where eq(2.12) holds true. A similar method was first applied by Menenti (1984) to an evaporation front inside a drying soil. Afterwards, the resulting equation will be rendered independent of the state variables at the phase interface as well as at the external surface, by adaptation of a method developed by Penman (1948).

At the external surface, where no phase transition takes place, the energy balance reads (see fig. 2.1):

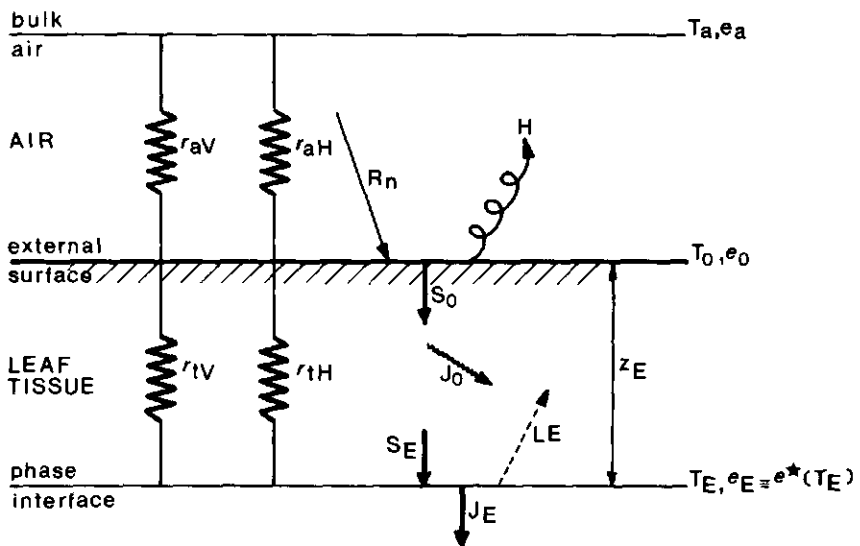


Fig. 2.1. Schematic representation of heat and vapour transport for the phase transition taking place inside a leaf. The transport resistances are shown and  $z_E$  is the depth of the phase interface.

$$R_n = H + S_0 \quad \text{W} \cdot \text{m}^{-2} \quad (2.14)$$

where  $S_0$  is the flux density of sensible heat transmitted by conduction below the surface. On the other hand, the energy balance at the phase interface may be written as:

$$S_E = LE + J_E \quad \text{W} \cdot \text{m}^{-2} \quad (2.15)$$

where  $S_E$  is the sensible heat brought by conduction to the interface, and  $J_E$  is the flux transmitted below it. Moreover, if  $J_0$  is the thermal storage in the layer between the external surface and the phase interface, obviously:

$$S_E = S_o - J_o \quad \text{W} \cdot \text{m}^{-2} \quad (2.16)$$

and, when it is considered that

$$J = J_o + J_E \quad \text{W} \cdot \text{m}^{-2} \quad (2.17)$$

by definition, the combination of eqs(2.14) to (2.17) yields:

$$R_n = H + LE + J \quad \text{W} \cdot \text{m}^{-2} \quad (2.18)$$

Eq(2.18) is formally identical to eq(2.1), with the relevant difference that now the energy has to be brought to the phase interface through the leaf layer, and vapour has to be carried away through the pores of the same layer. Hence the partition of available energy between sensible and latent heat at the phase interface, is determined by the ability of that layer to carry heat and vapour, which has to be cast in the form of a set of transfer equations for that layer. In fact, heat transfer by conduction in the layer takes place according to:

$$S_o = \frac{\lambda_t}{z_E} (T_o - T_E) = \frac{\rho_t c_t}{r_{tH}} (T_o - T_E) \quad \text{W} \cdot \text{m}^{-2} \quad (2.19)$$

where  $\lambda_t$  is the thermal conductivity of the leaf tissue ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ) and  $z_E$  is the thickness of the layer between the external surface and the phase interface. By the second one of eqs(2.19) a resistance to the transfer of heat in the leaf tissue has been defined, having the units of  $\text{s} \cdot \text{m}^{-1}$ .

On the other hand, an equation for vapour transfer through the layer may be derived as follows: since under the present assumption, no vapour is produced at the external surface, the continuity equation for the flow of latent heat can be written:

$$LE = \frac{\rho_a c_p}{\gamma r_{tV}} (e_E - e_o) = \frac{\rho_a c_p}{\gamma r_{aV}} (e_o - e_a) \quad \text{W} \cdot \text{m}^{-2} \quad (2.20)$$

where  $r_{tV}$  is the resistance to vapour flow in the leaf tissue layer. Elimination of  $e_o$  yields:

$$LE = \frac{\rho_a c_p}{\gamma(r_{aV} + r_{tV})} (e_E - e_a) \quad \text{W} \cdot \text{m}^{-2} \quad (2.21)$$

The combination of the energy balance and transfer equations may be used now to derive an equation for the transpiration flux, in which the state variables of the leaf do not appear explicitly. The phase interface has been previously defined as the surface being saturated at its temperature, so that:



$$e_E = e^*(T_E) = e^*(T_a) + \delta(T') \cdot (T_E - T_a) \quad \text{Pa} \quad (2.22)$$

where  $\delta(T')$ , hereafter  $\delta'$ , is the slope of the saturated vapour pressure curve ( $\text{Pa} \cdot \text{K}^{-1}$ ), calculated at a temperature ( $T'$ ), between  $T_E$  and  $T_a$ , according to Lagrange's theorem (fig. 2.2a). The difference  $T_E - T_a$  can be written as:

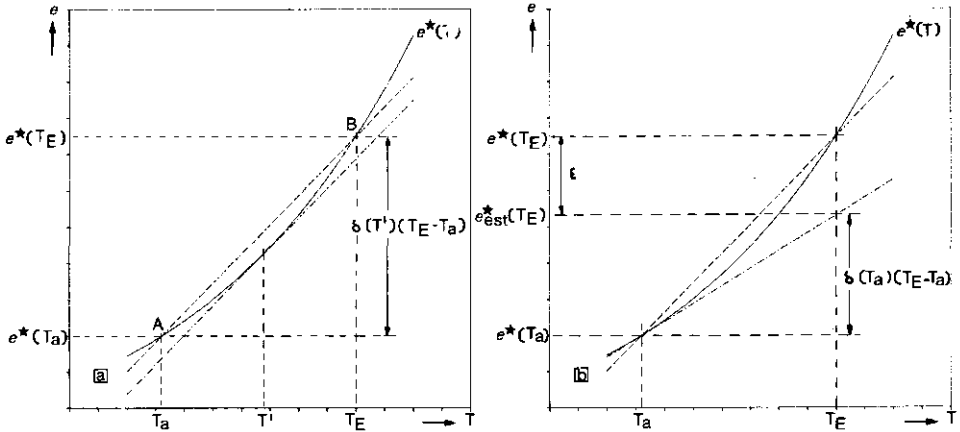


Fig. 2.2a. Graphic representation of Lagrange's theorem. There is always a value  $T'$ , within the interval  $T_E - T_a$ , extremes excluded, where the slope ( $\delta$ ) of the saturated vapour pressure function is the same as that of the line through A and B.

Fig. 2.2b. Graphic representation of the error ( $\epsilon$ ) involved in the use of  $\delta(T_a)$  instead of  $\delta(T')$ . If  $T_E \approx T_a$  then  $\epsilon < e^*(T_a) + \delta(T_a) \cdot (T_E - T_a)$ .

$$T_E - T_a = (T_E - T_o) + (T_o - T_a) \quad \text{K} \quad (2.23)$$

The first term on the right hand side can be calculated by means of the combination of eqs(2.15), (2.16), (2.17) and (2.19), and the second one by eqs(2.10) and (2.18); that yields:

$$T_E - T_a = \frac{r_{aH}}{\rho_a c_p} R_n - \left( \frac{r_{aH}}{\rho_a c_p} + \frac{r_{tH}}{\rho_t c_t} \right) (LE + J) \quad \text{K} \quad (2.24)$$

$r_{aH}$  will be shown in the next section to be at least  $100 \text{ s} \cdot \text{m}^{-1}$ , whereas  $\rho_a c_p$  is about  $1200 \text{ J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ . Eq (2.19) may be used to value the ratio  $r_{tH}/\rho_t c_t$ :  $z_E$  is within 0.5 mm, while a reasonable guess for  $\lambda_t$  might be  $0.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$  (Jones, 1983). It follows that:

$$\frac{r_{aH}}{\rho_a c_p} > 10^2 \frac{r_{tH}}{\rho_t c_t} \quad \text{m}^2 \cdot \text{K} \cdot \text{W}^{-1} \quad (2.25)$$

This means that the resistance to heat transfer in the leaf layer external to the phase interface is negligible against the resistance of the boundary layer, i.e.:

$$\frac{r_{aH}}{\rho_a c_p} \cong \frac{r_{aH}}{\rho_a c_p} + \frac{r_{tH}}{\rho_t c_t} \quad \text{m}^2 \cdot \text{K} \cdot \text{W}^{-1} \quad (2.26)$$

Eq(2.24) after substitution of eq(2.26) can be combined with eq(2.22) and then substituted into eq(2.21), yielding:

$$\text{LE} = \frac{\delta' r_{aH} (\mathbf{R}_n - \mathbf{J})}{\gamma(r_{aV} + r_{tV}) + \delta' r_{aH}} + \frac{\rho_a c_p (e_a^* - e_a)}{\gamma(r_{aV} + r_{tV}) + \delta' r_{aH}} \quad \text{W} \cdot \text{m}^{-2} \quad (2.27)$$

where  $e_a^* = e^*(T_a)$ .

Therefore, the transpiration flux, given by eq(2.11), may be represented by eq(2.27) as well. In the latter equation, that flux is shown to be the sum of two parts: the first term, independent of the humidity content of the air, gives the transpiration rate which would take place in a saturated ambient, as the leaf surface has a different temperature from the ambient, due to its radiative exchange. The second term, independent of the net radiation, represents the transpiration rate of a leaf (not exchanging radiation with the ambient), immersed in a non-saturated air (fig. 2.3).

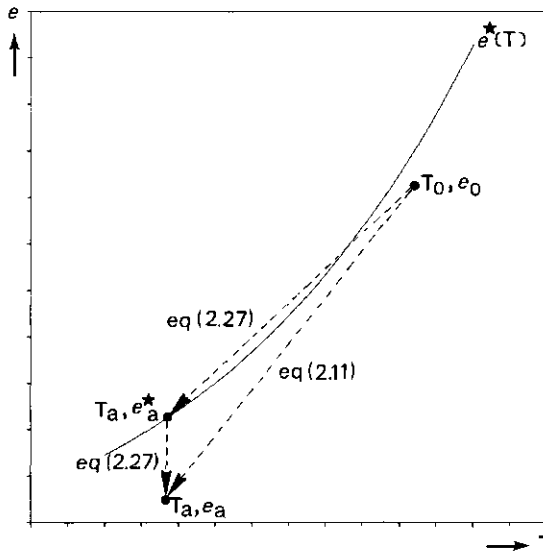


Fig. 2.3. Graphic comparison between eq(2.11) and eq(2.27). There is a potential for vapour leaving the leaf surface at temperature  $T_0$  and vapour pressure  $e_0$ , immersed in air at temperature  $T_a$  and vapour pressure  $e_a$ . The same potential may as well be thought of as the sum of two parts, one of the surface with respect to saturated air, the other of saturated with respect to unsaturated air.

Eq(2.27) can be substantially simplified by two commonplace assumptions: in the first place, if  $T_E$  and  $T_a$  may be expected to differ only marginally,  $\delta'$  can be replaced by  $\delta(T_a)$ , hereafter simply  $\delta$  (fig. 2.2b). Further, if one considers that, since heat as well as vapour transport in the air layer is convective and not diffusive,  $r_{aH} = r_{aV}$  may be assumed.

On the other hand, it is the present author's opinion that the usual identification of  $r_{IV}$  with the stomatal resistance should be avoided. In fact, the definition given here of phase interface does not need it to be the surface of the substomatal cavities; and, as pointed out by Cannon et al., 1979, 'the exact location of the evaporating surface is still a subject of discussion'. Moreover, a leaf transpires via both surfaces, each one characterized by a more or less waxy cuticle, perforated by stomata. The areal density of stomata on the two sides is not necessarily the same: the number of stomata per unit area of the adaxial surface of a tomato leaf was reported by Gay and Hurd (1975) as varying between 2 and 28 mm<sup>-2</sup>, and of the abaxial surface between 83 and 105 mm<sup>-2</sup>, depending on light conditions during growth. Cuticular resistance, although being generally acknowledged to be large, is not infinite, and is certainly comparable with the resistance of closed stomata. This considered, the statement of Monteith (1981a) that 'the resistances of individual pores ... behave as if they were wired in parallel with each other and with the cuticle which they perforate' with the two leaf sides being wired in parallel, does not provide a tool for the appraisal of  $r_{IV}$ . It should also be realized that, as none of the individual resistances on the vapour pathway can be measured independently from the others, there is hardly a possibility to check theoretical estimates of stomatal resistance, based on the diffusion coefficient of vapour and the dimensions of the pore, although generally these end up in values smaller than experimental values of total leaf resistance (Monteith, 1965; Kreith and Sellers, 1975).

This said, the present author prefers the terminology used by Gates (1968) of internal resistance for  $r_{IV}$ . Then, the name external resistance should be used for  $r_{aV}$  (assumed here equal to  $r_{aH}$ ). Hence, the symbol  $r$  with the subscripts e (external) and i (internal) will be used hereafter. When all of this is taken into account, eq(2.27) reduces to:

$$LE = \frac{\delta r_e (R_n - J)}{(\delta + \gamma) r_e + \gamma r_i} + \frac{\rho_a c_p (e_a^* - e_a)}{(\delta + \gamma) r_e + \gamma r_i} \quad \text{W} \cdot \text{m}^{-2} \quad (2.28)$$

which is a combination-like formula for actual transpiration. The term containing the net radiation is generally referred to as radiative evaporation whereas the term function of the saturation deficit of the air is said to be aerodynamic evaporation. A reason for these definitions has been provided above. It should be observed that in principle, eq(2.28) represents an instantaneous evaporation rate

and its use therefore, is by no means restricted to time averages over periods of days or longer, although this opinion is fairly widespread. Such a view is probably caused by the fact that the accuracy with which the variables are known is limited.

Although a complete discussion of eq(2.28) will be provided in § 2.5, and the resistances appearing as parameters will be analyzed in § 2.3 and 2.4, some comments are due here about the two simplifying assumptions that have been used to deduce eq(2.28) from (2.27). The use of  $\delta$  – the slope of the saturated vapour pressure curve calculated at air temperature – instead of  $\delta'$ , is only needed to provide an analytical solution for the transpiration flux density. Such a replacement will be shown (§ 2.5) to yield neglectable deviations whenever  $T_E$  is within a few degrees of  $T_a$ , whereas an iterative solution should be otherwise adopted.

The equivalence of heat and vapour transfer resistances in air is a question which is not yet definitely settled. The theory of mass and heat transfer already points out that they are (almost) equal. It might safely be stated that the two are equal within the accuracy with which they can be determined. This was the conclusion of an extensive review of previous experimental works, published by Yaglom in 1977. Moreover Chen (1984) observed that one could just as well state that  $r_{aH}$  and  $r_{aV}$  are equal by definition. Any inequality between them would then add to  $r_{iV}$  which should be better described as an excess resistance to vapour transfer.

### 2.2.2 Temperature of the external surface

A procedure quite similar to the one applied in the previous section allows for the difference in temperature between the external surface of a leaf and bulk air to be cast in a form independent from the transpiration flux. Such a difference is commonly referred to as temperature excess which, deceptively, suggests it to be always positive.

The parametrization of the temperature of that surface and not of the phase interface is, in the first place, an acknowledgement of the fact that the temperature of the external surface (if any) is the one that it is possible to measure. Moreover, the continuity equation for the transfer of heat implies that  $H$  and  $S_0$  are equal. Hence the comparison of eqs(2.10) and (2.19), after allowing for eq(2.25), yields:

$$|T_0 - T_a| \gg |T_E - T_0| \quad K \quad (2.29a)$$

i.e.

$$T_E - T_a \cong T_0 - T_a \quad K \quad (2.29b)$$

Accordingly, eq(2.10) with substitution of eqs(2.18) and (2.28) can be solved for the temperature excess, resulting in:

$$T_0 - T_a = \frac{\gamma r_e (r_e + r_i)(R_n - J)}{\rho_a c_p [(\delta + \gamma) r_e + \gamma r_i]} - \frac{r_e (e_a^* - e_a)}{(\delta + \gamma) r_e + \gamma r_i} \quad K \quad (2.30)$$

In fact, the temperature of a wet surface is the temperature of the air in which it is immersed plus the net result of two effects: an offset proportional to its radiation balance and a sort of evaporative cooling. Prediction of the sign of the net result however, is not straightforward since, as it may be inferred from eq(2.30), there is a wide range of air temperatures in which leaves may be a few degrees warmer or cooler than the surrounding air. The theory (and abundant evidence from the literature) therefore disproves the suggestion by Linacre (1964) that observed leaf temperatures are usually below air temperature when the latter exceeds 32°C and vice versa. The experimental results on which this contention was based might be explained by the fact that in nature, high air temperatures are seldom unaccompanied by strong irradiation.

It is easy to realize that for a negligible external resistance (and a not nil internal one) the temperature of the surface approaches air temperature, whatever the conditions. On the other hand, the temperature of a non transpiring surface may be inferred from eq(2.30) if the internal resistance is assumed to be infinite: the second term on the right hand side becomes nil, which provides a good reason for its definition of 'evaporative' cooling. In this case, however, eq(2.30) would yield unlikely large temperature excesses for a net radiation, say, of a few hundreds  $W \cdot m^{-2}$ . It has already been stated that such an extrapolation is not allowed. Indeed, Monteith (1981b) showed that, when accounting for increase of the extantance of the surface, the resulting estimate of  $T_o - T_a$  would be much smaller (§ 2.5.4). The contention by Priestley (1966) that temperature is primarily limited by transpiration looks, therefore, questionable: re-radiation may be quite an efficient cooling process as well.

It should be clear that, as eq(2.7) shows,  $R_n$  is no independent variable but a function of surface temperature (which, by the way, both resistances may also be to some extent – § 2.3 and 2.4). Hence, eq(2.30) is more a formal solution for the temperature excess than an analytical one. Its use in the present form is, therefore, only correct whenever the 'independent' variables are either measured or otherwise known.

## 2.3 External resistance at a leaf surface

### 2.3.1 General

Transfer of sensible heat across an air layer can take place either by conduction or convection. Conduction is the exchange of energy at molecular level. One speaks of convection when parcels of air are physically displaced to regions with a different temperature by an air flow. Convection can take place as a result of some externally induced flow (forced convection) but can also be caused by differences of density among various regions of the fluid, due to temperature differences (free or natural convection). Even at the very low wind speeds typical of

greenhouse environments, convection is several orders of magnitude more efficient a mechanism than conduction. Accordingly, conductive heat transfer to and from a leaf surface will not be considered hereafter.

It was stated, in § 2.1.2 (eq(2.10)), that the flux density of sensible heat to or from a surface is proportional to the difference of temperature between the surface and bulk air. The proportionality factor was defined as the inverse of a boundary layer resistance (or external resistance), i.e. a conductance. It was also remarked that such a proportionality factor is actually defined by the transfer equation of sensible heat, having thus to be regarded as typical of each possible condition. It is, however, reasonable to assume that similar systems do have similar conductances, so that previous experiences and some theory should yield useful information for the actual circumstances.

Theory, and indeed intuition, make it apparent that there is a lot of difference in whether heat transfer is due to free or to forced convection. For free convection the difference of temperature between the surface and the air is likely to be a prominent parameter, whereas the speed of the air flow is more likely to be one for forced convection. Moreover, it has some consequence whether the flow is turbulent or laminar. Non-dimensional groups, as the Reynolds (Re) and Grashof (Gr) number, are commonly used to assess the (dis)similarity of heterogeneous systems. In fact, the former is a function of air velocity:

$$Re = u\ell/\nu \quad - \quad (2.31)$$

where:  $u$  is the air velocity ( $m \cdot s^{-1}$ )

$\ell$  is a characteristic dimension of the surface (m)

$\nu$  is the kinematic viscosity of air ( $m^2 \cdot s^{-1}$ )

and the latter of the difference of temperature:

$$Gr = \frac{g\beta\ell^3}{\nu^2}(T_0 - T_a) \quad - \quad (2.32)$$

where  $g$  is the acceleration due to gravity ( $m \cdot s^{-2}$ ) and  $\beta$  is the coefficient of thermal expansion of air ( $K^{-1}$ ).

It can be inferred that a non-dimensional conductance, the Nusselt number (Nu):

$$Nu = \frac{\rho_a c_p \ell}{\lambda_a r_e} \quad - \quad (2.33)$$

can be written as a function of either the Reynolds or the Grashof number. Moreover, some relationship between the two should provide a criterium to identify the prevailing heat transfer regime for a given system. As a matter of fact, yet another dimensionless number should be mentioned in this context, the Prandtl

number (Pr). However, as Pr is exclusively a property of the fluid and as here only air is dealt with, Pr can be incorporated into the numeric coefficients of the following equations and will not be specified.

Measurements of heat loss from flat surfaces in air can be described by the general relations:

$$\text{Nu} = C_1 \text{Re}^n \quad - \quad (2.34)$$

or

$$\text{Nu} = C_2 \text{Gr}^m \quad - \quad (2.35)$$

The parameters  $C_1$ ,  $C_2$ ,  $m$  and  $n$  change with the geometry and type of system. Figures for them, for various arrangements, are tabulated in many heat transfer handbooks (e.g. Kreith, 1976). Monteith (1975) summarized those of importance to plant ecologists. For forced convection, the exponent of Re is shown to be 0.5, for a laminar boundary layer flow. For a turbulent one, experimental results suggest it to be about 0.8. The exponent of Gr for natural convection may be shown to be not larger than 1/3. It is 1/4 for a laminar boundary layer flow.

Experimental determination of the external resistance has to be based upon its defining equation (2.10):

$$\mathbf{H} = \frac{\rho_a c_p}{r_e} (T_0 - T_a) \quad \text{W} \cdot \text{m}^{-2} \quad (2.36)$$

Since the flux density of sensible heat is seldom known, this term has to be found through the energy balance equation i.e., for steady state:

$$\mathbf{H} = \mathbf{R}_n - \mathbf{LE} \quad \text{W} \cdot \text{m}^{-2} \quad (2.37)$$

However, for transpiring leaves,  $\mathbf{H}$  is normally much smaller a flux than either net radiation or transpiration. This results in unaffordable errors in its determination through eq(2.37), if the inaccuracy of net radiation and transpiration estimates is taken into account. Indeed, an attempt by Hunt et al. (1968) to evaluate the external resistance of sunflower leaves in the field in this way, yielded unlikely small values for it.

A common device to eschew this problem is the use of synthetic, non-transpiring leaves. Many experiments dealt with dissipation of heat from metal samples warmed by a known electrical flux, while the exchange of radiation was either prevented or measured. Thom (1968) found that heat transfer from a convex leaf could still be well represented by the square root of the Reynolds number, for wind speeds exceeding  $0.5 \text{ m} \cdot \text{s}^{-1}$ . This result has been confirmed by Parkhurst et al. (1968a) for flat leaves of various dimensions and shapes, when an appropriate

mean length is defined. For Reynolds numbers smaller than 1000 however, Kuiper (1961), Slatyer and Bierhuizen (1964) as well as Pearman et al. (1972) could observe Nusselt numbers exceeding significantly (even by a factor two) those predicted by the theory of either forced or natural convective transfer above flat plates. It is likely that in those conditions, heat transfer could be induced by a combination of both modes, as already suggested by Monteith (1965).

Several criteria have been proposed to identify the prevailing regime for a given system. Most of them can thus be condensed:

$$\text{for } Gr \gg C_3 Re^q \rightarrow \text{free convection} \quad (2.38a)$$

$$\text{for } Gr \ll C_4 Re^q \rightarrow \text{forced convection} \quad (2.38b)$$

where  $q$  is of the order of magnitude of 2 whereas  $C_3$  and  $C_4$  are about one. However, it is easy to show that all criteria – when applied to the present issue – point to a (wide) region of transition between natural and forced convection. As an example, let us assume having a leaf of 5 cm typical dimension, being some 2 K warmer than the surrounding air, the latter being at 20°C ( $\nu = 1.51 \cdot 10^{-5} \text{ m}^2 \cdot \text{s}^{-1}$ ). With a mean wind speed of 10  $\text{cm} \cdot \text{s}^{-1}$ :  $Gr \sim 3.5 \cdot 10^4$  and  $Re \sim 3.5 \cdot 10^2$ , which results in none of eqs(2.38) being fulfilled, for any  $q \sim 2$ . Hence, one is not entitled, in this  $Gr$  and  $Re$  range, to use either eq(2.34) or (2.35). By regarding non-dimensional numbers as vectors having the same orientation as the corresponding motion, Börner (1965) showed that it is possible to evaluate an equivalent Reynolds number ( $Re'$ ) for free convection, defined by equating eq(2.35) to (2.34). For a given value of  $Gr$  one thus obtains the module of the vector  $Re'$ , having the same orientation of the natural flow. He suggested then that the Nusselt number of the system be calculated as the vectorial combination of the two Reynolds vectors. As it will be shown in § 2.3.3, such a procedure could indeed yield deviations from the Nusselt number for forced convection about as large as those observed by the authors mentioned above.

Moreover, there is experimental evidence that the presence of surrounding canopy elements could lower the threshold for which transition to turbulent flow takes place (Sunderland, 1968), which can also result in some enhancement of transfer, up to about 30%, according to Haseba (1973). In similar circumstances Chamberlain (1974) observed mass transfer to be about 25% larger than would otherwise be predicted. Grace and Wilson (1976) also observed that transition from laminar to turbulent flow over a poplar leaf, starts at lower Reynolds numbers than predicted by stability theory (Lin, 1970); they credited the roughness of the surface with this effect. In a similar way Cannon et al. (1979) did interpret a comparable result for a porous flat plate. On the other hand, Lim (1969), studying heat dissipation of copper plates of various shapes in a mixed regime (15 K warmer than the surrounding air and exposed to an air velocity from 0 to 0.3



m·s<sup>-1</sup>), found that the measurements could not be correlated using a Nusselt number based on a simple mean dimension as defined by Parkhurst et al. (1968a).

From the review provided above, one must conclude that the experimental data available in the literature are not conclusive about a unique equation to predict external resistance of a leaf exposed to very low windspeeds, in the presence of external sources of turbulence, and being only a few degrees warmer or cooler than the surrounding air. As only these conditions are characteristic of a greenhouse environment, the need for determining experimentally heat dissipation in such a circumstance was felt to be mandatory.

### 2.3.2 Experimental determination of the external resistance

Convective heat transfer from plates of various dimensions and shapes, placed like natural leaves in a canopy, was measured in a glasshouse where a tomato crop was grown. The heating element of the plates was a copper coil, 0.035 mm thick, etched into a one-sided, epoxy-glass, flexible print-plate. The latter was sandwiched between two layers of 0.1 mm aluminium, by means of double sided adhesive foils (fig. 2.4), providing also for electric insulation. The 1 mm wide coil was

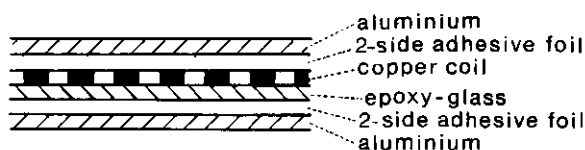


Fig. 2.4. Schematic section of a synthetic leaf, as used in the present research.

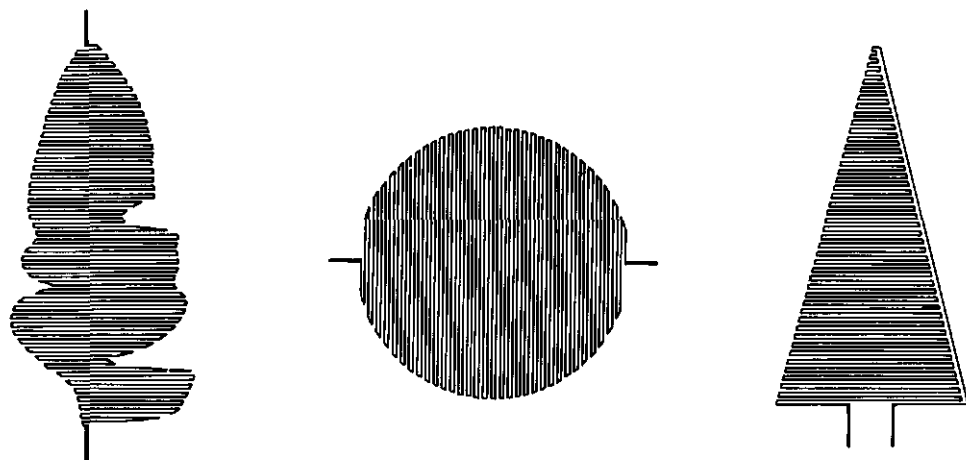


Fig. 2.5. Replicas of the copper coils within the synthetic leaves. The coils reached within 1 mm of the rim of each plate. Three pairs were used with a leaf shape (one 5.5 cm long, two 8 cm long); three pairs of circular plates (3, 5.5 and 8 cm in diameter); and four pairs of triangular plates (6, 11 – two pairs – and 16 cm long, the base being half the length).

evenly distributed on the surface, with 1 mm wide interspaces (fig. 2.5) so as to ensure a uniform flux, as is normally experienced by a leaf exposed to sunshine.

Another scheme to reproduce actual leaves was applied by Wigley and Clark (1974) who used low thermal conductivity material. A possible consequence, however, is the occurrence of unnaturally large temperature gradients within the plate, as reported by Simmons (1970), since the cooling effect of the transpiration of wet leaves is not simulated in this way. In fact, thermography of real leaves, during the present experiment, showed the distribution of temperature on the surface to be within two degrees (fig. 2.6). Moreover, Sparrow and Gregg (1956) indicated on the basis of theoretical considerations that Nusselt numbers of uniform flux and of uniform temperature plates have to be within 15% of each other. Indeed, not more than such a difference was measured by Iqbal and Stoffers (1975) on plates placed in an artificial canopy. Hence the aluminum surface needed to minimize radiation errors (as will be explained shortly) was thought to have not unacceptable effects on the distribution of temperature.

The resistance vs. temperature characteristic function of each plate was calibrated before the experiment, so that the temperature of the plates could later be determined by measuring the resistance of the coil.



Fig. 2.6. Thermography of a tomato leaf, in the greenhouse. The temperature difference between white and the darkest grey is 2 K. Courtesy of Ir G.J.A. Nieuwenhuis (ICW, Wageningen).

It was not convenient to measure the net radiation flux to each plate when they were installed throughout the canopy, neither was it feasible to prevent radiation exchange without severely upsetting the environment. Therefore it was preferred to expose in each case, two identical plates and provide only one with electric heating. In this case, the combination of steady state energy balance and heat transfer equations for the 'warm' and 'cold' leaf read, respectively:

$$R_{n,w} + Q = \frac{\rho_a c_p}{r_{e,w}} (T_w - T_a) \quad \text{W} \cdot \text{m}^{-2} \quad (2.39)$$

$$R_{n,c} = \frac{\rho_a c_p}{r_{e,c}} (T_c - T_a) \quad \text{W} \cdot \text{m}^{-2} \quad (2.40)$$

$Q$  is the electric power per unit area and the subscripts  $w$  and  $c$  refer to the warmed and not warmed plates, in this order. Because of the similar exposure, it is reasonable to assume that of all components of net radiation, namely: incoming and reflected shortwave flux, in and outgoing longwave one (eq(2.7)), only the latter is not the same for the two cases; it can be calculated however, by using the Stefan-Boltzmann law. With the additional assumption that the external resistance is the same for the two plates, subtraction of eq(2.40) from eq(2.39) yields:

$$Q - \sigma \varepsilon (T_w^4 - T_c^4) = \frac{\rho_a c_p}{r_e} (T_w - T_c) \quad \text{W} \cdot \text{m}^{-2} \quad (2.41)$$

which is the equation used to deduce  $r_e$  from the measured temperatures. Observe that the aluminum coating (large reflectance and small emittance:  $\varepsilon=0.15$ , in the present case) reduces the magnitude of all radiation fluxes, thus ensuring that possible inaccuracies in the assumption about their balance result in small errors in eq(2.41). During the experiments, moreover, the warming flux  $Q$  was always several times larger than the correction for the difference in emitted longwave flux. The second assumption leading to eq(2.41), namely that the warm and cold plate have a similar external resistance is, strictly speaking, correct only insofar as the latter is independent of temperature, i.e. for forced convection alone. For natural convection however, according to eqs(2.35), (2.32) and (2.33)

$$\frac{\rho_a c_p}{r_{e,w}} = K (T_w - T_a)^m \quad \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \quad (2.42)$$

and

$$\frac{\rho_a c_p}{r_{e,c}} = K (T_c - T_a)^m \quad \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \quad (2.43)$$

where  $K$  is a coefficient. The eqs(2.42) and (2.43) may be substituted in eqs(2.39) and (2.40), respectively. Then, subtraction of those two equations yields a form of eq(2.41) valid for free convection:

$$Q - \sigma \varepsilon (T_w^4 - T_c^4) = K [(T_w - T_a)^{1+m} - (T_c - T_a)^{1+m}] \quad \text{W} \cdot \text{m}^{-2} \quad (2.44)$$

It is clear, however, that the one viable equation is eq(2.41), since K and m are unknown. Therefore eq(2.41) was applied to the experimental data, whereby a 'mean' external resistance is defined. As the comparison of eq(2.41) with (2.44) shows, that resistance may be calculated as:

$$\frac{\rho_a c_p}{r_e} = K \frac{(T_w - T_a)^{1+m} - (T_c - T_a)^{1+m}}{T_w - T_c} \quad W \cdot m^{-2} \cdot K^{-1} \quad (2.45)$$

The first two terms of the Taylor expansion (with respect to  $T_c$ ) of eq(2.45) for  $T_c \sim T_a$  yield:

$$\frac{\rho_a c_p}{r_e} \cong K(T_w - T_a)^m + K(T_w - T_a)^{m-1} \cdot (T_c - T_a) \quad W \cdot m^{-2} \cdot K^{-1} \quad (2.46)$$

Eliminating K between eqs(2.42) and (2.46), one gets:

$$\frac{\rho_a c_p}{r_e} = \frac{\rho_a c_p}{r_{e,w}} \left( 1 + \frac{T_c - T_a}{T_w - T_a} \right) \quad W \cdot m^{-2} \cdot K^{-1} \quad (2.47)$$

Hence, the external resistance of the warm plate can be inferred by applying to the one calculated through eq(2.41) a correction which can indeed be relevant for small temperature excesses of the plate. Pearman et al. (1972) compared the external resistance of warmed plates, as determined by means of various experimental techniques, in which a method similar to the present one was included. Indeed, failure to apply such a correction as given by eq(2.47) could be a cause for their reporting smaller resistances through the present experimental technique than through the others they used.

In total, 10 pairs of plates, of shapes and dimensions as listed in fig. 2.5, were installed in the glasshouse, scattered within the canopy in an approximate horizontal position (fig. 2.7). The warmed plates were connected in series to a current generator, the output of which could be changed manually: a range of 200 to 500 mA was used during the experiment. To measure the resistance (i.e. temperature) of the not warmed plates, a current of 0.5 mA was circulated in them. Voltage drop across each element was measured at 5 minute intervals by a data logger; provision for variations in current intensity was done by gauging the latter each time, by measuring the voltage drop across precision resistances, inserted in both circuits. A microcomputer connected to the data logger provided for the storage on mag-tape of temperature of both elements and of power per unit area of each pair, together with air temperature and velocity within the canopy, for each individual scan. The velocity of air was measured with a set of four hot-bulb anemometers arranged at various heights. On the other hand, temperature of the air was measured with 0.1 mm thin thermocouples glued to the dry bulb of Assmann aspirated psychrometers, suspended at three levels, above, below and within the foliage. In both cases, the mean value of all sensors was used for the data processing.



Fig. 2.7. A pair of artificial leaves, as installed in the glasshouse.

A total of 14 twentyfour-hour experiments was performed in April and May, 1985. The current through the warm plate was changed from one experiment to the other, in order to experience a broad range of temperature differences between the plates and the air; the largest ever was 17 K. It has to be observed, however, that eq(2.41) is correct only for steady-state, since no provision was made for thermal storage in the plates. It can, therefore, be applied only to long-term mean values: day and night time means for each experiment were used for the present analysis.

### *2.3.3 Results and discussion*

The values for the external resistance as calculated from the data by means of eq(2.41), were, despite the substantial spreading, best-fitted by a function of tem-

perature and not of air velocity, for almost all dimension and shape classes. Hence, free convection seemed to be dominant. Accordingly, the correction given by eq(2.47) was applied to all points. On the other hand, to render the results in terms of dimensionless quantities, the diameter has been used as typical dimension of the round plates, the base for the triangular ones and an eye-estimated mean width for the lobed shape.

From the results shown in fig. 2.8, no significant difference in performance as heat dissipators can be proved among the three shapes, whereas points are clearly

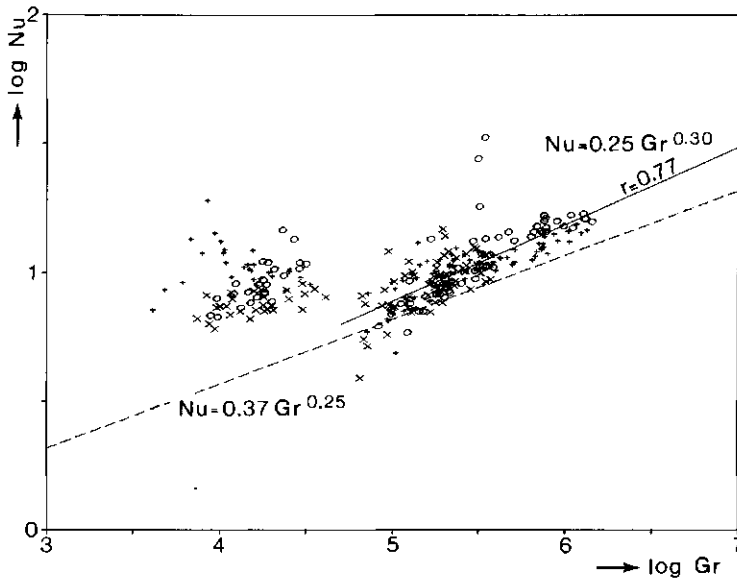


Fig. 2.8. Representation of the experimental results in terms of dimensionless numbers: x = leaf shape; o = round and + = triangular plates. Each point is a time average over a day or a night. The full line is the best-fit of the experimental points with  $Gr$  exceeding  $5 \cdot 10^4$  ( $r$  is the linear correlation coefficient). The dashed line is the theoretical relationship for natural convection.

clustered into two groups, only one of them (having  $Gr > 5 \cdot 10^4$ ) indicating a  $Nu$  vs.  $Gr$  relationship. These latter points are best-fitted (linear correlation coefficient  $r = 0.77$ ) by the relationship:

$$Nu = 0.25 \cdot Gr^{0.30} \quad - \quad (2.48)$$

In fact, the air movement around the plate results from the interference of the flow in the boundary layer of the plate itself (which, by all accounts, could be expected to be laminar) with a general greenhouse flow of whatever origin (which has to be turbulent). Hence, the magnitude of the resulting exponent of  $Gr$ , i.e. 0.30 can be accounted for by the argument that the air flow nearby the plate is neither perfectly turbulent nor laminar. For a perfectly turbulent natural convec-

tion, the exponent of Gr is said to be 0.33, as it has to be independent of the dimension of the plate. For laminar flow, on the other hand, Parkhurst et al. (1968b) suggested the relationship for a warmer-than-air, horizontal, rectangular plate to be:

$$Nu = 0.37 \cdot Gr^{0.25} \quad - \quad (2.49)$$

i.e. the mean of the equations for the upper and lower surfaces (the coefficients being then 0.50 and 0.25, respectively). By calculating the arithmetic mean, however, it is implicitly assumed that the two surfaces have the same temperature, which for a real leaf could be debatable, but may be not far from the reality for the present experimental circumstances. Moreover, the mutual interference of the fluxes over the two surfaces is neglected by writing eq(2.49) as such. Both lines – eqs(2.48) and (2.49) – are shown in fig. 2.8. Indeed, it may be deduced that all plates are better heat dissipators than it would be inferred from laminar natural convection considerations alone. Of course, it could be argued that the external resistance of lobed plates has to be smaller than it is for more regular ones, as Vogel (1970) experimentally showed. From fig 2.8, however, round plates appear to be no worse heat dissipators than both other shapes, within the present experimental error. It has to be remarked that the way temperature was measured, as described in § 2.3.2, did not combine high accuracy with its unquestionable convenience. This resulted in experimental errors of about one degree for the temperature difference between the two plates. The consequence of such an error shoots up for decreasing temperature differences, i.e. Grashof numbers. There are certainly other possible reasons for the wide scattering of the experimental points. Eq(2.41) was deduced on the basis of a considerable number of unproven assumptions: that the two plates were identical and exposed to identical radiation fluxes; that any possible difference between the heat transfer resistance of the two plates is accounted for by the correction applied (eq(2.47)). With respect to this last point, one should observe that in fact, the warm plate experienced a uniform flux, whereas the cold one was more likely to have a uniform temperature. The difference of heat transfer in the two cases has just been said to be small, but not zero. This whole rationale, however, could well account for the large dispersion of the experimental points for small Gr, but not as easily for their sizeable and consistent deviation from the laminar natural convection line.

It can be inferred, from the same paper of Vogel (1970), that forced convection significantly contributes to reduce external resistance, even for Re as small as 1000 and Gr as large as  $4 \cdot 10^6$ . That would mean, in the present case, that the general greenhouse flow should be able to affect the flow in the boundary layer of the plate, which indeed is indicated by the exponent of eq(2.48), as suggested above. In fact, a guess of the magnitude of the air velocity in the boundary layer of the plate (as due to natural convection) can be derived from the theory. For the pre-

sent experimental circumstances, it would be contained between 4 and 10  $\text{cm}\cdot\text{s}^{-1}$ , which is indeed comparable with the measured velocity of the general air flow. It appears, therefore, that the general and particular flows may be somehow additive. Hence the mentioned approach of Börner (1965) was applied to the present data. Since the data are better represented in a  $\text{Nu}$  vs.  $\text{Gr}$  fashion, with  $\text{Re}$  accounting for deviations (as Wang (1982) did), a variant of that method was devised such that an equivalent Grashof number ( $\text{Gr}'$ ) was calculated. That was done by determining which  $\text{Gr}$  would cause the velocity as it is due to the forced air flow. For laminar boundary layer flow, eq(2.35) is represented by eq(2.49) and eq(2.34) by:

$$\text{Nu} = 0.60 \cdot \text{Re}^{0.5} \quad - \quad (2.50)$$

then, it can be calculated that:

$$\text{Gr}' = 6.92 \cdot \text{Re}^2 \quad - \quad (2.51)$$

Börner's approach further asks for the vectorial sum of the motions due to free and forced convection. This is a problematic question, given the erratic behaviour of air flow within a canopy. It is likely however, that being natural convection from several surfaces the chief cause of air movement in a greenhouse, the main direction of the flow is the vertical one, although it has a fluctuating nature. Having also considered the experimental finding of Scheupp (1980) that a fluctuating flow can expand heat transfer of up to 30%, the strongest assumption was adopted, namely, that  $\text{Gr}$  and  $\text{Gr}'$  have the same orientation. Then:

$$\text{Nu} = 0.37(\text{Gr} + \text{Gr}')^{0.25} = 0.37(\text{Gr} + 6.92 \text{Re}^2)^{0.25} \quad - \quad (2.52)$$

Eq(2.52), for various  $\text{Re}$  values, is plotted in fig 2.9 together with the experimental points, divided into corresponding  $\text{Re}$  classes. As the relatively large experimental error would mask the expected trend in  $\text{Re}$  anyway, the author feels entitled to nothing more gratifying than observing that eq(2.52) indeed could provide an explanation for the apparently strange results, not only of the present research, but also of others as reviewed. In fact, the use of eq(2.49) instead of (2.52) can (for small  $\text{Gr}$ ) underestimate the Nusselt number a 50%, even with  $\text{Re}$  as small as 100. The present result is of some consequence for greenhouse canopies, since there, leaves are, most of the time, within a few degrees of air temperature, which means that small  $\text{Gr}$  numbers are the norm and not the exception. Observe that the reasoning and the equations do not change for cooler-than-air leaves, only being the role of best heat exchanger (and the corresponding  $\text{Nu}$ ) bartered from the upper to the lower surface, while the Nusselt number of the whole leaf is still given by eq(2.49).



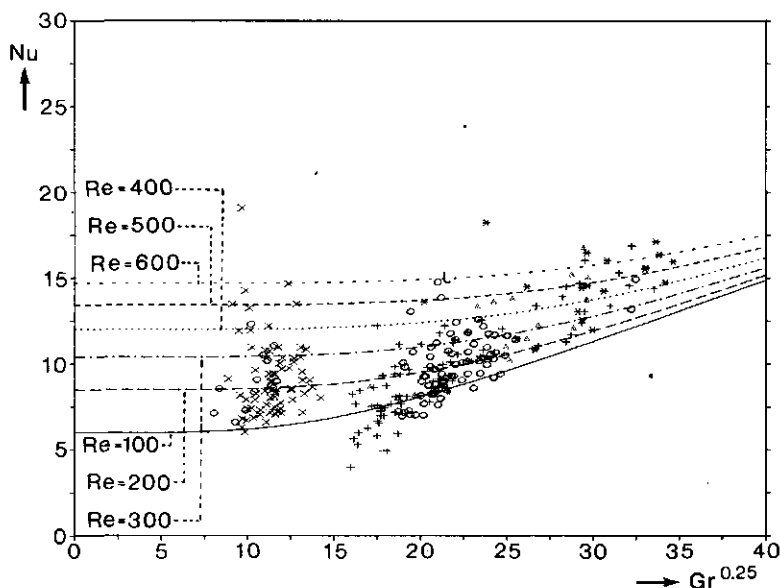


Fig. 2.9. Eq(2.52) calculated for various Reynolds numbers, as indicated at each curve, and the experimental points, divided in Re classes according to: x = Re between 100 and 200; o = 200-300; + = 300-400; \* = 400-500 and  $\Delta$  = 500-600.

However, given the proven difficulty of identifying a characteristic dimension for something like an irregularly shaped leaf immersed in a flow of not-well-defined nature, the practical application of eq(2.52) presents two awkward issues: how and how accurately such a dimension is to be determined and how good has the measure (or estimate) of wind speed to be, for eq(2.33) (with substitution of eq(2.52)) to yield reasonable appraisals of the external resistance? Substitution of the constants for air (at 20°C) in the combination of eqs(2.33) and (2.52) produces:

$$r_e = \frac{1174 \ell^{0.5}}{(\ell |T_0 - T_a| + 207 u^2)^{0.25}} \quad \text{s} \cdot \text{m}^{-1} \quad (2.53)$$

The resulting external resistance, for various combinations of  $\ell$  and  $u$  is shown in figs. 2.10 and 2.11. As it had to, eq(2.53) is reduced to the forced convection equation for either large wind speeds or small dimensions or, which is trivial, for  $T_0 = T_a$ . Both figs. 2.10 and 2.11 show that for growing wind speed as well as dimension, the consequence of an error in their estimate shrinks. For instance, it may well be feasible to assess  $r_e$  on the basis of a roughly estimated typical length of a crop of cucumbers, but not of roses; on the other hand, variations of wind speed above say  $20 \text{ cm} \cdot \text{s}^{-1}$ , have little effect on the external resistance, whereas it may matter a lot whether air flow in a greenhouse is  $5$  or  $15 \text{ cm} \cdot \text{s}^{-1}$ . The reader may well be disappointed therefore, that the resulting equation for the external resistance seldom lends itself to simplifications to be used for the range of

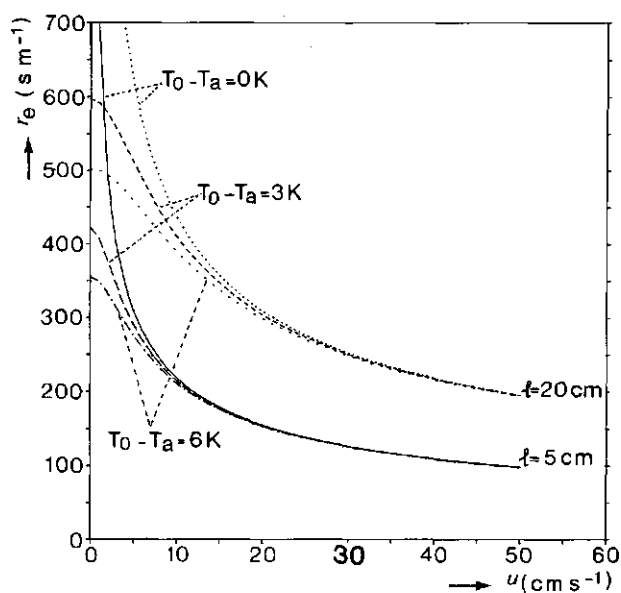


Fig. 2.10. External resistance, as calculated by eq(2.53), as a function of wind speed, for two leaf dimensions ( $l$ ) and three temperature excesses.

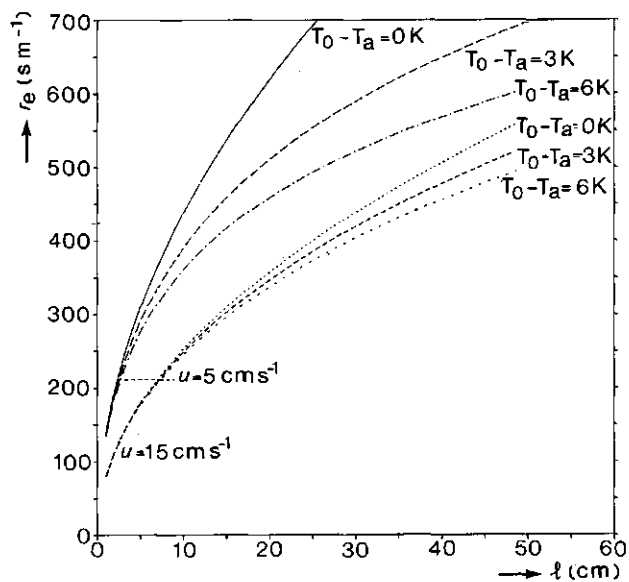


Fig. 2.11. External resistance, as calculated by eq(2.53), as a function of the characteristic leaf dimension, for two wind speeds ( $u$ ) and three temperature excesses.

wind speeds and temperatures typical of greenhouse microclimate, without considerable loss of accuracy. The specific purpose of this section, however, has been to show that the external resistance of arbitrary leaves can be calculated. On the other hand, how much do variations of the external resistance itself matter for the transpiration and surface temperature of such a leaf is left to be discussed in § 2.5.4.

## 2.4 Internal resistance

The internal resistance has been previously defined (§ 2.2.1) as the resistance on the vapour transfer pathway between the phase interface within a leaf and its external surface. It has also been stated that it could, in principle, be partitioned into components of that pathway, i.e. cuticle, stomatal ante-chamber, stomatal pore, sub-stomatal cavity, cell walls, etc., down to the phase interface, if the site of the latter was known. All these individual resistances are known to differ largely, not only between species, but also among individuals of a certain species, and even between individual leaves of a plant. It appears that adaptation to different climatic conditions and habitats, together with leaf age, are responsible for those variations. Slatyer (1977), for instance, observed different behaviour among four *Eucalyptus* populations, grown at different altitudes; Gay and Hurd (1975) measured large variations in stomatal frequency of corresponding leaves of tomato plants grown in different light regimes. Greenhouse plants for instance, are reported to have a rather small internal resistance at dark (Bot, 1983), whereas their minimum resistance upon exposure to light is relatively large (Körner et al., 1979). It is recognized however, that of all the individual resistances, only the resistance of the stomatal pore displays a remarkable degree of variability in time, which can be identified with its opening and closing in response to external and internal factors. Therefore, short term control of transpiration (if present, § 2.5), has to be performed by the stomata. Hence, an equation attempting to describe the behaviour of the internal resistance (for the sake of the model that is being developed here) should chiefly account for the variability of the stomatal resistance, whereas the other ones, either very large (cuticular) or very small (stomatal cavity), could simply be represented as constants.

In 1959 already, Gaastra showed that stomatal conductance and  $\text{CO}_2$  uptake were strongly correlated. He inferred that the stomata control the entry of  $\text{CO}_2$  into the leaf, as well as the loss of water. Since then many attempts have been made to provide for a satisfactory conceptual model to include the known effects of the environment upon  $r_i$ . In 1972 Stigter reviewed the literature about stomatal behaviour admitting that 'which are the exact mechanisms responsible for the influence stomata are able to exert' was still an object of discussion. The whole matter was again reviewed by Raschke (1975). Apparently, however, the subject had

not made much progress, as Jarvis (1981) pointed out: 'there is some argument as to whether the stomata do in fact control the rate of photosynthesis or whether photosynthesis controls stomatal conductance', and went on to state that Gaasstra's supposition 'seems still to be valid'.

The whole subject is of obvious importance since it affects water use efficiency of crops (Kimball, 1983). Also the many different forecasts about the influence on yield of the ongoing  $\text{CO}_2$  accumulation in the atmosphere (Idso, 1984; Liss and Crane, 1984) are based upon the one or other assumption on this subject. The present author however, as a physicist with no biological knowledge worth mentioning, is certainly unable to bring any contribution to the matter. Moreover, for the purpose of this work, it is more important to know how the internal resistance is affected by the microclimate than which mechanism is responsible for that influence, though it is not denied that in general, the knowledge of mechanisms is helpful in the task of forecasting the behaviour of systems.

Therefore in this book, the internal resistance of a leaf will be regarded as a black box. However, it is not maintained here that the huge amount of work performed since, in 1900, Brown and Escombe tried to relate transpiration by leaves to the measured diffusion of water vapour in simple physical systems, has not delivered some knowledge of what is inside the black box.

#### *2.4.1 Response to environmental factors*

The internal resistance of a leaf is known to be affected by a number of physiological and environmental parameters. Only the latter group will be considered in the present context; of these, shortwave irradiation ( $I_s$ ) appears to be the most important one (Meidner and Mansfield, 1968). Further, leaf to air vapour pressure difference ( $e_o - e_a$ ) (Lange et al., 1971), leaf surface temperature ( $T_o$ ) (Neilson and Jarvis, 1975),  $\text{CO}_2$  concentration of the air (Meidner and Mansfield, 1968) and leaf water potential (Stälfelt, 1955), are known to play a role. The latter will not be considered hereafter, since no effect of it has been shown at the small water potentials typical of greenhouse crops.

A phenomenological model to predict  $r_i$  can be made from experimentally determined relations between the latter and the mentioned variables of the microclimate. The response of  $r_i$  to a given parameter, however, can scarcely be determined from experiments performed in natural conditions, since a factor can seldom change independently from the others. This problem, unfortunately, makes the interpretation of many earlier studies quite difficult, given the correlation between irradiation and temperature (Gregory and Pearse, 1937) or between temperature and vapour pressure (Mansfield, 1965). Stanhill et al. (1973) used multiple regression to describe the internal resistance of a glasshouse rose crop as a function of nairradiance, leaf relative water content and leaf surface temperature and found out that 85% of the diurnal variation of  $r_i$  could be accounted for by variations of  $T_o$ , the latter being obviously correlated to both other factors. This

technique, however, is entirely empirical and has thus little predictive value for other crops and combinations of environmental conditions. Consequently, the form of the functional relations between the internal resistance and each driving variable is best determined in controlled environment studies.

The general form of these relations has indeed been determined, as shown in fig. 2.12. There is still however, uncertainty about the extent of the interactions

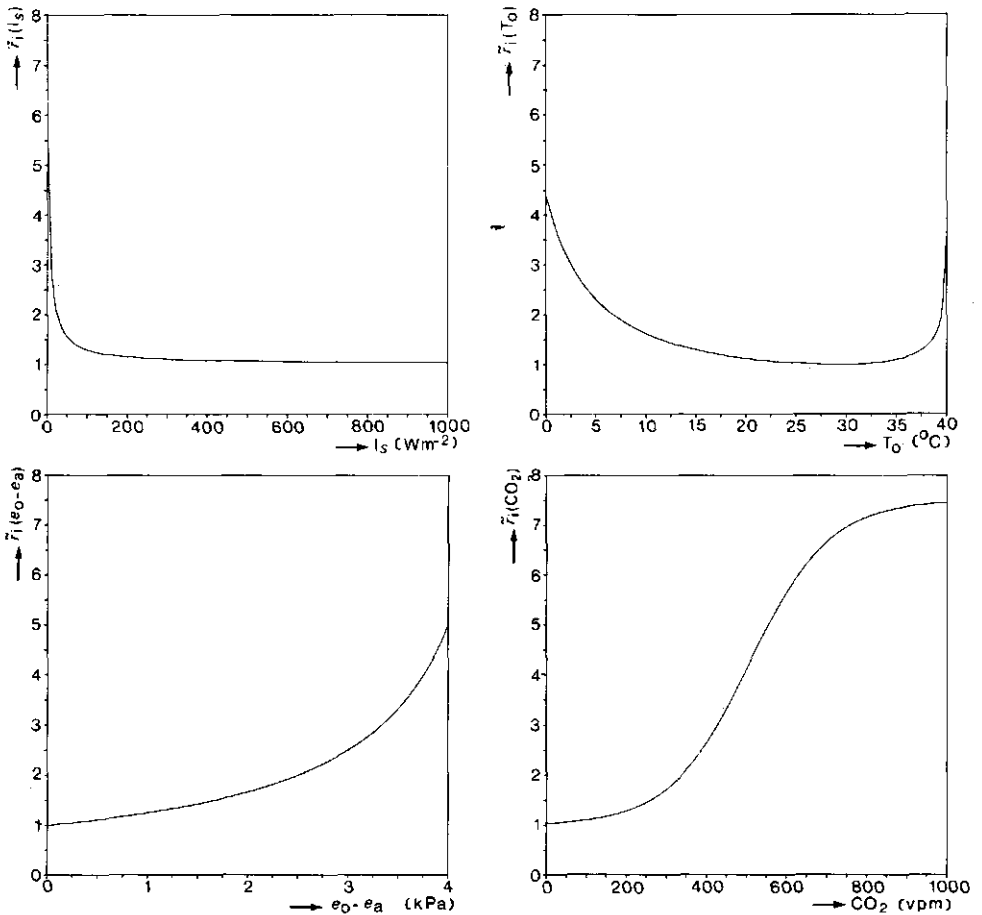


Fig. 2.12. A schematic representation of the response of the internal resistance  $r_i$  to shortwave irradiation ( $I_s$ ) (*Pinus sylvestris*; after Ng and Jarvis, 1980), leaf temperature ( $T_o$ ), vapour pressure difference between the leaf and the air ( $e_o - e_a$ ) (both Sitka spruce; after Jarvis, 1976) and to the carbon dioxide concentration of the ambient ( $CO_2$ ) (maize; after Takakura et al., 1975).

between the variables. Faute de mieux, Jarvis (1976) adopted the simplest hypothesis, i.e. that the observed resistance is the result of the influence of all variables, without any synergistic interaction, namely:

$$r_i(I_s, T_0, e_0 - e_a, CO_2) = r_{min} \cdot \tilde{r}_i(I_s) \cdot \tilde{r}_i(T_0) \cdot \tilde{r}_i(e_0 - e_a) \cdot \tilde{r}_i(CO_2) \quad s \cdot m^{-1} \quad (2.54)$$

where  $r_{min}$  is the minimum possible resistance, and  $CO_2$  is the  $CO_2$  concentration ( $m^3 \cdot m^{-3}$ ) of ambient air. The symbols  $\tilde{r}_i$  represent dimensionless functions larger than unity, quantifying the relative increase of the internal resistance, whenever one of the parameters is limiting the rate of transfer of water vapour. The magnitude of the minimum resistance on the other hand, has a purely physiological origin. It should be observed that the response of the internal resistance to the microclimate is also of a physiological nature, therefore the parameters of the functions  $\tilde{r}_i$  are quite likely to be species-specific.

The mathematical function one chooses in particular to reproduce the trends of the individual  $\tilde{r}_i$  as shown in fig. 2.12, is in the first place, dictated by the available capabilities of non-linear best-fit programs, since the scatter of the experimental points implies that the fine details of the one or the other shape cannot be recognized. Given the non linearity of almost all the functions suggested, and the ensuing difficulties for best-fit procedures, some of the parameters are normally fixed beforehand. The most obvious is the minimal resistance which may be defined as the extreme among the specific experimental results (Ng and Jarvis, 1980; Avissar et al., 1985), or, more widely, deduced from the literature. From the discussion at the beginning of this section, it is clear that such data should be available for each species (and habitat), which is far from the reality. The existing data moreover are difficult to interpret, given the unhomogeneity of the leaf surface area to which the measured resistance is referred to, as Körner et al. (1979) pointed out in their ample review. The many different methods used to measure what is mostly called 'stomatal' resistance do add something to the difficulty. In fact, the direct measure of the opening of the stomatal pore (e.g. Hashimoto et al., 1982) is not equivalent to the measure of the leaf diffusion resistance through a porometer (e.g. Stigter et al., 1973) nor to the deduction of the internal resistance from canopy transpiration (e.g. this work, § 3.5).

A few data are worth mentioning however, in order to provide the reader with some order of magnitude of the internal resistance, before the next section. Moreshet and Yocum (1972) reported the minimum resistance of greenhouse grown tomato plants to be about  $300 \text{ s} \cdot \text{m}^{-1}$  as a mean of the resistances of the upper and lower surfaces, whereas Kuiper (1961) measured a value around  $500 \text{ s} \cdot \text{m}^{-1}$ . This difference could be due to the different experimental techniques, as well as to different varieties. Kuiper (1961) also provided a value for dark resistance (maximum resistance) of the same plants, as being about  $20000 \text{ s} \cdot \text{m}^{-1}$ , in good agreement with an earlier work of Raschke (1960). Observe that this adds up to a likely ratio of 40 to 60 between the maximum and minimum resistances. On the other hand, Seginer (1984) could infer a  $r_i$  value of about  $2500 \text{ s} \cdot \text{m}^{-1}$  from his

measurements of nighttime transpiration of a greenhouse rose crop, whereas Zhao et al. (1985) measured values between 2000 and 6500 s · m<sup>-1</sup> for chrysanthemums. In the last mentioned paper the spreading of the results was credited to the different experimental techniques applied, as well as to different environmental conditions; infrared heating apparently caused a higher nighttime resistance than convective heating. It has to be observed that all existing methods of determining the internal resistance of a leaf always result in considerable errors when the latter is large.

## 2.5 Discussion

In this section, the influence of the microclimate on both temperature and transpiration of the surface will be discussed. As far as possible the effect of each parameter will be considered independently. Furthermore, for the sake of this discussion,  $R_n - J$  will simply be regarded as the available energy at a given instant. It is therefore overlooked, how  $J$  is a function of both the surface temperature  $T_0$  and of the time. It is worthwhile rearranging eqs(2.28) and (2.30), the equations for the transpiration rate and the temperature of the surface, in a more lucid form, namely:

$$LE = \frac{\frac{\delta}{\gamma} (R_n - J) + \frac{\rho_a c_p}{\gamma r_e} (e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \quad \text{W} \cdot \text{m}^{-2} \quad (2.55)$$

and

$$T_0 - T_a = \frac{\frac{(r_i + r_e)}{\rho_a c_p} (R_n - J) - \frac{1}{\gamma} (e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \quad \text{K} \quad (2.56)$$

It will be observed that transpiration rate and temperature excess are explicit functions of five variables. Each function may, therefore, be represented by a hypersurface in a 6-dimension space, whose other axes are net radiation of the surface ( $R_n - J$ );  $\delta$ , which is an univocal, monotonous function of the temperature of the air ( $T_a$ ); saturation deficit ( $e_a^* - e_a$ ) of the latter; and the external ( $r_e$ ) and internal ( $r_i$ ) resistances. In view of this, any attempt to calculate transpiration, or temperature, as functions of a smaller set of parameters (i.e. to reduce their dimensions) should be regarded with suspicion. In most natural circumstances however, radiation, temperature, saturation deficit and even the external resistance (through the wind speed), are somehow correlated. It might be feasible, therefore, that each function may be represented by a relation with less independent variables. In geometrical terms, this translates into the fact that, in a given sub-

space, both transpiration and surface temperature might be represented by a surface with less than five dimensions. It is common experience, in fact, that most transpiration and surface temperature data can be satisfactorily fitted by empirical formulae where not all the five 'independent' variables appear explicitly. When using such formulae however, care should be taken to check whether the relations implicitly assumed to hold among the variables do apply to the present circumstances.

Moreover, when considering each function on a time span for which one or more of the variables can be assigned a constant (mean) value, the number of dimensions can be reduced accordingly. Since all five variables are likely to be more or less cyclic, with at least a daily period, it should be expected that, when longer term estimates of transpiration or leaf temperature are considered, the corresponding equations would be noticeably simpler than either eq(2.55) or eq(2.56).

### 2.5.1 Net radiation as a function of surface temperature

It has already been mentioned that the net radiation of the surface is a function of its temperature. It should be realized, therefore, that eqs(2.55) and (2.56) may not be used for the purpose of making forecasts about the influence of the microclimate, since the net radiation  $R_n$  is not a variable exclusively of the microclimate. In consequence of this, neither eq(2.55) nor eq(2.56) are, in the present form, suitable for this analysis, since each parameter will be considered here as an independent variable. The component of net radiation that is a function of the temperature of the surface has, therefore, to appear explicitly in both equations. As eq(2.7) shows, net radiation may be regarded as the sum of two parts. Only one:

$$R_{absorbed} = (1 - \tau_s - \rho_s) I_s + I_l \quad \text{W} \cdot \text{m}^{-2} \quad (2.57)$$

is independent from the surface temperature. Hence:

$$R_n = R_{absorbed} - \sigma T_o^4 \quad \text{W} \cdot \text{m}^{-2} \quad (2.58)$$

Monteith (1975) introduced the concept of 'isothermal' net radiation as the net radiant flux the surface would absorb if it were at air temperature. Accordingly, isothermal net radiation  $R_{n,a}$  can be written as:

$$R_{n,a} = R_{absorbed} - \sigma T_a^4 \quad \text{W} \cdot \text{m}^{-2} \quad (2.59)$$

However, it is worthwhile stressing that, since isothermal net radiation cannot be inferred from measured radiation fluxes in a simple way, it is no more than a device to be used in a discussion such as this. Measured (or estimated from measured fluxes § 3.2) net radiation, on the other hand, already accounts for varia-



tions in the temperature of the foliage; hence it is correct to apply eqs(2.55) and (2.56) to measured data. The combination of eqs(2.58) and (2.59) anyway, gives the relationship between net radiation and isothermal net radiation:

$$R_n = R_{n,a} - \sigma (T_o^4 - T_a^4) \quad W \cdot m^{-2} \quad (2.60)$$

However, substitution of eq(2.60) in either eqs(2.55) or (2.56) results in fourth degree equations for transpiration and surface temperature which can be analytically solved only after a linearization similar to the one applied to the saturated vapour pressure curve in eq(2.22), i.e.

$$\sigma (T_o^4 - T_a^4) = 4 \sigma T'^3 (T_o - T_a) \quad W \cdot m^{-2} \quad (2.61)$$

where  $T'$  is a temperature in the interval  $T_o, T_a$  according to Lagrange's theorem. For small surface-to-air temperature differences the replacement of  $T'$  with  $T_a$  does not yield considerable deviations. The combination of eqs(2.60) and (2.61) (with  $T' = T_a$ ), and their substitution in eq(2.18) yields a new version of the energy balance:

$$R_{n,a} = H + LE + J + 4\sigma T_a^3 (T_o - T_a) \quad W \cdot m^{-2} \quad (2.62)$$

Hence, it is enough to substitute  $R_{n,a} - 4\sigma T_a^3 (T_o - T_a)$  for  $R_n$ , in eqs(2.55) and (2.56) in order to get the transpiration and surface temperature equations looked for:

$$LE = \frac{\frac{\delta}{\gamma}(R_{n,a} - J) + \frac{\rho_a c_p}{\gamma} \left( \frac{1}{r_e} + \frac{1}{r_R} \right) (e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{1}{r_R} (r_i + r_e)} \quad W \cdot m^{-2} \quad (2.63)$$

and

$$T_o - T_a = \frac{\frac{1}{\rho_a c_p} (r_i + r_e)(R_{n,a} - J) - \frac{1}{\gamma} (e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{1}{r_R} (r_i + r_e)} \quad K \quad (2.64)$$

where  $r_R$  is a resistance to radiation transfer defined by:

$$r_R = \rho_a c_p / (4 \sigma T_a^3) \quad s \cdot m^{-1} \quad (2.65)$$

Of course there is only a formal difference between eqs(2.63) and (2.64) and the corresponding eqs(2.55) and (2.56). Here the fact that radiation is a third mode (besides release of sensible and latent heat) for the surface to attain the equilibrium of its energy exchanges is explicitly accounted for, instead of being hidden within the (apparently) independent variable  $R_n$ .

Some values of the typical ratio  $\delta/\gamma$  and of the radiation resistance  $r_R$ , for various ambient temperatures, are summarized in tab. 2.1.

$T_a$	$\delta/\gamma$	$r_R$
0	0.67	282
5	0.92	263
10	1.23	244
15	1.64	228
20	2.14	213
25	2.78	199
30	3.57	186
35	4.53	174
40	5.70	164

Table 2.1. Dimensionless ratio of the slope of the saturated vapour pressure curve  $\delta$  to the thermodynamic psychrometric constant  $\gamma$  and the radiation resistance ( $r_R = \rho_a c_p / (4\sigma T_a^3)$ , s·m<sup>-1</sup>) both as function of air temperature  $T_a$  in °C

The evaporation and temperature of a surface completely wet (as after rainfall), or the condensation and temperature of a surface where condensation takes place, may be calculated by means of eqs(2.63) and (2.64) – or, for this matter, eqs(2.55) and (2.56). One should realize, however, that in both cases, the internal resistance  $r_i$  has to be zero. Inspection of the conditions for eq(2.63) to yield  $LE \leq 0$  or eq(2.64) to result in  $T_o \leq T_{dew}$  (the latter being defined by  $e_a = e^*(T_{dew})$ ) gives the micrometeorological condition for condensation, namely:

$$\frac{\delta(R_{n,a} - J)}{\rho_a c_p (e_a^* - e_a)} r_R \leq - \left( 1 + \frac{r_R}{r_e} \right) \quad - \quad (2.66)$$

The term on the left hand side of eq(2.66) will appear in the following to be a parameter of some importance. It is therefore handy to define:

$$\tilde{r} \equiv \frac{\delta(R_{n,a} - J)}{\rho_a c_p (e_a^* - e_a)} r_R \quad - \quad (2.67)$$

Stewart and Thom (1973) defined a 'climatological resistance' in a similar fashion. The present definition is however preferred, as the presence of  $\delta$  and  $r_R$  better accounts for the influence of air temperature.

### 2.5.2 Error due to the linearizations

It is possible to estimate the order of magnitude of the error caused by the linearizations: 'true'  $LE$  and  $T_o - T_a$  have to be contained between the values given by their equations, with  $\delta(T_a)$  and  $4\sigma T_a^3$  at one extreme and  $\delta(T_o)$  and  $4\sigma T_o^3$  at the other. The equations with the surface temperature appearing explicitly on the right hand side are, of course, to be solved by numerical iterations. Let us choose

as an example, a typical greenhouse microclimate:  $r_i = r_e = 200 \text{ s} \cdot \text{m}^{-1}$ ;  $T_a = 20^\circ\text{C}$ , relative humidity 75%,  $R_{n,a} = 100 \text{ W} \cdot \text{m}^{-2}$ . Eq(2.64) using  $T_a$  for the calculation of  $r_R$  and  $\delta$  yields  $T_o - T_a = 4 \text{ K}$  and, when  $T_o$  is used, it converges to  $T_o - T_a = 3.7 \text{ K}$  i.e.  $T_o = 23.7^\circ\text{C}$ . Use of the latter in eq(2.63) results in a transpiration rate of  $55.3 \text{ W} \cdot \text{m}^{-2}$ , whereas use of  $20^\circ\text{C}$  ( $T_a$ ) would yield  $\text{LE} = 52.7 \text{ W} \cdot \text{m}^{-2}$ . Thus, in these conditions, linearization is likely to result in an error of about 4% in transpiration rate as well as in the temperature excess of the surface. On the other hand, for the same conditions but  $R_{n,a} = 500 \text{ W} \cdot \text{m}^{-2}$  the resulting error is about 20% in both functions. Therefore, eqs(2.63) and (2.64) (and eqs(2.55) and (2.56) to a minor extent) should be used with some scepticism, whenever the surface-to-air temperature difference exceeds a few degrees. Those conditions however, can be easily identified if one realizes that eq(2.64) produces an overestimate of the temperature excess, whenever the latter is positive. On the other hand, it is unlikely that the surface is more than a few degrees cooler than the surrounding air, in any condition. Even more so under a greenhouse cover that restricts radiative cooling.

### 2.5.3 Net radiation, saturation deficit and air temperature

Looking at eqs(2.63) and (2.64), one can observe that both transpiration and surface temperature are linear functions of both the available radiation and saturation deficit. However, it is an acknowledged fact that for most climates, transpiration can be better estimated as a function of measured radiation fluxes than of saturation deficit. For example, the latter is not even mentioned as a relevant parameter in handbooks such as FAO's (Doorenbos and Pruitt, 1977). The far larger relative variation of radiation rather than of saturation deficit is a most obvious reason for the effect of the former to prevail, in a temperate climate. For more arid regions, however, disregard of the variation of the aerodynamic term is reasonable only as long as saturation deficit is itself a strong function of irradiation, which indeed it may be. It is worthwhile remarking here that the controlled climate of a greenhouse is such as to ensure a relatively constant (and small) saturation deficit. In this case, the conditions for (long term) transpiration to be estimated by a straight line with net radiation are likely to be met. A lot of these relations have in fact been published for various crops and crop ages, since the pioneering work of Morris et al. (1957). Greenhouse irrigation systems based on such relationships (De Graaf and Van den Ende, 1981) are successfully in use (De Graaf, 1985).

A rule of thumb for daytime transpiration in a greenhouse can be easily deduced, if one realizes that  $\delta/\gamma \sim 2.5$  and, more approximately,  $r_i \sim r_e \sim r_R \sim 200 \text{ s} \cdot \text{m}^{-1}$ . Moreover, it is important noticing that, within a greenhouse,  $R_{n,a}$  has the same order of magnitude as the global radiation  $I_s$ , whereas the ratio  $(e_a^* - e_a)/\gamma$  is normally contained between 10 and 20 K. Thus,

$$\text{LE} \sim 0.35 \cdot I_s + 30 \quad \text{W} \cdot \text{m}^{-2} \quad (2.68)$$

Indeed, Yamoaka (1958), De Graaf (1978) and Hamaker and De Graaf (1978) could deduce from their experiments, empirical relations remarkably similar to eq(2.68).

On the other hand, comparison of eqs(2.55) and (2.56) shows that, if the coefficient of net radiation in eq(2.55) can be approximated by a constant, more or less the same should happen for the coefficient of saturation deficit in the equation for temperature excess, since they only differ by a factor  $\delta$ . Indeed, the relationship between leaf surface temperature and saturation deficit has been shown by Idso (1982) to be represented by straight lines for a range of agricultural crops. This is, undoubtedly, a result of practical importance, although there could be more arguments than the author seems ready to concede (Idso et al., 1984) about whether the same lines would hold outside the (narrow) range of microclimates they refer to.

In fact, things cannot be that easy in less straightforward climates. For while the aerodynamic term of transpiration can be regarded as being fairly constant in many circumstances, as mentioned above, the radiative part of temperature excess is more likely to be the reverse. Hipps et al. (1985) did show that in a more variable environment as that of most of Idso's experiments, the scatter of the temperature excess vs. saturation deficit lines was quite large. Net radiation for a crop within a greenhouse is, in The Netherlands, an all too variable quantity. Hence, no such straightforward relationship should be expected to hold between the temperature excess and the ambient saturation deficit. Indeed, temperature excess measured during the present research (§ 3.5.1) repeatedly resulted in a better linear correlation with net radiation than with saturation deficit. The regression lines for different days, however, could be quite different, pointing to relevant variations of the daily mean of at least some of the variables.

The influence of the ambient temperature is more difficult to analyze since both the internal and the external resistance are affected by it, in an ambiguous fashion. However, one could observe that any increase of the ambient temperature makes more energy available to the surface through the sensible heat flux. It is therefore bound to result in a higher equilibrium temperature for the surface. On the other hand this excess energy may be released either by transpiration or by radiation (or both). Consequently, only a more detailed knowledge of the behaviour of the internal resistance would show whether the surface getting warmer also means that it loses more water (§ 4.1.3).

#### *2.5.4 External resistance*

The influence on the transpiration rate of a variation of the external resistance, as it is revealed by fig. 2.13 might be quite surprising, as it suggests that an increase of the resistance can sometime cause the flux to enlarge. In fact, the transpiration rate is always a decreasing function of the external resistance, for sufficiently

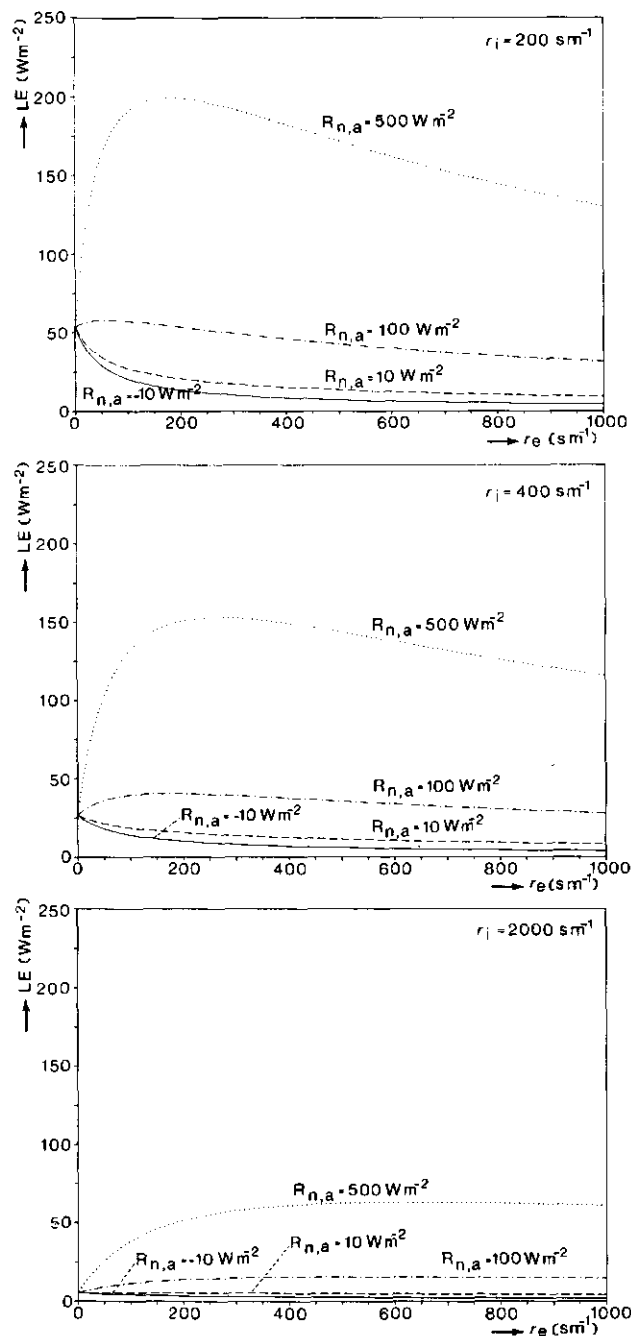


Fig. 2.13. The transpiration rate as a function of the external resistance, for various values of the isothermal net radiation, as indicated. Air temperature  $20^\circ$  and relative humidity 75% ( $e_a^* - e_a = 0.6$  kPa) have been assumed throughout.

large values of the latter, since the surface then gets rid of its excess energy more easily through radiation. In fact:

$$\lim_{r_e \rightarrow \infty} LE = 0 \quad \text{W} \cdot \text{m}^{-2} \quad (2.69)$$

On the other hand, it may be somehow surprising that:

$$\lim_{r_e \rightarrow 0} LE = \frac{\rho_a c_p (e_a^* - e_a)}{\gamma r_i} \quad \text{W} \cdot \text{m}^{-2} \quad (2.70)$$

i.e. for a negligible external resistance the surface transpires at pure isothermal conditions, whatever the absorbed radiation, since sensible heat release then is the most efficient way to reach the equilibrium of the energy fluxes.

In the wide region between these extremes however, the outcome of any variation of the size of the external resistance is less predictable (fig. 2.13), because the transpiration rate might be enhanced as well as reduced, as a result of an enlargement of the external resistance. In other words, the transpiration rate as a function of the external resistance may (or may not) have an inversion point (namely a maximum), depending on the conditions. A better definition of these conditions is provided by the discussion of the partial derivative  $\partial LE / \partial r_e$ , which requires an admittedly boring amount of computations. Therefore only a summary is given here.

The transpiration rate will be a monotonous, decreasing function of the external resistance whenever

$$\tilde{r} < \frac{r_R}{r_i} \left( 1 + \frac{\delta}{\gamma} \right) \quad - \quad (2.71)$$

Otherwise, there is always a finite value ( $r_e'$ ) of the external resistance for which the maximum rate of transpiration for a given microclimate is reached, i.e.  $LE$  is either an increasing, stationary or decreasing function of  $r_e$ , depending on whether  $r_e \leq r_e'$ . The latter can be calculated through:

$$r_e' = \frac{r_R}{\tilde{r} + 1} \left\{ \left[ 1 + (\tilde{r} + 1) \left( \frac{r_i}{r_R} \tilde{r} - 1 - \frac{\delta}{\gamma} \right) \right]^{1/2} - 1 \right\} \quad \text{s} \cdot \text{m}^{-1} \quad (2.72)$$

The somewhat unexpected result that in many conditions an increase in the external resistance causes an increase in the rate of transpiration was experimentally observed by Yamoaka (1958) (fig. 2.14) in a laboratory experiment. Indeed, this analysis not only provides an account for the 'inexplicable' finding of Yamoaka, it also allows to determine (under certain assumptions) how large had the internal resistance to be, for Yamoaka's observations to be possible (fig. 2.14).

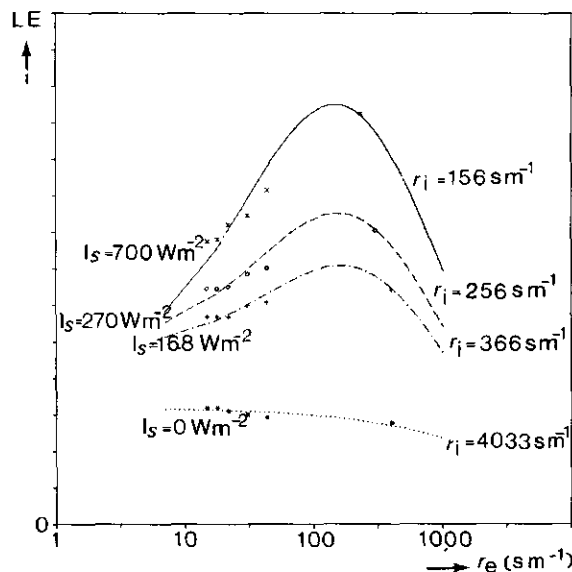


Fig. 2.14. Relation between transpiration rate (arbitrary units) of branches of *Cryptomeria japonica* and the external resistance (after Yamoaka, 1958). The external resistance has been calculated (eq(2.53)) from the wind speeds and temperature differences given in the original paper, assuming  $l \sim 1$  cm. The symbols are actual measurements by Yamoaka, for the irradiances indicated. The lines represent the transpiration rate (eq(2.63)) for the same conditions, assuming internal resistances as indicated and  $R_{n,a} = I_s$ .

The importance of the fact that wind influences transpiration in a non-obvious fashion was pointed out by Grace (1981) in an analysis of the effect of wind on plants. A couple of examples as summarized in tab. 2.2 shows that there is a broad range of greenhouse conditions for which the actual external resistance may be about the same, or smaller, than the value which maximizes the transpiration rate for those conditions (fig. 2.14).

	$R_{n,a} - J$ $W \cdot m^{-2}$	RH %	$\tilde{r}$ —	$r_i$ $s \cdot m^{-1}$	$r_e'$ $s \cdot m^{-1}$	$LE(r_e')$ $W \cdot m^{-2}$
nighttime	5	90	0.53	5000	403	1
cloudy day	100	80	5.28	500	227	33
sunny day	500	70	17.62	250	195	183

Table 2.2. Values of the external resistance  $r_e'$  that maximize the transpiration rate for the conditions indicated. An ambient temperature of 20°C has been assumed throughout and RH is the relative humidity (%).

Hence the widespread belief that a fan whirling above a greenhouse canopy 'stimulates transpiration' because it decreases the external resistance (Zandbelt, 1983), is questionable. Moreover, as the plots of the derivative  $\partial LE / \partial r_e$  (fig.

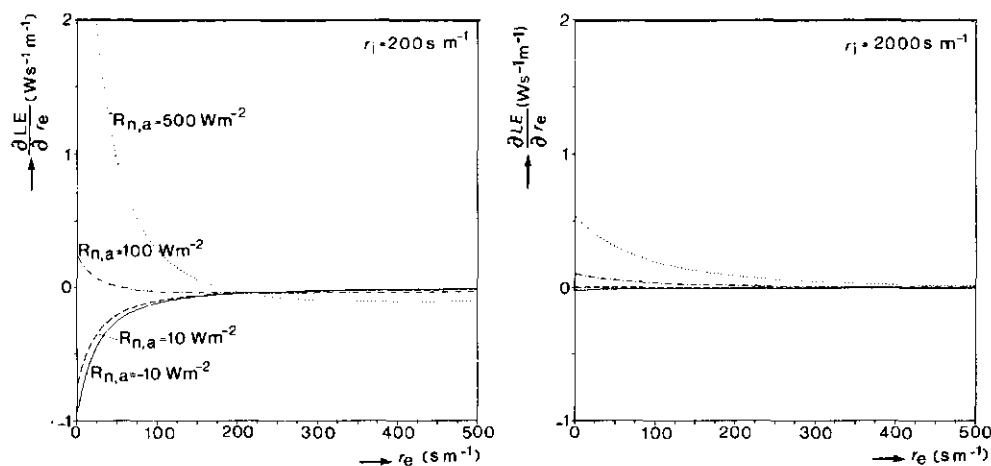


Fig. 2.15. The partial derivative  $\partial LE / \partial r_e$ , as a function of the external resistance, for the conditions indicated. Air temperature 20°C, relative humidity 75%. Line types in [b] refer to the isothermal net radiations ( $R_{n,a}$ ) indicated in [a].

2.15) make clear, LE may be regarded as a strong function of  $r_e$  only for values of the latter well smaller than  $r_e'$ . For larger values, the transpiration rate is scarcely affected by variations of the external resistance. Just to summarize, if switching on the mentioned fan has any discernible effect at all, it is more likely to be an unexpected drop in the transpiration rate.

The fact that the transpiration rate seldom is a strong function of the external resistance, although (somehow more implicitly) already mentioned by Monteith (1965), has not been given the attention it deserves. Gates (1968) gave it a reductive reading, stating that 'when the amount of absorbed radiation is low then for moist air conditions a change of wind speed will result in little change of water loss'. From this point of view an explanation could be provided for the fact that so many evaporation formulae, based on wildly heterogeneous parametrizations of the external resistance – the present author also having contributed an entry (Stanghellini, 1983b) –, could claim some accuracy. They could, indeed, if at least the order of magnitude of the external resistance was correctly estimated.

The following rationale should make these apparently strange results better understood. Any increase of the external resistance has two consequences: transfer of vapour away from the surface is somehow inhibited (which should result in warming the surface) and exchange of sensible heat between the surface and the air is restricted (of which the outcome is obviously dependent on the direction of the flux). Any variation of the temperature of the surface, however, works upon its vapour pressure, the driving force for transpiration being accordingly influenced. All the discussion above shows that there is a regime for which the two



mentioned consequences of an increase of the external resistance would set opposite courses, whose outcome is not easily forecast.

As far as the temperature of the surface is concerned, one might expect that the analysis of the relationship between the surface temperature and the external resistance yields comparable results, which are, hereafter, highlighted.

It has already been pointed out that for a negligible external resistance the surface temperature is equal to ambient temperature, whatever the conditions. On the other hand it may be deduced from eq(2.64) that:

$$\lim_{r_e \rightarrow \infty} (T_o - T_a) = r_R (R_{n,a} - J) / \rho_a c_p \quad K \quad (2.73)$$

although, as it has been made clear in § 2.5.2, the use of  $T_a$  to evaluate the radiation resistance through eq(2.65) may result in a large overestimate of the actual temperature excess in such a case. To guess what happens between these two extremes, one should observe that an increase of the external resistance causes the absolute value of both terms in the right hand side of eq(2.64) to expand, the radiative term growing relatively more than the other. Accordingly, if the temperature excess was positive, it is bound to become larger, if it was negative – the radiative term being also negative – the surface is cooling further while it can be inferred that there is a point of inversion if the radiative gain is positive but so small as not to offset the evaporative cooling (fig. 2.16). The discussion of the partial derivative  $\partial(T_o - T_a)/\partial r_e$ , allows the conclusions that:

a. the temperature of the surface is a monotonous, growing function of the external resistance whenever

$$\tilde{r} \geq \frac{\delta}{\gamma} \frac{r_R}{r_i} \quad - \quad (2.74)$$

Apparently, the conclusion by Thofelt et al. (1984) that the surface always gets warmer for a larger external resistance was based on experiments performed exclusively in this range.

b. the temperature of the surface decreases for any increase of the external resistance if

$$\tilde{r} \leq - \frac{\delta}{\delta + \gamma} \quad - \quad (2.75)$$

c. on the other hand, if the condition:

$$- \frac{\delta}{\delta + \gamma} < \tilde{r} < \frac{\delta}{\gamma} \frac{r_R}{r_i} \quad - \quad (2.76)$$

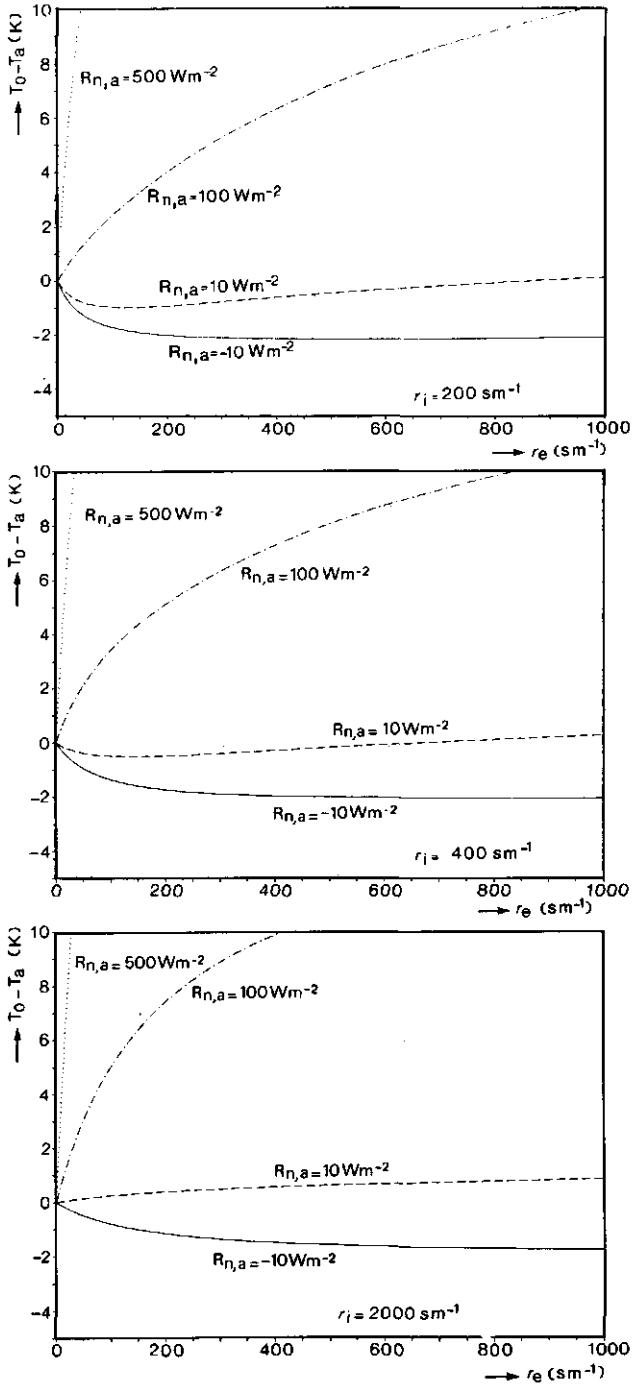


Fig. 2.16. The temperature excess as a function of the external resistance, for the conditions indicated. Air temperature  $20^\circ\text{C}$  and relative humidity 75% have been assumed throughout.

is satisfied, there is a value of the external resistance which minimizes the temperature excess. Comparison of eq(2.76) with the definition of  $\bar{r}$  (eq(2.67)) allows the deduction that eq(2.76) identifies a possible nighttime regime for a greenhouse canopy. In fact, these results confirm the observation made a priori that not even the relationship between the surface temperature and the external resistance is trivial. As it is quite difficult to grasp the practical meaning of the conditions quantified by eqs(2.74) to (2.76), a more intuitive description of this analysis will be provided in § 4.1.4 (fig. 4.4b).

Furthermore, for sufficiently large values of the external resistance, the temperature excess may be shown to be almost proportional to the latter, as it could have been deduced also from fig. 2.16. Hence, release of sensible heat is, in those conditions, fairly independent from the external resistance – eq(2.10). It follows from the energy balance – eq(2.62) – that also release of latent heat has to be almost independent from the external resistance, as it has been otherwise shown above. A windfall of this discussion is, therefore, that a (quite possible) error in the estimate of the external resistance does not translate into an error that large in the estimate of both the sensible and latent heat release of the surface. Indeed, in the case of Douglas fir and bracken, respectively, McNaughton and Black (1973) and Roberts et al. (1980) have shown that only small errors in the computed transpiration will arise from errors in the estimate of  $r_e$ .

### 2.5.5 Internal resistance

It may seem that after so much work has been devoted to investigate stomatal activity, and after beautiful scanning electron microscope pictures have been published of opening and closing stomata (e.g. Shiraishi et al., 1978; Jones, 1983), the fact that internal resistance concurs with a number of external conditions in determining the rate of transpiration, should be beyond discussion. However, as Van Bavel (1968) pointed out, 'from a hydrologic or an engineering view, what matters is whether this role is of consequence'. This precise question has stimulated a lively discussion in the literature (Lee, 1967; Idso, 1968; Lee, 1968a; Van Bavel, 1968; Lee, 1968b; Sheperd, 1972). Experimental evidence has been mentioned by Idso (1983), which prompted him to change his mind; however, it seems worthwhile to expand on it. In the context of the present work, it is of some importance to determine whether plant canopies are passive evaporating surfaces or significant regulators of evaporative water losses.

In fact, eq(2.63) allows the estimation of the effect on the transpiration rate, of an increase  $\Delta r_i$  of the internal resistance:

$$\frac{LE(r_i + \Delta r_i)}{LE(r_i)} = \frac{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{r_i}{r_R} + \frac{r_e}{r_R}}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{r_i}{r_R} + \frac{r_e}{r_R} + \frac{\Delta r_i}{r_e} + \frac{\Delta r_i}{r_R}} \quad - \quad (2.77)$$

or, by substituting

$$A = 1 + \frac{r_e}{r_R} \quad - \quad (2.78)$$

one gets:

$$\frac{LE(r_i + \Delta r_i)}{LE(r_i)} = \frac{1 + \frac{\delta}{\gamma A} + \frac{r_i}{r_e}}{1 + \frac{\delta}{\gamma A} + \frac{r_i}{r_e} + \frac{\Delta r_i}{r_e}} \quad - \quad (2.79)$$

In the first place, as eq(2.79) readily shows, any variation of the internal resistance has to be large in relation to the external resistance, if it is to yield a significant depression of the rate of transpiration. This could well be one of the reasons for plants with large leaves such as banana or kiwi (which might be expected to have a large external resistance; fig. 2.11) to be, in general, more sensitive to heat damage than other species (Doorenbos and Kassam, 1979). Moreover, as both  $\delta/\gamma$  and  $A$  are functions of air temperature, the latter concurs with the ratio of the internal to external resistance in determining the outcome of any variation of the former. For reference, tab. 2.3 displays values of the ratio  $\delta/(\gamma A)$  for various ambient temperatures and three typical external resistances.

$T_a$	$r_e = 50$	$r_e = 200$	$r_e = 500 \text{ s} \cdot \text{m}^{-1}$
0	0.57	0.39	0.24
5	0.77	0.52	0.32
10	1.02	0.68	0.40
15	1.34	0.87	0.51
20	1.73	1.10	0.64
25	2.22	1.39	0.79
30	2.81	1.72	0.97
35	3.51	2.11	1.17
40	4.37	2.57	1.41

Table 2.3. Dimensionless ratio  $\delta/(\gamma A)$  for three values of the external resistance, as a function of air temperature  $T_a$ , °C

Accordingly, for an air temperature of say, 20 °C, and an external resistance of 200  $\text{s} \cdot \text{m}^{-1}$ , a doubling of the internal resistance from 200 to 400  $\text{s} \cdot \text{m}^{-1}$  will yield a depression of only 25% in the transpiration rate. Observe that in cooler air the variation would be more relevant while the reverse is true for warmer air. The reasoning outlined above is given some ground by the results of Sheperd (1972) who observed, around noon on high irradiation days, a transpiration depression of 17% (potatoes) or 6% (pasture) relative to the rates typical of early morning and late afternoon. Therefore, the study of the transpiration from naturally exposed canopies of vegetation, that Van Bavel (1968) suggested as a way to settle the issue of the internal control, did not deliver the evidence hoped for, possibly because the lysimeters used for such studies (see Meijer et al., 1985, for a review)

did not have the accuracy implied by eq(2.79). From this point of view, it might be argued indeed, following Van Bavel (1968), that, as far as time span and accuracy of most hydrological studies are concerned, internal control of water losses from well watered crops is unlikely to produce easily detectable effects and, hence, might be considered irrelevant.

It should be borne in mind, however, that in the present work, shorter time spans are dealt with and it is aimed at greater accuracies than most field studies. It should be clear by now that no general conclusion is allowed in this case. Such a consideration was already implicit in the results of Slatyer and Bierhuizen (1964) who compared wind tunnel transpiration of cotton leaves with evaporation of wet blotting paper replicas. They found transpiration to be strongly dependent on external resistance with light intensities exceeding  $75 \text{ W}\cdot\text{m}^{-2}$  and very low wind-speeds. Under lower light intensities internal resistance was dominant, and with external resistances smaller than  $50 \text{ s}\cdot\text{m}^{-1}$ , transpiration appeared to be primarily limited by  $r_i$  at all light intensities. Azam Ali (1984) arrived at the same conclusion, after a set of field experiments performed on groundnut crops, characterized by  $r_e \sim 40 \text{ s}\cdot\text{m}^{-1}$  and  $r_i \sim 6\cdot r_e$ .

On the other hand, the extent of a variation of the surface temperature resulting from a similar adaptation of the internal resistance is dependent on more parameters of the microclimate, as the calculation of the partial derivative  $\partial(T_o - T_a)/\partial r_i$  shows:

$$\frac{\partial(T_o - T_a)}{\partial r_i} = \frac{\text{LE}/(\rho_a c_p)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{r_i}{r_R} + \frac{r_e}{r_R}} \quad \text{K}\cdot\text{m}\cdot\text{s}^{-1} \quad (2.80)$$

Hence the outcome of a variation  $\Delta r_i$  of the internal resistance may be calculated through:

$$\begin{aligned} \frac{T_o(r_i + \Delta r_i) - T_o(r_i)}{T_o(r_i) - T_a} &= \frac{(T_o - T_a)(r_i + \Delta r_i) - (T_o - T_a)(r_i)}{(T_o - T_a)(r_i)} = \\ &= \frac{\text{LE}(r_i)/H(r_i)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e} + \frac{r_i}{r_R} + \frac{r_e}{r_R}} \cdot \frac{\Delta r_i}{r_e} \end{aligned} \quad (2.81)$$

The ratio  $\text{LE}/H$  is the inverse of a quantity commonly identified as the Bowen ratio. Indicative values for the latter are known to be: 2 or more in arid conditions; about 1 in temperate to semi-arid and 0.2 to 1 for humid climates (Curran, 1979). It follows that for the same conditions and variation of  $r_i$  as indicated above, the resulting variation of the temperature excess ranges from 10% (arid) to 35% (humid). Therefore, some increase of the internal resistance in an arid climate yields a relatively larger reduction of the water loss than warming up of the surface. On

the other hand, a similar enlargement of its resistance would do more to warm up a leaf in a greenhouse environment than to reduce its transpiration.

## 2.6 Summary

In the beginning of this book (§ 1.2) it was stated that the most promising way to develop a model for the effect of the microclimate on the transpiration of greenhouse crops was to adapt a method already successfully applied for the estimation of the water use of field crops. This method is based on the combination of the energy balance and the transfer equations of (sensible and latent) heat of a wet surface. It was pointed out, however, that the development of a model (based on the same approach) for the assessment of the transpiration rate of a greenhouse crop, would present many conceptual and practical problems to the solution of which this work is meant to contribute.

The first step of the development of this model has been dealt with in this chapter. As all models of the microclimate within a canopy consist of a set of one or more simpler components dealing with the exchange of energy within a single, homogeneous layer, the development of that component was the subject of this chapter.

The properties of such an ideal leaf surface and of its nearby environment have been defined in § 2.1. By this means both the energy balance equation of such a leaf and the equations for the transfer of sensible and latent heat between the leaf and its environment have been derived. It was then shown (§ 2.2) that it is enough to postulate the existence (somewhere within the leaf) of a surface saturated at its temperature (the phase interface), to enable the deduction of analytical equations for both the temperature and the transpiration rate of such a leaf.

However, those equations require the transfer resistances for heat and vapour (defined, in fact, by the corresponding transfer equations) either to be given or to be known functions of the microclimate. As far as the resistance to heat transfer (external resistance) is concerned, it has been shown that it may be determined by experimental means consistent with its definition (§ 2.3). The actual external resistance of leaves immersed within a greenhouse canopy has been found to be less than could be inferred from the traditional theories of heat transfer in a regime of either forced or natural convection. A model based on the combination of the two regimes was shown to yield reasonable predictions of the magnitude of the external resistance.

The awkwardness of experimentally determining the internal resistance of a leaf (i.e. the resistance offered to the transfer of vapour by the leaf layer contained between the phase interface and the external surface) was the subject of § 2.4. The extent to which the internal resistance might be expected to be similar to the stomatal resistance was analysed. The kind of relationship one might ob-

serve between the microclimate and the internal resistance of a leaf has been specified.

A discussion of the analytical equations derived (in § 2.2) for the temperature and the transpiration of such an ideal leaf has been carried out in § 2.5. For the sake of this discussion, a slightly different form of those equations was derived, whereby the radiation available to the surface has been written as an explicit function of its temperature. Then, the influence of each one of the relevant parameters of the microclimate was shortly discussed. It has been shown that the transpiration might be estimated through simple formulae based on only one parameter of the microclimate (as irradiation, temperature or saturation deficit), only under very restrictive conditions. The effect of the external resistance has been elucidated and a couple of surprising peculiarities have been unearthed. It has been demonstrated that an enlargement of the external resistance does not necessarily reduce the transpiration rate, nor does it have an obvious effect on the temperature of the leaf. However, a more practical observation was that, in many natural conditions, a variation of the external resistance hardly causes the transpiration rate to change. After the observation that the internal resistance only appears in the ratio internal to external resistance in both the temperature and transpiration equations, it was pointed out that any variation of the internal resistance plays a role only to the extent to which that ratio is affected. It might be observed, therefore, that an error in the estimate of one of both resistances (luckily) yields a relatively smaller error in the assessment of the transpiration rate.

### 3. ENERGY BALANCE OF A GREENHOUSE CANOPY

Chapter 2 has been devoted to showing that temperature and transpiration of a leaf are assigned when some (not unreasonable) assumptions are accepted and five parameters of the leaf microclimate are known. Assessment of either temperature or transpiration of a canopy with  $N$  leaves would require therefore, the time course of  $5N$  variables to be given. Evidently such a procedure would be neither workable nor worthwhile since the leaf-by-leaf spatial distribution of transpiration or temperature within a canopy is more than one could possibly be interested in. Hence, it should be appreciated that in any representation of the complex microclimate of a canopy, a trade-off has to take place between our ability to supply input variables and the spatial distribution required for the output ones. Thus, which specific representation is best suited to a given application is dictated, in the first place, by the terms of that trade-off. In addition, the quality of the output (at least for predictive purposes) is warranted only by the 'reasonableness' of the assumptions made about the physical reality.

In chapter 2 a leaf was idealized (to some extent) as a flat surface contained in an envelope of air – the leaf boundary layer – where no influence of the surrounding leaves could be felt. This abstraction caused the (sensible and latent) heat exchanges of the leaf to be dependent only on the state of the leaf surface and of the external surface of that envelope. Moreover, by regarding the two surfaces as uniform, those heat exchanges were made one-dimensional.

Obviously, the application of a similar formalism to a canopy requires an even larger degree of abstraction. To begin with, a boundary layer has to be defined for the canopy. For a greenhouse crop, the greenhouse itself could, rather intuitively, be recognized as a sort of envelope. However, since the physical cover (glass or whatever) may itself be a source or sink of energy, it is more convenient to define the envelope as surrounding the canopy but excluding the cover. Therefore, the boundary layer of a greenhouse canopy will be defined as the join of the boundary layers of the individual leaves. Observe that the leaves are the only constituents of a canopy which are taken into account as possible sources or sinks of energy, in the present work. Moreover, the air within the greenhouse and outside the canopy boundary layer will be assumed to be homogeneous, with respect to its temperature as well as its vapour pressure.

Another conceptual limitation for the application to a canopy of the formalism developed so far for the leaf-atmosphere exchanges, arises from the (here unwar-



ranted) assumption of horizontal homogeneity, i.e. of only one-dimensional fluxes. Schenk and Stigter (1975) reported, for instance, the measurement of horizontal differences of temperature and vapour pressure at short distances within a maize crop, albeit within 1 K and 0.4 kPa, respectively. Of course, the vertical transport phenomena within a canopy are also affected by the density of the foliage, which normally is not distributed uniformly on any horizontal plane. Therefore, some horizontal anisotropy should be reckoned with. To the best of the present writer's knowledge, however, only one-dimensional models of the microclimate in a canopy have been developed. It appears, therefore, that Shuttleworth's (1976) feeling that 'even in one dimension, the general description of the vegetation-atmosphere interaction is very complex, perhaps too complex for direct practical application' is, implicitly or explicitly, shared. This entails, however, that such models may be expected to be representative only on a horizontal scale large enough for the canopy to be regarded as homogeneous, i.e. much larger than the typical dimension of any foliage element as say, leaves, branches, inter-row spacing or row width. The representativeness of one-dimensional models moreover, is confined to a central part of the canopy, surrounded by a region of the same, large enough to enable the solid assumption that no significant transport of energy could take place along a horizontal dimension, within that central part.

There is another isotropy problem, however. The different micrometeorological conditions (irradiation, temperature, vapour pressure, wind etc.) existing at the upper and lower extremes of a canopy, imply that there are not negligible vertical gradients of the functions of state. Indeed, no natural canopy may be regarded as homogeneous in the vertical direction; and it is normally attempted to reproduce the profiles within a canopy by representing the latter as a stack of semitransparent, semipermeable layers. The number of those layers has been described as anything between one (Monteith, 1963) and a continuum which is actually discretized by a numerical solution (Perrier, 1976). Obviously, only multi-layer models are (somehow) able to reproduce profiles of radiation, temperature, wind or vapour content within a canopy.

It is clear however, that the knowledge needed for decision making about vapour and canopy temperature management in greenhouses adds up to one value of 'mean' transpiration and/or temperature for each one of the units that can be independently acted upon, normally a greenhouse compartment. In other words, the profiles themselves are not useful information and one could be satisfied with mean values. What is then left for pondering is whether supplying mean values as inputs ensures that the outputs are also representative means, i.e. whether or not (or how much) the processes may be regarded as linear. In this respect, it has already been shown in § 2.5, that both the transpiration and surface temperature equations are almost linear in relation to all the variables, except the internal resistance. It might be concluded therefore, that no cogent argument exists for a multi-layer model in this case. Of course, the easiest approach is then to examine

in the first place how an accurate description of canopy transpiration and temperature can be delivered by a single-layer model.

In this chapter, therefore, a greenhouse canopy will be regarded as one homogeneous layer, characterized by one value of temperature and vapour pressure. Such a layer is bounded by an ideal surface within the greenhouse, which is in turn, homogeneous. The properties with which this layer has to be endowed, to enable the application of the formalism developed in chapter 2, will be reviewed in the next section.

### 3.1 Definitions

Let us consider the energy balance of a portion of a greenhouse canopy, excluding a guard area large enough for the assumption of horizontal homogeneity to be acceptable. That canopy segment is regarded as an ideal porous volume, through which flow of air is possible. The energy fluxes at the upper and lower surfaces of that volume are, therefore, the net result of the exchanges of energy taking place within the 'pores' of the canopy segment. It is a common device to consider a volume resting on the ground with its lower side, so that the energy exchange across that side equals the heat flux just below the soil surface. For this reason the heat flux into the soil ( $G$ ,  $W \cdot m^{-2}$ ) is explicitly mentioned in the literature concerning the energy balance of canopies. For a greenhouse crop, however, there may be an additional source of energy in any vertical section of the canopy, namely the heating system. Hence, the conservation of energy has to be applied to a volume that incorporates the canopy but excludes the elements of the heating system, fig. 3.1.

Then, if the storage of energy in the products of photosynthesis is overlooked (§ 2.1.4), the balance of the energy fluxes requires that, at any time, the net radiation absorbed by the foliage contained in the volume be equal to the sensible and latent heat released by it, plus the thermal energy which is being stored within the foliage. When all these fluxes are divided by the base area of the volume, one can write a *mean* energy balance equation:

$$R_n = H + LE + J \quad W \cdot m^{-2} \quad (3.1)$$

It will be observed that eq(3.1) is in its form identical to eq(2.18), the energy balance of a leaf. There are however, a couple of important differences. In the first place, all symbols in eq(3.1) represent mean flux densities: the unhomogeneity of the canopy on a small scale implies that the actual fluxes at any place may significantly deviate from these means. Further, although eq(3.1) is written per unit ground area, the actual source or sink for the energy fluxes is the mean foliage area existing in a vertical section of the canopy, having a unit base area. It was al-

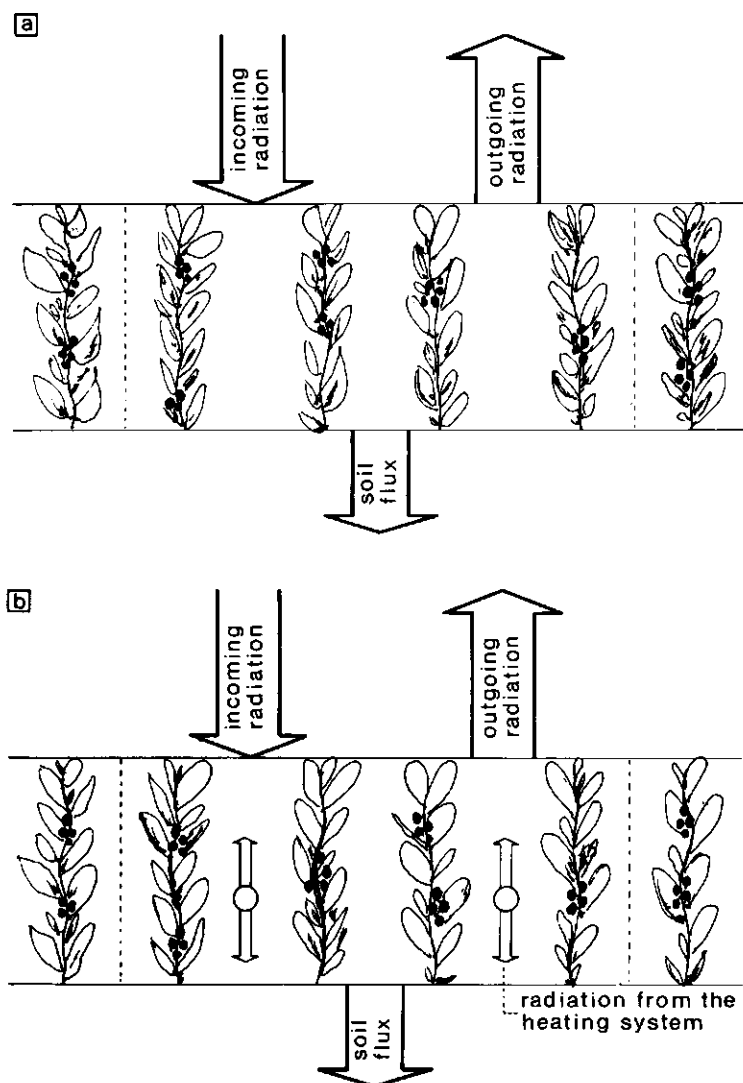


Fig. 3.1. The net radiation available for a field canopy is the difference between the net radiation measured above it and the heat flux transmitted into the soil; [a]. This statement is no longer true for a greenhouse canopy, due to the presence of a heating system; [b].

ready observed (§ 2.1) that even for a single leaf the effective surface area is not necessarily the same for the various energy exchanges. Obviously, the difference among the effective exchange areas of a canopy, in relation to the various fluxes, is likely to be even more important. In § 3.2 the subject of how an effective radiation exchange area for a greenhouse canopy may be inferred from (rather) simple measurements is dealt with. On the other hand, the analogy with the convention

adopted for a single leaf, requires that the total leaf area contained in a volume of unit base (namely  $2 \cdot \text{LAI}$ ) be considered as the exchange area for both sensible and latent heat.

### 3.1.1 External resistance of a canopy

If  $T_a$  is the average air temperature of the (bulk) air within the canopy volume and outside the canopy boundary layer, and  $T_o$  is a mean canopy temperature, an equation for the transfer of sensible heat between the foliage and the bulk air may be formally written as:

$$H = \frac{2 \cdot \text{LAI} \cdot \rho_a c_p}{r_e} (T_o - T_a) \quad \text{W} \cdot \text{m}^{-2} \quad (3.2)$$

The symbol  $r_e$  – here used to preserve the analogy with chapter 2 – indicates a mean canopy resistance to sensible heat transfer, or ‘canopy external resistance’ which is, in fact, defined by eq(3.2). It is acknowledged that the inadequacy of the flux-gradient transport theory within canopies, implies that the argument developed in § 2.1.2 and resulting in the transfer equation (2.10) does not apply here. Therefore, eq(3.2), while being formally analogous to eq(2.10), defines a transfer resistance whose physical meaning is even more elusive than the meaning of the ‘single-leaf’ resistance. An attempt to overcome this problem is represented by the use of multi-layer models. In such models the canopy resistance is represented as a combination of the familiar ones: each layer is endowed with an external resistance similar (for all purposes) to the leaf external resistance and an ‘aerodynamic’ resistance to transfer between layers is introduced (e.g. Goudriaan, 1977; Chen, 1984).

However, the combination of these two latter resistances, albeit more physically grounded, does not lend itself any more readily to an experimental determination than the resistance defined by eq(3.2). In fact, it could be argued that the external resistance as experimentally determined in this work (§ 2.3.2) could supply an adequate estimate of the mean external resistance of a canopy as defined here. It is worthwhile pointing out that the experiment was related to the heat transfer exchanged between leaves scattered throughout the canopy and the air above it, certainly outside the own boundary layer of any leaf. Hence, the assumption that  $r_e$  as defined by eq(3.2) may be calculated by means of eq(2.53) will be accepted here.

### 3.1.2 Internal resistance of a canopy

A canopy internal resistance to vapour transfer ( $r_i$ ) may be defined in an analogous fashion (eq. 2.21):

$$\text{LE} = \frac{2 \cdot \text{LAI} \cdot \rho_a c_p}{\gamma(r_i + r_e)} (e_E - e_a) \quad \text{W} \cdot \text{m}^{-2} \quad (3.3)$$

where  $e_E$  is the mean vapour pressure at the phase interface, and  $e_a$  is the mean vapour pressure of bulk air. However, it might indeed be questionable whether or not there is any physical meaning for the internal resistance  $r_i$  thus defined. By eq(3.3) the exchange area of latent heat has been defined as  $2 \cdot LAI$ , equal to the one of sensible heat; thereby the canopy internal resistance has been regarded as conceptually equivalent to the leaf internal resistance: that is not warranted. In fact, for a single leaf, the definition of internal resistance resulted from the assumption that, from the leaf surface onwards, transfer of heat and water vapour takes place in a similar way. Hence the additional resistance on the vapour pathway could be identified with the resistance of the leaf layer contained between the phase interface and the external surface. It was shown that such a layer offers, indeed, a negligible resistance to heat transfer.

Experimental results have been published however (e.g. Monteith et al., 1965), showing that the canopy internal resistance – dubbed by Thom (1972) ‘bulk stomatal’ resistance – may well be correlated with observed changes in stomatal opening. Jarvis et al. (1981) went as far as to state that the ratio of the canopy to the leaf internal resistance is equal to twice the leaf area index. This contention was supported by experimental findings by Choudhury and Idso (1985a) on a field-grown wheat crop. Indeed, Katerji and Perrier (1985) showed, by both a theoretical rationale and experimental results, that the afore-mentioned observation has to be expected whenever the leaf internal resistance is by far the largest of the possible components of the canopy internal resistance.

One could add a more general argument, however. The canopy internal and external resistances are obviously related by their definition. The present approach states that a canopy internal resistance to vapour transfer is the difference between a total resistance – the denominator of eq(3.3) – and the resistance to heat transfer. One could as well state that things are the other way around, i.e. that the external resistance of the canopy is defined by the difference between the total resistance and the leaf internal resistance times twice the leaf area index. The two definitions yield equations of identical form. We already know, from § 2.5.4, that the rate of vapour transfer resulting from those equations is scarcely affected by the external resistance. In other words: it is unimportant how the external resistance is defined. This latter conclusion applies directly to single-layer models, since those models, whatever their assumptions, result in transpiration equations formally identical to eq(2.63) (Gash and Stewart, 1975). On the other hand, Chen (1984) got to the same conclusion by a sensitivity analysis of his multi-layer model.

Therefore, one should adopt the definition of the two resistances which is consistent with the experimental technique applied. The fact that the heterogeneous quantities defined with the label ‘canopy internal resistance’ happen to be of comparable magnitude is indeed an indication that the leaf internal resistance is by far the largest component of the excess resistance a canopy offers to the transfer of

vapour, with respect to the transfer of heat. In the present work, the canopy internal resistance to vapour transfer will be regarded as being defined by eq(3.3), with  $r_e$  given by eq(2.53). A method for its experimental determination, consistent with this definition, will be described in § 3.5.1. On the other hand, in § 3.5.2, it will be analyzed how and how far the dependence on the microclimate of the canopy internal resistance may be interpreted in terms similar to the ones used for the internal resistance of a single leaf.

### 3.1.3 Transpiration and temperature of a canopy

An alternative way of reading eqs(3.2) and (3.3) would be to state that a canopy behaves, with respect to the heat and vapour transfer, as a leaf of unit area having internal and external resistances which are the corresponding resistances of one 'real' leaf, divided by  $2 \cdot \text{LAI}$ . This is formally equivalent to arguing that a canopy behaves as if all its leaves (or unit leaf areas) were wired in parallel. This observation enables the direct derivation of the equations for transpiration rate and temperature of such a canopy, without going through the computations of § 2.2. It is indeed enough to substitute in eqs(2.55) and (2.56),  $r_e/(2 \cdot \text{LAI})$  and  $r_i/(2 \cdot \text{LAI})$  for  $r_e$  and  $r_i$ , respectively, to get the equations sought for:

$$\text{LE} = \frac{\frac{\delta}{\gamma}(\mathbf{R}_n - \mathbf{J}) + \frac{2 \cdot \text{LAI} \cdot \rho_a c_p}{\gamma r_e}(e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \quad \text{W} \cdot \text{m}^{-2} \quad (3.4)$$

$$\text{T}_0 - \text{T}_a = \frac{\frac{(r_i + r_e)}{2 \cdot \text{LAI} \cdot \rho_a c_p}(\mathbf{R}_n - \mathbf{J}) - \frac{1}{\gamma}(e_a^* - e_a)}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \quad \text{K} \quad (3.5)$$

with  $\mathbf{R}_n$ , the mean net radiation of a canopy per unit ground area, as defined in the next section. A 'mean' net radiation of the canopy  $\bar{\mathbf{R}}_n$ , i.e. the mean net radiation available to a unit leaf area, may be defined by:

$$\bar{\mathbf{R}}_n = \mathbf{R}_n / (2 \cdot \text{LAI}) \quad \text{W} \cdot \text{m}^{-2} \quad (3.6)$$

Then, it is possible to deduce from eqs(3.4) and (3.5), respectively, that:

- a canopy transpires at the rate of an 'ideal leaf', having area  $2 \cdot \text{LAI}$ , internal and external resistances  $r_i$  and  $r_e$ , and subject to a net radiation flux equal to  $\mathbf{R}_n$ ;
- an effective temperature of the canopy is thereby defined, equal to the temperature of such a leaf.

### 3.2 Net radiation of a greenhouse canopy

A main limitation of the use of eqs(3.4) and (3.5), to assess transpiration and temperature of a greenhouse canopy, is the awkwardness of estimating  $R_n$ , i.e. the mean radiative energy available to such a canopy, per unit ground area. In fact, it is worthwhile pointing out once more that the equations being developed here are valid only for mean flux densities, considered on a surface large enough for the canopy to be regarded as homogeneous. In other words, if measured radiation fluxes are relied upon, it should be carefully considered whether those measured fluxes do provide a representative value. While that much can rather safely be stated for a radiometer placed a few meters above a short crop such as grass, the siting of a 'representative' radiometer above a forest, is obviously more of a problem. A tall greenhouse crop, as tomato, almost filling its environment, is likely to present the same problem. Moreover, the elements of the heating system provide important sources of thermal radiation within the volume of the canopy. The wild scattering of measured radiation fluxes at different places is, in fact, a common problem with greenhouse experiments. Therefore, for such crops, a representative mean has to be performed on the fluxes measured at a large number of sites. Regrettably this is not economically feasible, in most cases. This problem will be addressed in this section, where a simple method will be developed which makes use of an acceptable amount of measured data and of some geometrical and optical properties of the canopy, to size out the radiation actually absorbed by the canopy.

An exhaustive theoretical description of the radiative exchanges of a canopy is made almost impossible not only by the fact that the interaction of radiation with a canopy is actually the interaction with a huge amount of (different) components of that canopy. The shortwave radiation field is by no means isotropic at the upper surface of the canopy and it is disturbed further as light penetrates into the canopy. Moreover, the canopy itself is a source and sink of longwave radiation; a profile, therefore, is almost impossible to be determined. There are two means by which these problems may be (partly) overcome. On the one hand is the stochastic approach whereby radiation beams of different orientations are casually generated in a numerical model and the chance of each beam undergoing a particular interaction with a canopy element is analyzed. On the other hand, semi-theoretical considerations are applied, whenever a canopy is supposed to behave as a turbid medium in relation to the interaction with radiation.

To be sure, simulation models have been proposed in the literature (based on both approaches) which are able to figure out penetration of both short and long-wave radiation in a plant stand with reasonable accuracy (e.g. De Wit, 1965; Waggoner and Reifsnnyder, 1968; Perrier, 1976; Goudriaan, 1977; Myneni and Impens, 1985a). They rely, however, on time consuming calculations, performed

on a mainframe computer, though recently Chen (1984) did show that a more efficient use of mathematical methods could reduce the computational requirements of many of them. However, the vertical profile of radiation in a canopy is of fundamental importance for such processes as photosynthesis or photomorphogenesis, whereas such a detail might be unnecessary if only the total amount of radiative energy available for a greenhouse canopy is needed.

The mean radiation absorbed by a vertical section of a canopy, whose properties have been defined in § 3.1, is the difference of all the inward and outward radiation fluxes at the upper and lower surfaces of the section (fig. 3.2). Ob-

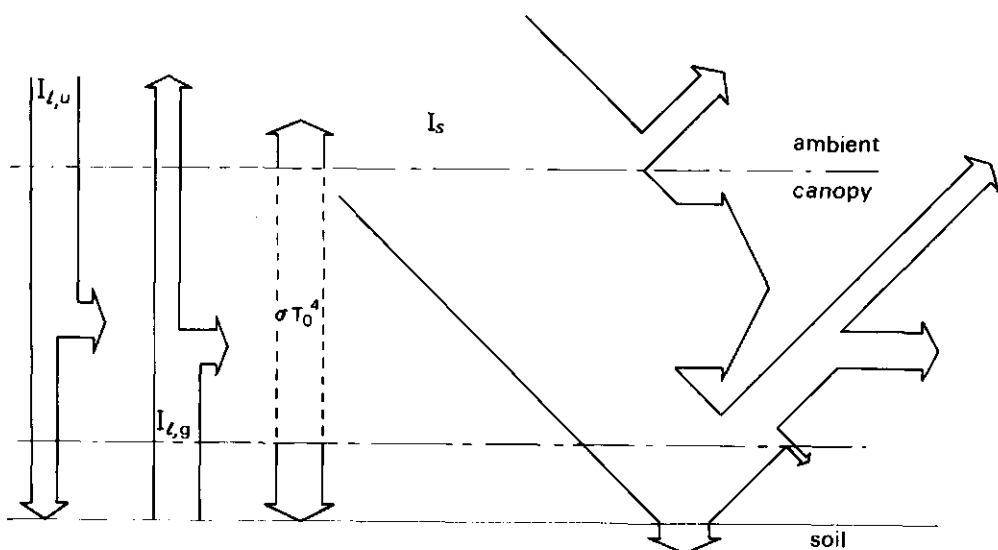


Fig. 3.2. The net radiation available for a canopy is the sum of all the radiation fluxes – both long ( $I_l$ ) and short wave ( $I_s$ ) – entering the canopy from both the upper and lower surfaces, minus the sum of all the fluxes leaving these surfaces.

viously, of the radiative flux entering any of those two ideal surfaces, the fraction that is absorbed is neither transmitted nor reflected. As the optical properties of the leaf tissue are not the same for the shortwave and longwave radiation ranges (§ 2.1.1), it may be inferred that also transmittance and reflectance of a canopy for short or longwave radiation are different. Hence, the interaction of a canopy with radiation of the two wavelength ranges will be considered separately in the following.

### 3.2.1 Longwave transmittance of a stand

Longwave transmittance –  $\tau_l$  (LAI) – of a plant stand having leaf area index LAI is defined as:

$$\tau_l(\text{LAI}) = I_l(\text{LAI}) / I_l(0) \quad (3.7)$$



where  $I_l(0)$  is the longwave radiative flux entering either the upper or the lower surface of a section of the canopy and  $I_l(\text{LAI})$  is the flux leaving the other end of that section. The longwave transmittance is also called 'transmittance of a stand of black leaves' since, in the longwave range, transmittance and reflectance of the leaf tissue are negligible (§ 2.1.1). It is trivial to observe that a stand of leaves having such properties will transmit only the radiation which is not even once intercepted by a leaf. Eq(3.7) therefore, describes the amount of shortwave radiation penetrating unintercepted a plant stand as well. Accordingly,  $\tau_l$  can be regarded as the fractional area occupied by sun flecks on the soil surface (with perpendicular irradiation and  $1-\tau_l$  represents the soil cover, i.e. the area of the vertical projection of the leaves on a unitary ground area.

It can be shown (Ross, 1981) that for diffuse longwave radiation,  $\tau_l(\text{LAI})$  is affected only by the geometrical properties of the canopy. Indeed, under some assumptions, the theoretical functions for extinction of radiation in a turbid medium may be applied to a canopy (e.g. Norman, 1975), to yield:

$$\tau_l(\text{LAI}) = e^{-k_l|\text{LAI}|} \quad - \quad (3.8)$$

with  $k_l$ , the extinction coefficient for longwave radiation, determined by the distribution of the angles between each leaf and a horizontal plane. The extinction coefficient can be analytically calculated for some idealized leaf angle distributions; some values of it, deduced from the literature (Monteith, 1975; Ross, 1975; Goudriaan, 1977) are supplied in tab. 3.1.

leaf angle distribution	$\alpha(^{\circ})$	Monteith	Ross	Goudriaan
Horizontal	0		1.000	1.050
Conical	30	0.87		
	45			0.829
	60	0.50-0.58		
Vertical	90		0.436	
Spherical	—		0.684	0.81

*Table 3.1.* Values of the extinction coefficient  $k_l$  of eq(3.8), as deduced from the literature, for idealized leaf angle distributions. The angle between the leaves and a horizontal plane is represented by the symbol  $\alpha$ . The data from Ross and Goudriaan refer to diffuse longwave radiation from a uniform sky. The data from Monteith concern only direct longwave radiation, though values only weakly dependent on the elevation of the source are selected here.

### 3.2.2 Shortwave transmittance of a stand

The shortwave radiation transmitted by a plant stand is the sum of the unintercepted radiation and the radiation that is either transmitted or reflected down-

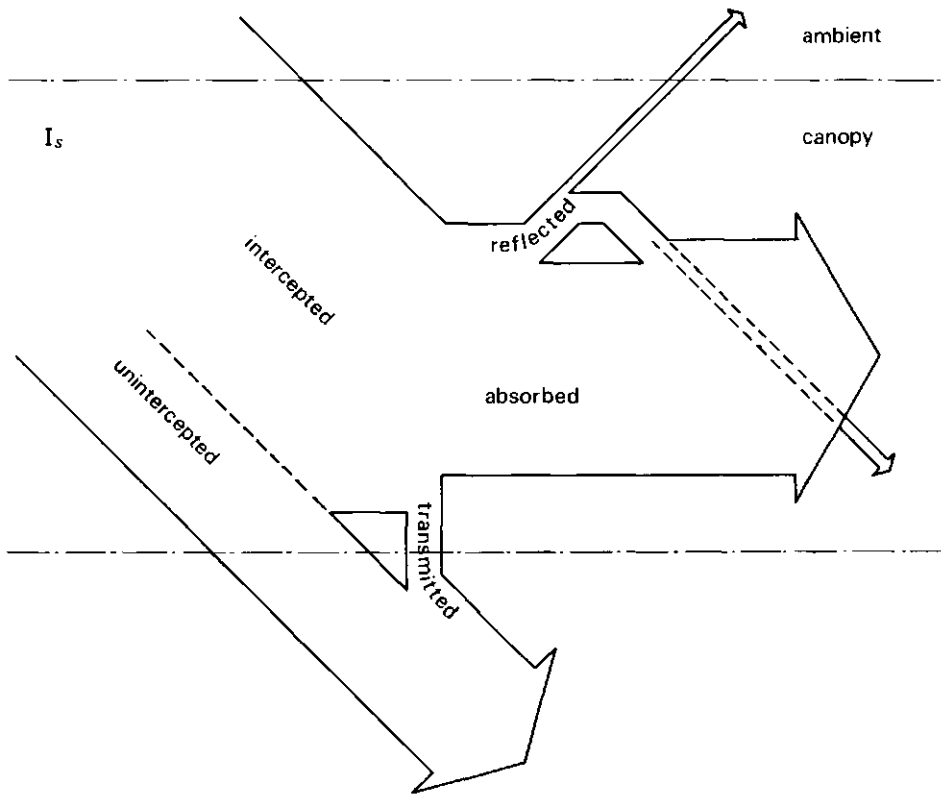


Fig. 3.3. A fraction of the shortwave radiation ( $I_s$ ) entering one side of a canopy is transmitted, which is the sum of the unintercepted radiation, the radiation transmitted through the leaves, and of the radiation that is reflected onward by multiple reflection.

wards (or both) by any leaf within the canopy (fig. 3.3). A detailed calculation of the latter is very complex and, indeed, could be superfluous, whenever the radiation transmitted through the leaves is a small fraction of the radiation transmitted. Kasanaga and Monsi (1954) proved that the shortwave transmittance  $\tau_s$  (LAI) for diffuse shortwave radiation of a stand with a leaf area index LAI, could be represented, with reasonable accuracy, by an exponential like eq(3.8):

$$\tau_s(\text{LAI}) = I_s(\text{LAI}) / I_s(0) = e^{-k_s \cdot \text{LAI}} \quad - \quad (3.9)$$

where the symbols have an obvious meaning. Of course  $k_s$  has to be a function of the optical properties of the leaves and Goudriaan (1977) calculated it through:

$$k_s = [(1 - \tau_l)^2 - \rho_l^2]^{1/2} \cdot k_l \quad - \quad (3.10)$$

with  $\tau_l$  and  $\rho_l$  the transmittance and reflectance of the leaf tissue, respectively (eqs(2.3) and (2.4)). Ross (1975) gave  $\tau_l = 0.20$  and  $\rho_l = 0.30$  as typical values, over the whole shortwave band, for a 'mean' green leaf and there appears to be little interspecific variations (Gausman et al., 1973). Observe that eq(3.10) results then in  $k_s = 0.74 k_l$ .

On the other hand, Monteith (1969) produced a review of empirical values of  $k_s$  for real canopies, ranging between  $k_s = 1.10$  for species with mainly horizontal leaves, like clover (*Trifolium repens*), and  $k_s = 0.29$  for species with mainly vertical leaves, such as ryegrass (*Lolium rigidum*). Newton and Blackman (1970) deduced from their experiments  $k_s = 0.20$ , for *Gladiolus*. More recently, Sivakumar and Virmani (1984) published some more values referring to mixed and pure canopies of maize, sorghum and pigeon pea, with  $k_s$  varying from 0.28 to 0.69.

### 3.2.3 Reflectance (albedo) of a stand

Reflection of radiation by a stand occurs by either the foliage or the underlying soil surface. Since not only the foliage but also most soil surfaces are practically 'black' for longwave radiation, reflectance of a canopy is, in the first place, a process relevant to the balance of shortwave radiation only.

Reflectance of a dense plant stand is always smaller than that of the leaves composing it. The mutual shading of leaves and the multiple scattering within the stand result in a sort of 'cavity' effect, which causes an additional absorption of radiation. In fact, Ross (1981) theoretically showed that when considering single scattering alone, the albedo of a dense stand consisting of randomly disposed horizontal leaves is half as large as that of a horizontal monolayer. He inferred that the albedo of a dense stand with any leaf orientation and for multiple scattering would always be contained in the interval  $\rho_l/2$ ,  $\rho_l$ , i.e. between 0.15 and 0.30, for the mentioned 'mean' green leaves. To figure out a formula for the albedo of a stand, simple enough to be applied here (fig. 3.4), a sort of effective reflectance will be used, to begin with. Moreover, it will be assumed that the canopy behaves as a dense stand in respect to the fraction (equal to  $1 - \tau_l$ , i.e. the soil cover) of the incident radiation it intercepts. It should be appreciated, furthermore, that the fraction of the reflected radiation, which is reflected by the soil surface, has undergone transmittance by the foliage twice. Hence:

$$\rho_s(\text{LAI}) = (1 - \tau_l(\text{LAI})) \rho_\infty + (\tau_s^2(\text{LAI})) \rho_g \quad - \quad (3.11)$$

where  $\rho_\infty$  is the reflectance of a dense stand and  $\rho_g$  is the one of the underlying soil surface. The present writer prefers to define a dense stand as a stand of unitary interception for diffuse radiation (or completely covering the soil) whereas, in the literature, it is more commonly defined as a stand of leaf area approaching infinity. Though the two definitions are identical, as both imply  $\tau_l$  to be nil (eq(3.8)), a soil cover approaching unity seems to be a better quantifiable concept

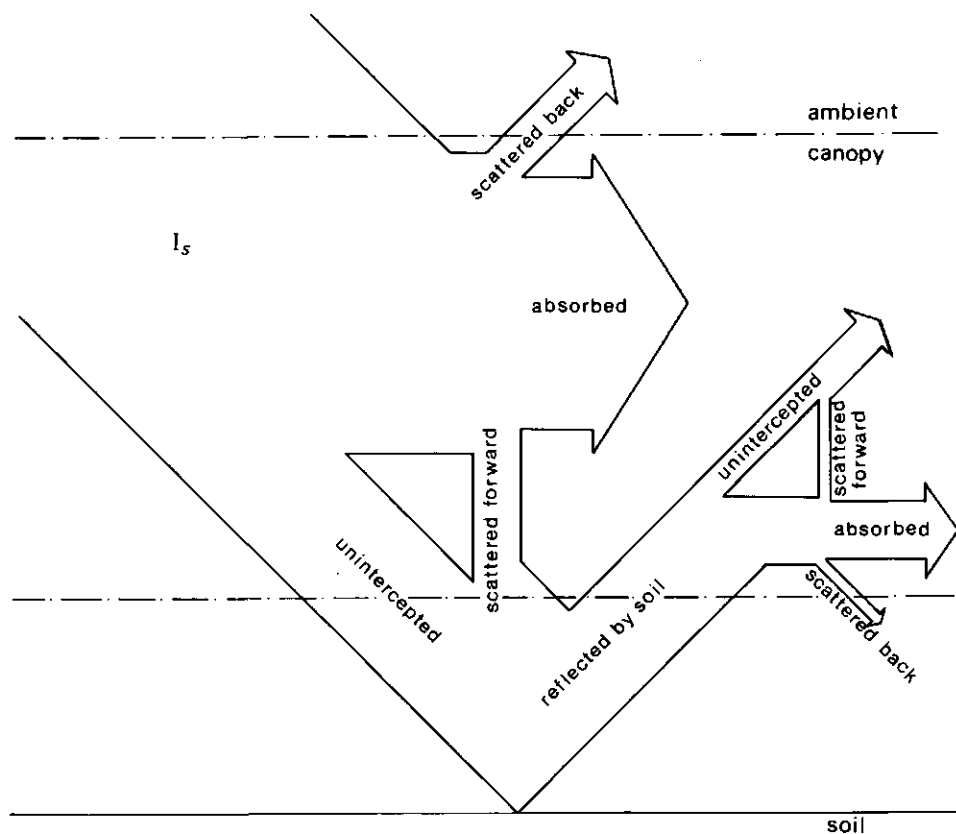


Fig. 3.4. A fraction of the shortwave radiation entering one side of a canopy ( $I_s$ ) is reflected backward, which is the sum of the radiation reflected by any canopy element and of the radiation which has been transmitted to, and reflected back from the soil surface and then again transmitted via the canopy.

than a leaf area approaching infinity. Interception above 98% (or  $\tau_t < 2\%$ ), for instance, implies LAI  $> 4$  for horizontal leaves to LAI  $> 9$  for vertical leaves (eq(3.8) and tab. 3.1).

### 3.2.4 Transfer of radiation in a greenhouse canopy

As it has been mentioned in § 3.2.1, a canopy absorbs a fraction equal to  $1 - \tau_t$ , of the longwave radiation it receives from the upper as well as from the lower hemisphere. A greenhouse crop has the useful peculiarity of being confined between well defined upper and lower surfaces, namely the cover and the soil surface. The amount of longwave radiation it receives from both sides could be calculated by means of the Stefan-Boltzmann law, if the effective radiation temperatures of the two surfaces were known. Another, less friendly, peculiarity of greenhouse crops is that there are elements of the heating system somewhere, which produce a non-neglectable amount of longwave radiation. Hence, the longwave radiation flux re-

ceived from either side of the canopy, should be calculated through the sum of the fluxes generated by each different surface; each flux, however, should be multiplied by the view factor between that particular surface and the canopy. On the other hand, under the present assumption that the canopy is a uniform layer, characterized by a temperature  $T_o$ , the amount of longwave radiation emitted by the canopy has to be given by the Stefan-Boltzmann law, multiplied by twice the soil cover.

As far as the shortwave radiation is concerned, one should appreciate that a flux density equal to  $\tau_s \rho_g I_s$  is available at the bottom surface of the canopy. That flux is, in fact, the fraction of the incoming radiation which is transmitted by the canopy and reflected by the soil surface.

All these arguments collectively allow for a formula for net radiation of a greenhouse canopy to be written as:

$$R_n = (1 + \tau_s \rho_g) (1 - \tau_s - (1 - \tau_l) \rho_\infty) I_s + (1 - \tau_l) (I_{l,u} + I_{l,g} - 2\sigma T_o^4) \quad \text{W}\cdot\text{m}^{-2} \quad (3.12)$$

with  $I_{l,u}$  and  $I_{l,g}$  the longwave radiation emitted by the upper and lower surfaces, respectively. Long and shortwave transmittances  $\tau_l$  and  $\tau_s$ , are given by the corresponding eqs(3.8) and (3.9), the indication of LAI as operand having been omitted here for simplicity. The parameters  $k_l$  and  $k_s$ , appearing there, as well as  $\rho_\infty$  and  $\rho_g$  have to be determined empirically, since they embody the influence of the crop peculiarities on the transfer of radiation.

### 3.2.5 Experimental determination of the coefficients

The experimental determination of the parameters of eq(3.12) was performed for a tomato crop growing in a glasshouse. The latter is a single-glass, Venlo-type, eight span, E-W oriented one. Heating is provided by hot water pipes lying a few centimeters above the soil surface. The ratio of the pipe section (the part of it 'seen' by the canopy) to the ground area is 0.07. The crop (cv. Sonatine) was grown on rockwool mats, 0.3 m wide and 1.6 m apart. It was trained in a V-shape, i.e. every other plant was tied to a wire stretched at 1.95 m height, 0.25 m to one side of the rockwool mat, while the other plant was tied on the other side. Both soil and rockwool were covered with white plastic sheets to increase the short-wave radiation available for the crop (a fairly common practice in The Netherlands).

Since an accurate description of the glasshouse and of the whole experimental set-up is to be found in De Jong (1985), here reference will be made only to the instrumentation relevant to this subject. Incoming shortwave radiation was measured, by means of solarimeters, above the house, directly below the cover, and above and below a crop row (fig. 3.5). Incoming shortwave radiation at the top of the canopy was estimated by applying the measured transmissivity of the house - 0.67 for diffuse light (Van den Kieboom, 1981, personal communication) - to the

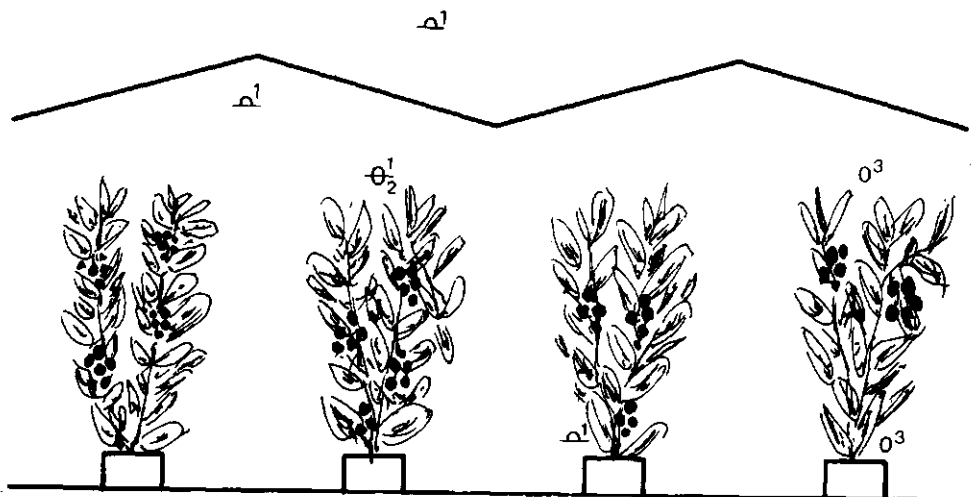


Fig. 3.5. Schematic representation of the position of the radiometers for the experimental determination of the extinction coefficients and of the reflectances: 1. solarimeters facing upward; 2. solarimeter facing downward; 3. tube net radiometers.



Fig. 3.6. One of the thermocouple sets used for measuring the temperature of the leaves.

global radiation measured above the roof. As quite a large fraction of the total irradiation is diffuse at springtime in The Netherlands (Slob, 1982), this procedure is likely to yield radiation values quite similar to the ones measured below the cover.

However, it was shown by Van 't Ooster (1983) to be more representative of the radiation actually available for the whole canopy during the day. The amount of reflected shortwave radiation was given by a similar solarimeter placed in reverse above a crop row.

The temperature of the heating pipes and of the plastic sheets on the ground was measured by thermocouples glued to the surfaces, while thinner thermocouples glued to the inner side of the glass cover were used to measure its temperature. A mean temperature of the leaf surface was provided by six sets of five thermocouples each, held touching the lower surface of leaves at three levels in the canopy and with various orientations (fig. 3.6). The mean of all the values has been used for the present calculations. For the subsequent validation of the model, two integrating net radiometers of one meter length each, were installed respectively above and below a crop row, with the long axis in the direction of the row length.

Since a leaf-area meter was not available, leaf area had to be estimated from the mean length of leaves, according to one of the empirical formulae proposed in the literature (e.g. Porter, 1937; Ross, 1946; Lyon, 1948; Cooper, 1959 and Van der Varst en Postel, 1972). The latter – shown by Sorbello-Herrendorf (1981) to provide a reasonable estimate of the leaf area for the Sonatine variety – was adopted here. That formula reads:

$$\text{area} = \frac{0.25 \ell^2}{1 - 1.48 \ell^2} \quad \text{m}^2 \quad (3.13)$$

Eq(3.13) gives the area of one side of a leaf ( $\text{m}^2$ ), when  $\ell$  is its length (m). Leaf area index was calculated relating the estimated leaf area to the ground area, taking into account the plant density of  $2 \text{ m}^{-2}$ .

Measurements were performed at 5-minute intervals by a data-logger. The results reported hereafter refer to 23 days, in the spring of 1984 and 1985, and to well developed canopies ( $2.2 < \text{LAI} < 4.2$ ).

### 3.2.6 Results and discussion

The mean extinction coefficient for shortwave radiation ( $k_s$ ) resulted to be 0.48, with a standard deviation of 0.16. If reflectance and transmittance values for a 'mean' leaf are used, eq(3.10) then yields  $k_l = 0.64$ . In fact, measured optical properties of leaves from these crops were shown to be 'mean' in the visible range (Van den Kieboom, 1984, personal communication). No gauging could be performed in the near infrared range, however, to achieve a picture of the whole shortwave band. The present value of the longwave extinction coefficient does not point to a well defined leaf angle distribution, as a similar value could apply to a conical as well as spherical leaf angle distribution (tab. 3.1). This writer (Stanghellini, 1983a) got a value of  $k_l \sim 1$  (nearly horizontal distribution), with another variety of tomato and a more open crop ( $\text{LAI} < 2.5$ ).

Best fit of eq(3.11) on the data set,  $\tau_s$  and  $\tau_l$  being calculated by means of the extinction coefficients given here above, yielded  $\rho_\infty = 0.12$  and  $\rho_g = 0.58$ , with a correlation coefficient of 0.96. The resulting value of the reflectance of a dense canopy,  $\rho_\infty$ , falls acceptably close to its theoretical range as mentioned above. Additionally, the apparent reflectance of the soil surface,  $\rho_g$ , agrees tolerably with the diffuse reflectance of the white plastic sheets, as measured after some use (0.55, in the visible range) (Van den Kieboom, 1983, personal communication).

The defining equations for the short and longwave transmittance (eqs(3.9) and (3.8), respectively) may be substituted in the equation for the net radiation of the canopy (eq(3.12)). Further, the coefficients may be assigned the values experimentally determined ( $k_s$ ,  $\rho_\infty$ ,  $\rho_g$ , with  $k_l$  given by eq(3.10)); 'weights' deduced from the geometry of the present greenhouse may be given to the thermal radiation emitted by the heating pipes and the soil surface (0.07 and 0.93, respectively). Finally one achieves the equation for the net radiation of the canopy, namely:

$$R_n = (1 + 0.58e^{-0.48LAI})(0.88 - e^{-0.48LAI} + 0.12e^{-0.64LAI})I_s + \sigma(1 - e^{-0.64LAI})(T_u^4 + 0.07T_p^4 + 0.93T_g^4 - 2T_0^4) \quad W \cdot m^{-2} \quad (3.14)$$

where  $I_s$  is the shortwave radiation measured at the top of the canopy and  $T_u$ ,  $T_p$  and  $T_g$  are the surface temperature of the cover, of the heating pipes and of the plastic sheets, respectively; the emittance of all these surface has been assumed to be 1. As the shortwave transmittance ( $\tau_s$ ) of the present crop was between 0.15 (LAI = 4) and 0.38 (LAI = 2), it may be observed that the use of white plastic to cover a soil of say, reflectance 0.1, increased the shortwave radiation available to the crop by about 8% (LAI = 4) to about 18% (LAI = 2). On the other hand, the term  $0.12 \cdot e^{-0.64LAI}$  represents the difference with respect to the simpler assumption that the canopy reflects as though it were a dense stand. That correction is in the present case between 1 and 3%. Hence, for a rough appraisal, the simpler assumption could be retained. Correct values of the absorption coefficient of both short and longwave radiation are supplied in tab. 3.2 for some leaf area indexes.

LAI	coefficient of $I_s$	coefficient of $I_l$
2.0	0.65	0.72
2.5	0.71	0.80
3.0	0.75	0.85
3.5	0.78	0.89
4.0	0.81	0.92
4.5	0.82	0.94

Table 3.2. Absorption coefficients for shortwave and longwave radiation, respectively, as given in eq(3.14), for various values of the leaf area index.



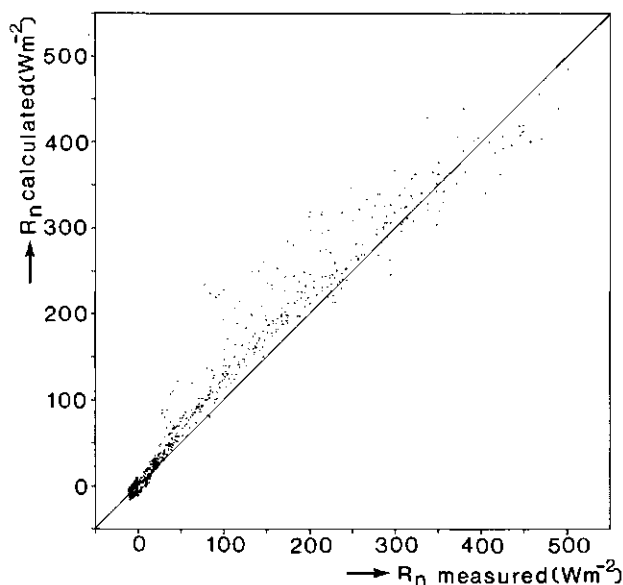


Fig. 3.7. Estimated (eq(3.14) vs. measured net radiation of the crop, for three days in the period 7 to 10 May, 1985.

In fig. 3.7 the net radiation of the crop is given, for a period of three days, as estimated through eq(3.14) and by the difference between measured net radiation above and below the canopy. As there is a sufficient agreement between the two estimates, it may be concluded that this method rather successfully diminishes the need for extensive (and expensive) radiation measurements. It requires, however, the a priori knowledge of some parameters typical of each crop.

### 3.2.7 Radiation exchanged by a row crop

The method developed so far applies to a canopy with a random leaf arrangement. Most agricultural crops, however, are cultivated in rows, i.e. the total leaf area is distributed in clusters, more or less regularly. Of course this represents a loss of light interception for the canopy, with respect to a complete cover. A correct appraisal of its extent is, therefore, of obvious importance in agriculture. Many models have been developed suitable to solving this problem, with varying degrees of complexity and – not unexpectedly – accuracy (e.g. Allen, 1974; Stoffers, 1975; Lang and Shell, 1976; Mann et al., 1980; Norman and Welles, 1983; Myneni and Impens, 1985b and Whitfield, 1986). Many of these models are exact only for beam light and most are simply too cumbersome or too detailed to be built into this work. The easiest way is to have a less than unity factor, hereafter called  $W$ , applied to the radiation interception of a homogeneous canopy, in order to account for the incomplete cover.

Let us assume the canopy is composed of an infinite number of infinitely long

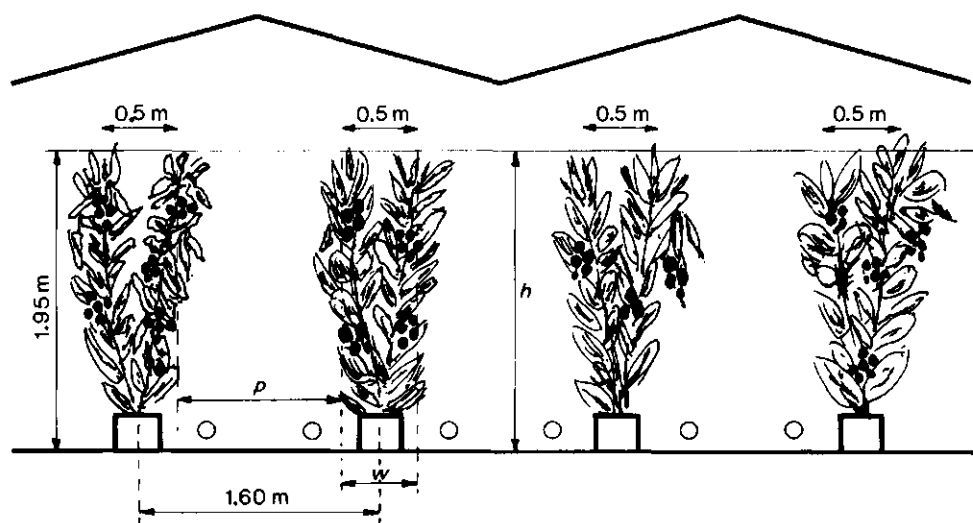


Fig. 3.8. Schematic representation of the crop rows, and of their outline.

rows, having a rectangular vertical cross section, of width  $w$  and height  $h$ , separated by a path of width  $p$ , fig. 3.8. The leaf distribution within a row is random. Thus within the space occupied by rows, the effect of the distribution of foliage elements on interception of radiation can be assessed through the porosity of a single row, i.e. by means of the equations derived in § 3.2.1 to 3.2.3. Such an assumption was experimentally shown to hold for a sorghum row canopy by Fuchs and Stanhill (1980). The radiation then intercepted by such a stand would be a fraction  $W = w/(w+p)$  of the interception of a homogeneous canopy, as a first guess. For the row-path arrangement of the canopy dealt with in the present research,  $w$  was 0.5 m and  $p$  was 1.1 m;  $W$  would be, therefore, 0.31. Actual interception, however, has to be more than that, since the leaves near the external surface of each row do receive more radiation than if they were within a homogeneous canopy. In fact, Goudriaan (1977) conjectured that the radiation exchanges of a row crop could be referred to an 'increased' row width, accounting for the larger irradiation of leaves nearby the external surface of any row, regarded as a solid. He suggested that, within an isotropic radiation field (i.e. a somehow idealized overcast sky), the apparent increase ( $\Delta w$ ) of the row width should be calculated by:

$$\Delta w = p + h - (p^2 + h^2)^{1/2} \quad \text{m} \quad (3.15)$$

Therefore, only a fraction  $W = (w + \Delta w)/(w + p)$  of the radiation entering either the upper or the lower surface of a canopy in rows, has a chance of being intercepted by a foliage element, i.e. of undergoing one of the processes analyzed in § 3.2.1 through 3.2.3. For the present canopy, since  $h$  was 1.95 m,  $\Delta w$  would

be 0.81 m which would yield  $W = 0.82$ , which is remarkably more than  $W = 0.31$ , provided above as a guess.

An additional correction should be applied however, since the light interception of a row is, for light with a large angle of incidence, smaller than the light interception of a homogeneous crop. A geometrical analysis of this problem was performed by Fuchs and Stanhill (1980) as well as by Stoffers (1975). The resulting equations are quite cumbersome, in both cases. However, Stoffers provided, in the same work, approximated equations he derived by best fitting the results he had got, for diffuse radiation, from his simulation model. Those equations may be used to calculate the diffuse light interception of a row crop, as well as of a homogeneous one. Of course, the ratio of the two, yields the factor  $W$  looked for. That ratio may be written in the form:

$$W = f(w, p, h) (1 - C_1 \cdot e^{-C_2 \cdot LAI}) \quad - \quad (3.16)$$

For the present row-path arrangement  $f(w, p, h)$  is 0.83, which is, whether by accident or by design, practically the same as estimated above, by the method of Goudriaan (1977). The coefficients  $C_1$  and  $C_2$  are a combination of the transmittance and reflectance of the homogeneous canopy and of the dimensions of the rows. The calculation of those coefficients for the present case finally allows for the conclusion that the amount of radiation exchanged by a greenhouse crop, having the radiative properties as experimentally determined and cultivated in rows whose outline has the dimensions reported above, is given by eq(3.14) times a reducing factor  $W$ , given by:

$$W = 0.83 (1 - 0.70 \cdot e^{-0.24 \cdot LAI}) \quad - \quad (3.17)$$

For instance, the loss of light interception due to cultivation in rows of this shape can vary from about 53% for a  $LAI=2$  ( $W = 0.47$ ) to 39% when  $LAI=4$  ( $W = 0.61$ ).

### 3.3 Thermal storage

The storage of thermal energy in a canopy is, obviously, the sum of the thermal energy stored into each element of the canopy, at any time. This apparently trivial remark implies that the thermal storage can be accurately calculated only if, at any time, the variation of temperature of any element of the canopy (as leaves, stems, fruits) is known, as well as the corresponding heat capacity. This is as to say that the thermal storage is never accurately known. It could be argued, however, that only the energy balance of the foliage is dealt with here. Indeed, in § 3.1 sensible and latent heat exchanges of the leaves alone have been considered

and in § 3.2 it has been implicitly assumed that all interception of radiation is due to the leaves. Of course this latter assumption is questionable though it might be argued with some reason, that the radiation exchanged by stems, flowers and fruits of a tomato crop is quite a small fraction of the radiation exchanged by the whole crop. If it is therefore accepted that we are busy exclusively with the foliage, the thermal storage term ( $J$ ) of the energy balance equation (3.1) has to be written, in analogy with eq(2.13), as:

$$J = \rho_l c_l \cdot d \cdot LAI \cdot dT_o/dt \quad W \cdot m^{-2} \quad (3.18)$$

where  $d$  is the average leaf thickness. The storage  $J$  is expressed as a flux density per unit ground area. Eq(3.18), therefore, requires the mass per unit leaf area ( $\rho_l d$ ) and the specific heat of the leaf tissue ( $c_l$ ) to be known. In § 2.1.5 an indicative value for the latter was reported to be  $c_l \sim 3.5 \cdot 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$  (Jones, 1983). On the other hand, literature can scarcely provide an appraisal of the mass per unit leaf area, since the latter is known to vary a lot between plant species. Less trivially, environmental conditions during growth may affect the leaf thickness (Nobel, 1974) and in the course of a day the water content of the tissue may perceptibly change (Ehrler et al., 1965), resulting in large variations of the mass per unit area.

The mass per unit leaf area of the tomato crops described in § 3.2.5 was measured before and after each experimental run, resulting in a mean value of  $0.442 \text{ kg} \cdot \text{m}^{-2}$ , with a standard deviation of  $0.145 \text{ kg} \cdot \text{m}^{-2}$ . However, variations as large as 30% in the measured mass were sometimes observed within a day. Consequently, an inaccuracy of 30% in the thermal storage is not unlikely; not even when making use of one's own weighings.

An estimate of the actual specific heat of the leaf tissue was attempted through the method described by Stanghellini (1983a). The thermal storage was calculated as the residual of the energy balance, assuming that all the other energy terms were correctly known. It was then parametrized as a linear function of the time derivative of the measured leaf temperature, namely:

$$R_n - H - LE = J = C_1 dT_o/dt + C_2 \quad W \cdot m^{-2} \quad (3.19)$$

The offset term  $C_2$ , though not consistent with eq(3.18) was explicitly considered, as a means of allowing for possible systematic deviations in the calculation of net radiation or when neglecting other energy fluxes (§ 2.1.4). However, the values of the offset resulting from the best-fit of eq(3.19) on the experimental results were reassuringly small (a few  $W \cdot m^{-2}$  for most runs). On the other hand, the correlation between  $J$  as calculated through the energy balance and  $dT_o/dt$  as deduced from the leaf temperature measurements was rather poor, which was to be expected, as pointed out by the following consideration. As the left hand side of

eqs(3.19) shows, the thermal storage is calculated as the (small) difference of three (large) fluxes, each one measured or guessed with a casual error of at least a few percents. Similarly, the time derivative of the temperature of the leaves is also calculated through the (mostly minimal) difference between two successive temperature measurements, which are obviously affected by an experimental error, too. Anyhow, the mean of the resulting coefficients  $C_1$ , divided by the corresponding LAI, yielded:

$$J = 1.2 \cdot 10^3 \cdot \text{LAI} \cdot dT_o/dt \quad \text{W} \cdot \text{m}^{-2} \quad (3.20)$$

which is equivalent to 0.28 kg water for a square meter leaf area (one side only), or 0.28 mm water depth. The measured mass per unit leaf area, combined with the mentioned value of the specific heat of the leaf tissue would have yielded  $1.5 \cdot 10^3 \text{ J} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  for the coefficient of eq(3.20). An estimate of the actual specific heat of the leaf tissue for the present crop may be provided for each run by the coefficient  $C_1$ , divided by the corresponding LAI and mass per unit leaf area. Indeed there were large variations in the resulting estimates, their mean being  $c_l = 2.7 \cdot 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ , with a standard deviation of  $6 \cdot 10^2 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ . The obvious inaccuracy of the whole procedure implies that it makes no sense to argue whether such a deviation from the expected value is a meaningful one or not. It is worthwhile pointing out, however, that Aston (1985) arrived at a remarkably similar value ( $2.8 \cdot 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ) for the specific heat of eucalyptus leaves, by other experimental means. Yet those leaves were found to be far less dense than the leaves of the present crop (0.215 instead of  $0.442 \text{ kg} \cdot \text{m}^{-2}$ ), which would result in the coefficient of eq(3.20) being half the present one. Considering the macroscopic difference between a hard, apparently dry, eucalyptus leaf and a soft, wet tomato one, one would like to conjecture that leaf water content should more appropriately be measured in  $\text{kg} \cdot \text{m}^{-2}$  instead of percent of weight, as is more commonly done.

### 3.4 Smoothing rules

Now that the various energy fluxes to and from a canopy have been quantified to some extent, it is worthwhile devoting some time to devising a couple of rules of thumb which should make the appraisal of the magnitude of those fluxes, and their relative importance easier.

#### 3.4.1 Net radiation

To begin with, one would certainly like to be provided with a simpler means of calculating the net radiation of the canopy than by using eq(3.14), reduced by the

row factor  $W$ , given by eq(3.17). In fact the equation for net radiation may be written as:

$$R_n = A_s \cdot I_s + A_l \cdot I_l \quad \text{W} \cdot \text{m}^{-2} \quad (3.21)$$

whereby the absorption coefficients for shortwave and longwave radiation have been respectively defined as:

$$A_s = 0.83 (1 - 0.70x)(1 + 0.58x^2)(0.88 - x^2 + 0.12x^{8/3}) \quad - \quad (3.22)$$

and

$$A_l = 0.83 (1 - 0.70x) (1 - x^{8/3}) \quad - \quad (3.23)$$

with  $x$ , an intermediate variable:

$$x = e^{-0.24 \cdot \text{LAI}} \quad - \quad (3.24)$$

Furthermore, in eq(3.21),  $I_s$  is the shortwave radiation incoming at the top of the canopy, whereas  $I_l$  is the longwave radiation exchange, given by eq(3.14):

$$I_l = \sigma (T_a^4 + 0.07 \cdot T_p^4 + 0.93 \cdot T_g^4 - 2 \cdot T_o^4) \quad \text{W} \cdot \text{m}^{-2} \quad (3.25)$$

The absorption coefficients, eqs(3.22) and (3.23), respectively, are shown in fig. 3.9, as functions of the leaf area index. A purposeful approximation of them is given by straight lines through the origin, which read, respectively:

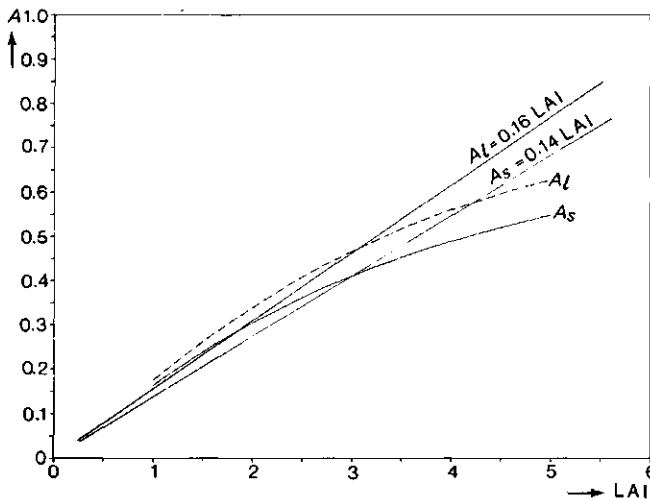


Fig. 3.9. Absorption coefficients for shortwave ( $A_s$ ) and longwave ( $A_l$ ) radiation, respectively, as function of the leaf area index (eqs(3.22) and (3.23)). The approximating lines, used in the text, are also given.

$$A_s \sim 0.14 \cdot \text{LAI} \quad - \quad (3.26)$$

and

$$A_l \sim 0.16 \cdot \text{LAI} \quad - \quad (3.27)$$

It can be calculated however, that for LAI exceeding 5.2 the absorption coefficients are approximated better by their asymptotic values (i.e. by 0.73 and 0.83, respectively) and cannot be regarded any longer as being proportional to LAI.

On the other hand, the equation (3.25) of the longwave radiation exchange could be linearized, without too much loss of accuracy, in a fashion similar to the one applied in § 2.5.1. If one considers that the temperature of the air inside the greenhouse cannot differ too much from the effective mean of the temperatures of the soil surface, of the heating system, of the cover and of the foliage, a minimum of computations yields:

$$I_l \sim 4 \sigma T_a^3 (T_u + 0.07 \cdot T_p + 0.93 \cdot T_g - 2 \cdot T_o) \quad \text{W} \cdot \text{m}^{-2} \quad (3.28)$$

Moreover, an apparent radiation temperature of the ambient may be introduced, defined by:

$$T_h = (T_u + 0.07 \cdot T_p + 0.93 \cdot T_g) / 2 \quad \text{K} \quad (3.29)$$

In § 2.5.1 – eq(2.65) – a ‘radiation resistance’  $r_R$  has been defined as the ratio  $\rho_a c_p / 4 \sigma T_a^3$ . Therefore eq(3.21), with substitution of eqs(3.26) to (3.29), may be rewritten as:

$$R_n \sim 2 \cdot \text{LAI} \cdot [0.07 \cdot I_s - 0.16 \cdot \rho_a c_p (T_o - T_h) / r_R] \quad \text{W} \cdot \text{m}^{-2} \quad (3.30)$$

and the term within square brackets may be interpreted as  $\bar{R}_n$ , i.e. the net radiation of the canopy per unit leaf area (eq(3.6)). It was already observed that substitution of eq(3.6) in eq(3.4) results in an equation for the transpiration rate of a canopy, which is formally identical to eq(2.55), the transpiration rate of a single leaf, times a factor  $2 \cdot \text{LAI}$ . The same procedure yields an equation (3.5) for the temperature of the canopy, of the same form as eq(2.56), i.e. the temperature of a single leaf. Hence, the discussion of § 2.5 (and its results) may be applied directly to a canopy, if only one realizes that the mean isothermal net radiation is, in this case, given by:

$$\bar{R}_{n,a} = 0.07 \cdot I_s - 0.16 \cdot \rho_a c_p \cdot (T_a - T_h) / r_R \quad \text{W} \cdot \text{m}^{-2} \quad (3.31)$$

It is worthwhile realizing that the magnitude of  $\bar{R}_{n,a}$  as given by eq(3.31) is definitely not the same as the magnitude of the incoming shortwave radiation at the

top of the canopy ( $I_s$ ). One should have this in mind when applying to a canopy tab 2.2 and figs. 2.13; 2.15 and 2.16.

### 3.4.2 Temperature of a canopy

In order to re-write the energy balance equation as an explicit function of the surface temperature, one more step is needed. If the familiar linearization of the saturation vapour pressure curve is applied to eq(3.3), the latent heat flux may be written as the following function of the surface temperature of the foliage:

$$LE = \frac{2 \cdot LAI \cdot \rho_a c_p}{\gamma(r_i + r_e)} [\delta(T_0 - T_a) + (e_a^* - e_a)] \quad \text{W} \cdot \text{m}^{-2} \quad (3.32)$$

Then, substitution in the energy balance – eq(3.1) – of the equations for the corresponding energy fluxes: net radiation, eq(3.30); sensible heat, eq(3.2); latent heat, eq(3.32); and the thermal storage, eq(3.20); results in:

$$2 \cdot LAI \cdot \rho_a c_p \left[ \frac{0.07}{\rho_a c_p} I_s - \frac{0.16}{r_R} (T_0 - T_h) - \frac{600}{\rho_a c_p} \frac{dT_0}{dt} - \frac{T_0 - T_a}{r_e} - \frac{\delta}{\gamma} \frac{T_0 - T_a}{r_i + r_e} - \frac{e_a^* - e_a}{\gamma(r_i + r_e)} \right] = 0 \quad \text{W} \cdot \text{m}^{-2} \quad (3.33)$$

A total transfer resistance  $r_{tot}$  may be defined by the combination of the coefficients of the surface temperature in eq(3.33):

$$\frac{1}{r_{tot}} = \frac{0.16}{r_R} + \frac{1}{r_e} + \frac{\delta}{\gamma} \frac{1}{r_i + r_e} \quad \text{m} \cdot \text{s}^{-1} \quad (3.34)$$

whereas the terms independent of the surface temperature of the foliage may be regrouped in an energy flux density  $F$ , thus defined:

$$F = \rho_a c_p \left[ 0.07 \frac{I_s}{\rho_a c_p} + 0.16 \frac{T_h - T_a}{r_R} - \frac{e_a^* - e_a}{\gamma(r_i + r_e)} + \frac{T_a}{r_{tot}} \right] \quad \text{W} \cdot \text{m}^{-2} \quad (3.35)$$

Therefore the equation of state (3.33) of the temperature of the foliage reads:

$$2 \cdot LAI \left[ F - \frac{\rho_a c_p}{r_{tot}} T_0 - 600 \frac{dT_0}{dt} \right] = 0 \quad \text{W} \cdot \text{m}^{-2} \quad (3.36)$$



As a first simplification, it is noteworthy that the temperature of the surface is independent of the leaf area. Strictly speaking, this observation is true only insofar as eqs(3.26) and (3.27) are correct. By those equations it was postulated that the net radiation of a canopy is proportional to its leaf area (i.e. that the mean net radiation  $\bar{R}_n$  is independent of the leaf area). From fig. 3.9 the extent to which this assumption is accurate for the LAI spanned by the present work may be deduced, whereas it has already been pointed out that for LAI > 5 it would be more accurate to state that the net radiation of a canopy is independent from its leaf area. One could safely state anyway, that the effective temperature of a canopy (as defined in the present work) is almost independent from the leaf area.

The differential equation (3.36) may be solved analytically only if  $r_{tot}$  as a function of the temperature of the canopy meets some analytical requirements. However, the relation between  $r_i$  and the canopy temperature has not been defined yet, and it is unlikely that those requirements will be met (§ 3.5.2) anyway. For the sake of the present discussion, therefore,  $r_{tot}$  will be regarded as being no function at all of the temperature of the canopy. One should realize accordingly, that the value of this discussion is confined to providing orders of magnitude.

The general solution of eq(3.36) – with the coefficients assumed to be constant – may be written as:

$$T_o(t) = T_o(\infty) - [T_o(\infty) - T_o(0)] \cdot e^{-t/\tau} \quad K \quad (3.37)$$

with the equilibrium temperature  $T_o(\infty)$  given by:

$$T_o(\infty) = r_{tot} F / \rho_a c_p \quad K \quad (3.38)$$

and  $\tau$ , the time constant of the system by:

$$\tau = 600 \cdot r_{tot} / \rho_a c_p \quad s \quad (3.39)$$

Of course, eq(3.38) is none other than a simplified version of the exact equation (3.5) for the effective temperature of the canopy. In fact, it was possible to derive eq(3.38) directly from eq(3.5), by neglecting the thermal storage (i.e.  $J = 0$ ) and by substituting eq(3.30) for  $R_n$ . It will soon be clear, however, that this procedure has not been for nothing, since it allows an appraisal of the importance of the dynamics of the temperature of the foliage (the time dependent part of eq(3.37)).

It is worthwhile quantifying, albeit roughly, the entities defined up to now. It should be clear, however, that this whole section only applies to a crop similar to the one with which the experiments were performed since empirical values are given to many constants. For an ambient air temperature of 20°C,  $\delta/\gamma$  is about 2 and  $r_R$  about 200 s·m<sup>-1</sup> (tab. 2.1). On the other hand one could deduce from figs. 2.10 and 2.11 a value of 200 s·m<sup>-1</sup> also for  $r_e$ , for a greenhouse tomato crop

( $l \sim 5 \text{ cm}$ ;  $u \sim 10 \text{ cm}\cdot\text{s}^{-1}$ ). Therefore, the first term on the right hand side of eq(3.34) can be neglected altogether, being about one sixth of the second one. However, the magnitude of the third term may change a lot as a consequence of the large variations of the internal resistance. For the sake of simplicity, let's say  $r_i$  is about equal to  $r_e$  at daytime, whereas it is about 10 times larger at night. Hence, the third term on the right hand side of eq(3.34) is about equal to the second one at daytime, whereas it is negligible at night. Then  $r_{tot} \sim r_e/2$  at day and  $r_{tot} \sim r_e$  at night. Accordingly, *for a crop as this one*, radiation is never a very effective way to exchange energy with the environment, whereas transpiration has a relevant influence only at daytime. It should not come as a surprise, therefore, that most growers use to supply energy to their crops by heating the air around them. One could point out that the present result is largely a consequence of the model adopted for the radiative exchanges. It is, to an extent. The maximum possible values for  $A_s$  and  $A_l$  are to be found for a homogeneous (no rows) canopy of horizontal leaves ( $k_l = 1$ ). Then, for the present leaf area range, the linearizations performed by eqs(3.26) and (3.27) would yield  $A_s \sim 0.28\cdot\text{LAI}$  and  $A_l \sim 0.32\cdot\text{LAI}$ . This is twice as much as provided by those equations, and not an order of magnitude more. Therefore, the conclusion that radiation seldom is a very effective mode of energy exchange should be applicable to all canopies having an external resistance not larger than the radiation one.

From the combination of eqs(3.35) and (3.38) it is possible to deduce the following formula for the temperature excess at equilibrium:

$$T_o(\infty) - T_a \cong r_{tot} \left[ 0.07 \frac{I_s}{\rho_a c_p} + 0.16 \frac{T_h - T_a}{r_R} - \frac{e_a^* - e_a}{\gamma(r_i + r_e)} \right] \quad \text{K} \quad (3.40)$$

where the symbol  $\cong$  has been used in order to remind the reader that some approximations contributed to this result. Eq(3.40) can be reduced, on the basis of the figures given above, to:

$$\text{daytime: } T_o(\infty) - T_a \sim 0.006 \cdot I_s + 0.08(T_h - T_a) - 0.25(e_a^* - e_a)/\gamma \quad \text{K} \quad (3.41)$$

$$\text{nighttime: } T_o(\infty) - T_a \sim 0.16(T_h - T_a) - 0.1(e_a^* - e_a)/\gamma \quad \text{K} \quad (3.42)$$

Indeed, within a greenhouse in The Netherlands, a crop as the one we are dealing with is quite unlikely to be much warmer than the air, though it is worthwhile pointing out once more that an effective 'mean' temperature (as defined in § 3.1) is dealt with here. Observe the fact that the positive contribution to the temperature excess due to shortwave irradiation is not more than about 4 K ( $I_s < 700 \text{ W}\cdot\text{m}^{-2}$ ), whereas the 'evaporative cooling' may be about 5 K (a typical range for  $(e_a^* - e_a)/\gamma$  is 10 to 30 K). The apparent radiation temperature of the ambient is un-

likely to differ much from the temperature of the air at daytime, hence its contribution may be neglected altogether. On the other hand, the importance of the evaporative cooling at nighttime is smaller (not only because of the smaller coefficient but also because the saturation deficit is normally smaller), whereas the radiation temperature of the ambient may be quite a few degrees lower than the air temperature, especially in an unscreened greenhouse. The application of a double roof, or of a screen, for instance, has the result that the apparent radiation temperature of the ambient and of the air are practically the same. The canopy is then only a little cooler than the air, due to some evaporative cooling. This effect, coupled with the likely suppression of gradients (Bailey, 1985) might explain why, notwithstanding the higher relative humidities, condensation-originated diseases are seldom observed. One might conclude that, in most conditions, the temperature of such a canopy is quite tightly coupled to the temperature of the air. The present conclusion seems to be allowed even for the large leaf area indices for which the present assumption about the absorption coefficients does not hold, as the relevance of the two radiation-dependent terms of eq(3.40) would be reduced, in that case.

Substitution of the corresponding values of  $r_{tot}$  in eq(3.39) results in an estimate for the time constant of about 50 s (daytime) to 100 s (nighttime). Hence it takes the temperature of the canopy something like one minute to get through 2/3 of a variation due to a change in the microclimate. Accordingly, when one is concerned with temperature estimates over time intervals not smaller than a few minutes, the dynamic part of eq(3.37) may be disregarded altogether. In other words, the thermal storage as an energy flux is unlikely to be very important, in most circumstances.

### 3.4.3 Transpiration rate

If it is accepted that the time dependent part of the transpiration rate be ignored, then the approximations adopted here above may be applied straightly to eq(3.4) in order to get a sort of rule of thumb also for the transpiration rate.

If the thermal storage ( $J$ ) is neglected and eq(3.30) is used for  $R_n$ , then eq(3.4) reduces to:

$$LE \cong \frac{2 \cdot LAI \cdot \rho_a c_p}{1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \left[ 0.07 \frac{\delta}{\gamma} \frac{I_s}{\rho_a c_p} + 0.16 \frac{\delta}{\gamma} \frac{T_b - T_0}{r_R} + \frac{1}{r_e} \frac{e_a^* - e_a}{\gamma} \right] \quad \text{W} \cdot \text{m}^{-2} \quad (3.43)$$

The extent of the internal resistance therefore determines the level of the transpiration rate but not the relative importance of the various terms which contribute to it (shortwave and longwave irradiation, saturation deficit of the ambient). In our hypothesis that the ratio of the internal to the external resistance is about

one at daytime and about ten at night, the leaf-area-dependent coefficient of eq(3.43) is between LAI (nighttime) and 3·LAI (daytime). Moreover, assuming the same conditions as in § 3.4.2, i.e.  $\delta/\gamma \sim 2$ ;  $r_R \sim r_e \sim 200 \text{ s}\cdot\text{m}^{-1}$ ; and with  $\rho_a c_p \sim 1200 \text{ J}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$  in mind, the order of magnitude of the various terms of eq(3.43) becomes:

$$\text{LE} \sim \frac{12 \cdot \text{LAI}}{3 + \frac{r_i}{r_e}} \left[ \frac{I_s}{40} + \frac{T_h - T_o}{3} + \frac{e_a^* - e_a}{\gamma} \right] \quad \text{W}\cdot\text{m}^{-2} \quad (3.44)$$

It has already been pointed out that  $(e_a^* - e_a)/\gamma$  is about 10 K or more. Hence, the longwave radiation term (the second one) is, in most conditions, negligible as it becomes comparable with the third one only if the difference between the radiation temperature of the ambient and the temperature of the canopy is about 30 K or more, which, in greenhouses, is unlikely. Also the contribution of the short-wave irradiation becomes relevant only for irradiations (at the top of the canopy) of a few hundreds  $\text{W}\cdot\text{m}^{-2}$ , i.e. in sunny days. One could wonder, therefore, whether the straight relationship often observed in greenhouses between irradiation and transpiration (see Stanhill and Scholte Albers, 1974, for a review), is not largely the result of the relationship between the irradiation and the saturation deficit. Of course it is, though the inverse relationship between the internal resistance and the irradiation (§ 3.5) is likely to be even more of a reason for this observation.

### 3.5 Internal resistance of a canopy

In § 3.1.2, the internal resistance of a canopy was introduced through a transfer equation analogous to the vapour transfer equation already derived (§ 2.1.3) for a single leaf. Nevertheless, it was pointed out that contrary to the single leaf case, such a resistance cannot be identified a priori with the resistance offered by a particular segment of the vapour pathway. Therefore, the only experimental determination of it, consistent with this argument, is one based on the direct use of eq(3.3). Obviously, that requires the measurement of the transpiration rate of a canopy and of the vapour pressure difference between the canopy and the air. Such an experiment will be described hereafter, whereas its results will be discussed in § 3.5.2.

#### 3.5.1 Experimental determination of the internal resistance of a canopy

The experiments were performed in the glasshouse and with the tomato crops described in § 3.2.5. The climate control system installed there also provided for enrichment of the ambient with pure carbon dioxide (Van Meurs, 1980), and the ac-

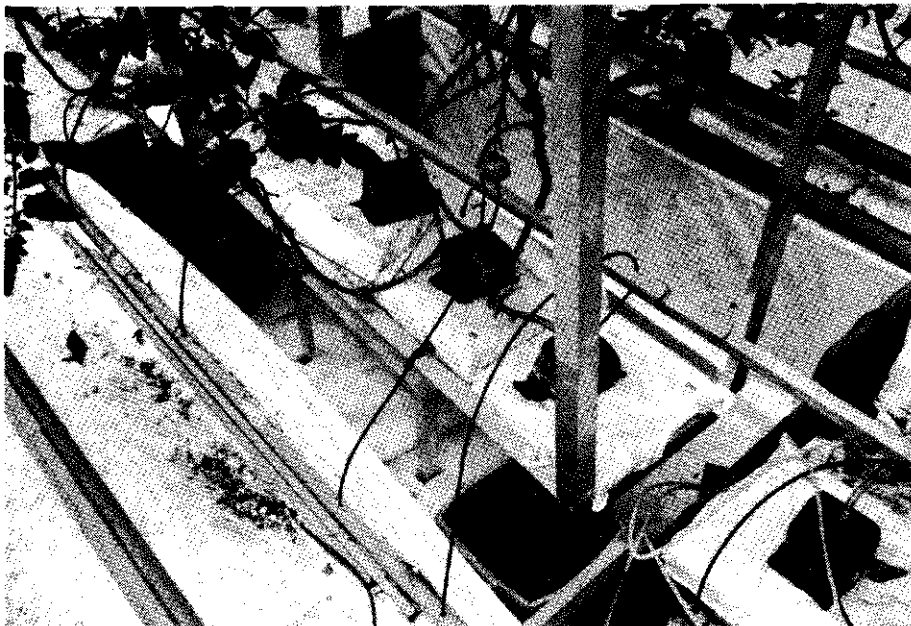


Fig. 3.10. One of the trays as installed for growing the plants on the balances. Details of the water gift system and of the support of the tray can also be seen. During the experimental runs no drainage was allowed out of the trays. The white surface at the bottom of the pit is the polyurethane insulation.

tual concentration of carbon dioxide could be measured by means of a commercially available device. The experimental runs, which took place in the spring and summer of 1984 and in the spring of 1985, stretched through one, two or three whole days. The transpiration rate was then determined by weighing in turn (at 3 or 5 min. intervals) two portions of a crop row, each of four plants, grown on a tray, held at ground level (fig. 3.10). Two electronic scales (in a similar set-up) were used for this purpose. They allowed, after some adjustment, for an accuracy of  $5 \cdot 10^{-6}$  (0.3 g/60 kg), i.e. roughly 1% and 10% of 5-minute day and nighttime transpiration, respectively, of a mature crop. In previous works (Stanghellini, 1983c, Meijer et al., 1985) it was shown that the fluctuations of pressure due to the movement of air in the house, pose a limit to the accuracy attainable by a weighing system. To be sure, the accuracy of the present system was worse, albeit marginally, than the theoretically attainable accuracy for such conditions. An observed drift, due to temperature, in the output of the scales was averted by thermostating the sensors. A sort of natural thermostat was produced by placing the scales in a 80 cm deep pit which was thermally insulated around and above but not at the base (fig. 3.11). The variations of the temperature in the underground chamber thus created never exceeded a few thousandths of a K in the time interval between two successive weighings. No temperature correction was, therefore, applied to the measurements.

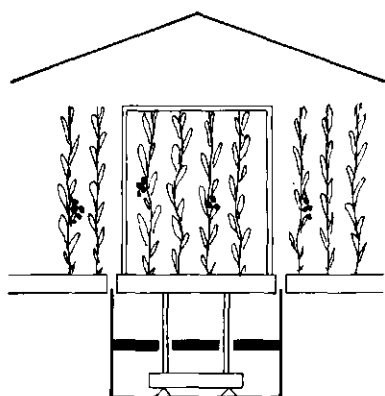


Fig. 3.11. Schematic representation of a longitudinal section of the lysimeter set-up.

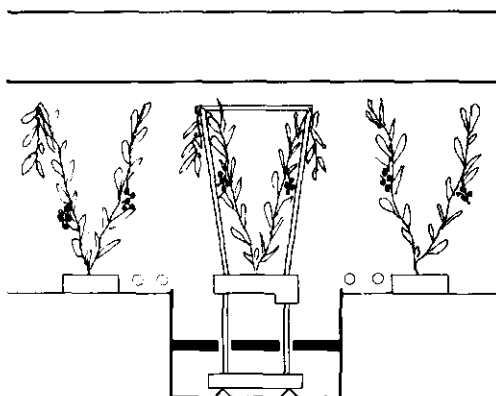


Fig. 3.12. Cross section of the lysimeter set-up.

Water gift was provided in the whole house by a trickle irrigation system, triggered either by a clock or by the amount of drainage. The plants grown on the scales did receive the same treatment as the others, the only difference being that during the experimental runs the drained water was not allowed out of the trays, which were provided with a reservoir for this purpose (fig. 3.12). Growth and production of those plants never were observed to deviate significantly from the general pattern of the whole canopy (Corver, 1984 and 1985).

As evaporation from the soil surface was prevented by the plastic cover – and the plant density in the house was  $2 \cdot \text{m}^{-2}$  –, the transpiration of the four plants on a tray was equivalent to the transpiration taking place from a two-square-meter section of the greenhouse ground area, though the actual surface area of the tray was less than that. This, and the time interval between two subsequent scans were taken into account in order to convert the measured mass decrease in an energy flux density, per unit ground area.

A mean vapour pressure of the foliage was estimated through the saturated vapour pressure at the mean of the leaf temperatures ( $T_o \cong T_E$ ; eq. 2.29b), measured by the thermocouple sets described in § 3.2.5. In order to assess the vapour pressure of the air, moreover, three Assmann aspirated psychrometers were used, just above, within, and below the foliage respectively, as described in § 2.3.2. The mean of the three vapour pressures (which were always within some tens of Pa of each other) was substituted as  $e_a$  in eq(3.3). When the vapour pressure difference between the canopy and the air, as well as the transpiration rate are known, that equation can be inverted to yield the total resistance on the vapour pathway. The canopy internal resistance was subsequently deduced by subtracting from the latter the canopy external resistance, given by eq(2.53), as defined in § 3.1.1.

The order of magnitude of the internal resistance was found to be  $250 \text{ s} \cdot \text{m}^{-1}$  (daytime) to  $2500 \text{ s} \cdot \text{m}^{-1}$  (nighttime) with rather large variations, whereas the ex-

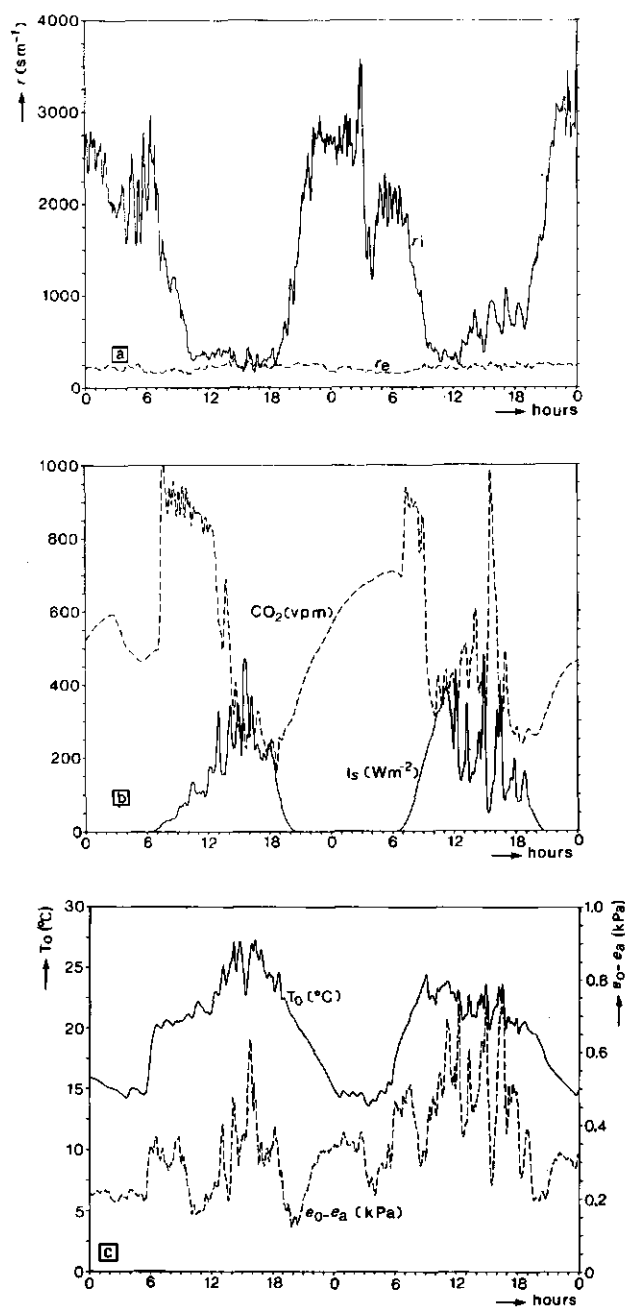


Fig. 3.13. Time course of both the internal ( $r_i$ ) and external ( $r_e$ ) resistances for two consecutive spring days (17-18 April, 1985), [a]. Also shown are: the corresponding incoming shortwave radiation at the top of the stand ( $I_s$ ),  $\text{CO}_2$  concentration within the house [b]; measured leaf temperature ( $T_o$ ) and vapour pressure difference between the leaves and the ambient ( $e_o - e_a$ ), [c].

ternal resistance was about  $200 \text{ s}\cdot\text{m}^{-1}$ . The daily course of both resistances, for two typical spring days, is shown in fig. 3.13a, together with the corresponding global radiation and  $\text{CO}_2$  concentration of the air inside the greenhouse (fig. 3.13b); also shown are the leaf temperature and vapour pressure difference between the leaves and the air (fig. 3.13c). It could be stated that, at least for a crop as this one, the external resistance might well be regarded as constant, whenever its variations are compared with the extent of the fluctuations of the internal one. The same had already been pointed out by Stanghellini (1985). In fact, though no generalization is being made here, it seems that in the present conditions, the control of water loss is mainly of internal nature. A predictive model for transpiration of such a canopy has, therefore, to be based on a reliable parametrization of the canopy internal resistance.

In § 3.1.2 some experimental findings, enriched by some abstract considerations, were listed in support of the hypothesis that the apparent behaviour of the internal resistance of the canopy is almost exclusively determined by the internal resistance of the leaves composing it. Accordingly, the observed behaviour of the internal resistance of a whole canopy should lend itself to a parametrization in respect to the microclimate quite similar to the one suggested for the internal resistance of a leaf. As outlined in § 2.4, the internal resistance of a single leaf was supposed to be the result of the independent action of each climate parameter upon a minimum possible resistance  $r_{min}$ , the latter having a purely physiological origin. Therefore, if one chooses to adopt the same approach for the canopy as a whole, the observed canopy internal resistance has to be described by an equation of the form (eq(2.54)):

$$r_i = r_{min} \cdot \tilde{r}_i(I_s) \cdot \tilde{r}_i(T_o) \cdot \tilde{r}_i(\text{CO}_2) \cdot \tilde{r}_i(e_o - e_a) \quad \text{s}\cdot\text{m}^{-1} \quad (3.45)$$

where  $r_{min}$  is the minimum possible canopy internal resistance for the present crop. The symbols  $\tilde{r}_i$  represent functions larger than unity, which describe the relative increase of the resistance if any of the relevant variables of the climate (shortwave irradiation ( $I_s$ ), leaf temperature ( $T_o$ ), carbon dioxide content of the ambient air ( $\text{CO}_2$ ), leaf to air vapour pressure difference ( $e_o - e_a$ )) is limiting the vapour transfer rate. In order to reproduce the trends outlined in § 2.4 (fig. 2.12), for the dependence of the internal resistance on the various parameters, the following functions were chosen:

–  $\tilde{r}_i(I_s)$  was assumed to be a rectangular hyperbola:

$$\tilde{r}_i(I_s) = \frac{I_s + C_1}{I_s + C_2} \quad (C_1 > C_2) \quad - \quad (3.46)$$

where  $\bar{I}_s$  is the mean flux density per unit leaf area, defined in a fashion similar to eq(3.6):



$$\bar{I}_s = A_s I_s / (2 \cdot LAI) \quad \text{W} \cdot \text{m}^{-2} \quad (3.47)$$

An argument for using the 'mean' irradiation,  $\bar{I}_s$ , as operand in eq(3.46) instead of just the irradiation at the top of the canopy ( $I_s$ ), may be provided by the following observation. As the leaf area increases, the irradiation actually available per unit leaf area (i.e. the irradiation actually eliciting stomatal response) diminishes. This would result in the observed canopy resistance to increase with the leaf area, the other conditions being the same. Indeed, Aston (1984), on the basis of a similar argument showed that an observed trend in the measured transpiration rate could be accounted for by defining an 'effective leaf area'.

- the influence of the leaf temperature was described by a parabola:

$$\bar{r}_i(T_0) = 1 + C_3(T_0 - T_m)^2 \quad - \quad (3.48)$$

where  $T_m$  is the temperature at which the resistance is minimal.

- a parabola was also assumed to represent the influence of the carbon dioxide concentration of the ambient air. The concentration value for which the resistance is minimal was, somehow arbitrarily, placed at 200 vpm (Bruggink, 1986), whereas Jarvis (1976) had suggested that  $\bar{r}_i(\text{CO}_2)$  is minimal, and constant, for any concentration below 100 vpm:

$$\bar{r}_i(\text{CO}_2) = 1 + C_4(\text{CO}_2 - 200)^2 \quad - \quad (3.49)$$

- the same function was also applied to the vapour pressure difference, with the proviso that the resistance is minimal when the vapour pressure difference is nil (Choudhury and Monteith, 1986):

$$\bar{r}_i(e_o - e_a) = 1 + C_5(e_o - e_a)^2 \quad - \quad (3.50)$$

There is always a fair degree of subjectivity in the choice of the best function to reproduce a known trend. Here no exception to this rule is dealt with, therefore only a short defence of the choices of this writer will be attempted hereafter. Almost everybody (e.g. Jarvis, 1976; Ng and Jarvis, 1980; Squire and Black, 1981; Jones, 1983) seems to agree that a rectangular hyperbola does represent the effect of shortwave irradiation. With reference to eq(3.48), on the other hand, the simplest function (i.e. the function with the least parameters) to achieve a minimum is indeed a parabola, which was then an obvious choice for the function of the leaf temperature. It was less obvious for both the  $\text{CO}_2$  function and the vapour pressure difference one, both known to be monotonous. The present choice was based on figures suggesting an increasing steepness of the vapour pressure func-

tion away from its minimum (Lösch and Tenhunen, 1981). In fact, the relationship proposed by Choudhury and Monteith in a recent review (1986) implies that  $\bar{r}_i (e_o - e_a)$  may be described by the increasing branch of a rectangular hyperbola contained between  $e_o - e_a = 0$  and a vertical asymptote somewhere around 6 kPa. Such a branch could be thought of as the increasing branch of a parabola as well. Least defensible of all would be, therefore, a parabola for the  $\text{CO}_2$  function, were it not for the simplicity. Indeed, in § 3.5.2, it will be argued that extrapolation of these last two functions outside the range of conditions for which they were derived, could yield overestimates of the actual resistance.

To determine which combination of the unknown parameters made eq(3.45) – with substitution of eqs(3.46), (3.48), (3.49) and (3.50) – best reproduce the observed canopy internal resistance, an optimization program was used, based on the method described by Birta (1977) with the data of three consecutive days (16–19 April, 1985). The criterion for selecting the data was to have an as broad as possible range for all the parameters.

It has already been stated that by inspecting the canopy internal resistance, one is, in fact, observing a mean internal resistance of the individual leaves, i.e. the processes involved are the same. The vapour leaving the phase interface of a leaf reaches the external surface through a diffusion across the leaf tissue. The path through the sub-stomatal cavities and the stomata, is decidedly the one of lowest resistance, when the stomata are open. Therefore, factors known to affect the stomatal opening are likely to affect the leaf internal resistance (or the canopy internal resistance) only at daytime. Accordingly, it is not to be expected that the same parametrization applies to both day and night. Hence, nighttime and daytime data (the latter defined by  $I_s > 3 \text{ W} \cdot \text{m}^{-2}$ ) were feeded separately into the program. It will be observed, moreover, that when  $I_s$  is nil, the parameters  $C_1$  and  $C_2$  cannot be determined. Therefore, the procedure only yields the combination  $r_{min} \cdot C_1/C_2$ , when applied to nighttime data.

### 3.5.2 Results and discussion

The resulting best-fit combinations of parameters are summarized in tab. 3.3, whereas the shape of the various  $\bar{r}_i$  functions, corresponding to the calculated parameters, and the range of the variables for which they were derived, is shown in fig. 3.14. To begin with, it is worthwhile pointing out that the very fact that a parametrization as this is successful, is a strong argument in favour of the statement that, of all the components of the canopy internal resistance, the one of paramount importance is the internal resistance of the leaves composing the canopy.

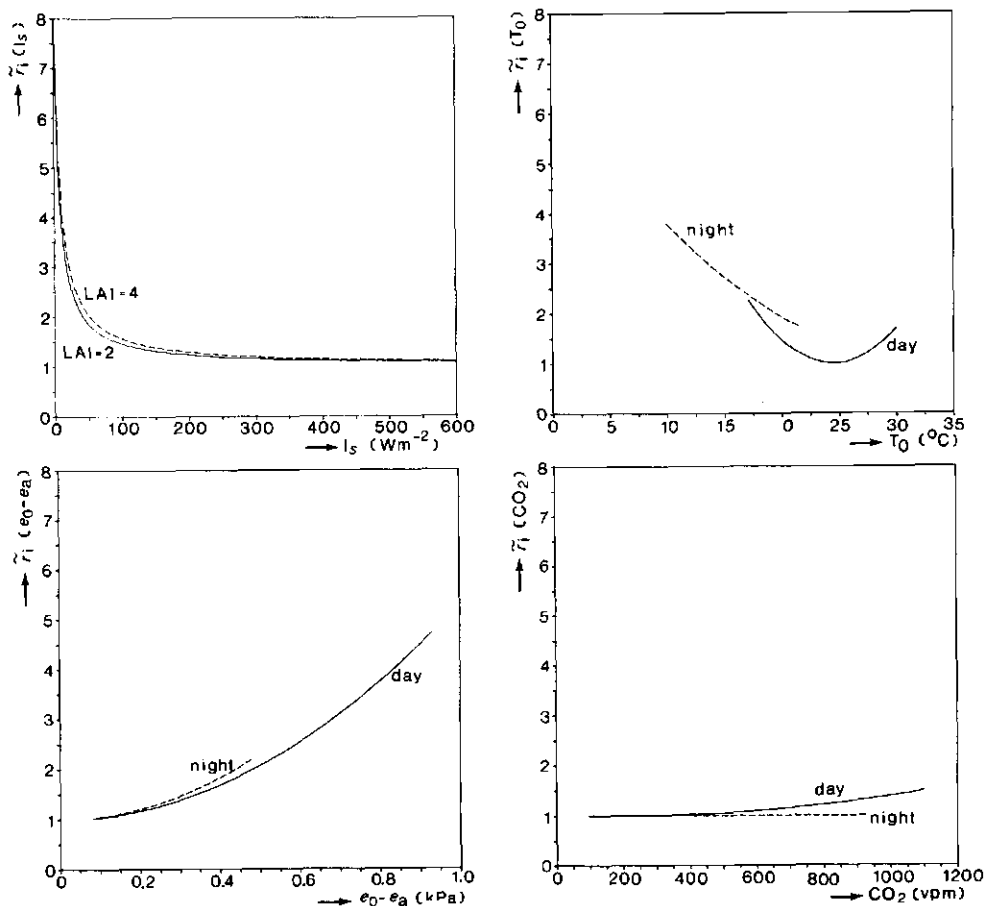


Fig. 3.14. Resulting trends for the various  $f_i$  from the optimization routine. The functions are shown only for the range stretched by the data.

daytime			nighttime	
$r_{min}$		82.0		$\text{s} \cdot \text{m}^{-1}$
			658.5	$\text{s} \cdot \text{m}^{-1}$
$f_i(I_s)$	$C_1$	4.30		$\text{W} \cdot \text{m}^{-2}$
	$C_2$	0.54		$\text{W} \cdot \text{m}^{-2}$
$f_i(T_0)$	$C_3$	$2.3 \cdot 10^{-2}$	$0.5 \cdot 10^{-2}$	$\text{K}^{-2}$
	$T_m$	24.5	33.6	$^{\circ}\text{C}$
$f_i(\text{CO}_2)$	$C_4$	$6.1 \cdot 10^{-7}$	$1.1 \cdot 10^{-11}$	$\text{vpm}^{-2}$
$f_i(e_0 - e_a)$	$C_5$	4.3	5.2	$\text{kPa}^{-2}$

Table 3.3. Values of the parameters of the various  $f_i$  functions, as a result of the optimization program.

It is worthwhile also noting the reassuring feature that the nighttime combination  $r_{min} \cdot C_1 / C_2$  is within a few  $s \cdot m^{-1}$  (or about 1%) of its daytime value. However, for the sake of consistency, only one value had to be applied in the final model: the value arrived at by the daytime data was adopted.

Further, irradiation appears to be relevant in determining the canopy resistance only at small intensities, as the minimum possible resistance is already attained for an irradiation of a few hundred  $W \cdot m^{-2}$ . Another parametrization did yield the same result, for the 1984 experiment (Stanghellini, 1987). This result is consistent with findings by e.g. Gaastra (1963), Takakura et al. (1975) and Avissar et al. (1985), for single leaves or young plants. Choudhury and Idso (1985b), however, apparently observed a somewhat less steep decrease with irradiation, of the mean stomatal resistance of a field-grown wheat crop. This result could be partly explained by the larger leaf area index of their canopy (fig. 3.14a).

With regard to the resistance as a function of leaf temperature, the two trends of  $\bar{r}_i(T_o)$  might be due to two different processes. The decreasing trend for increasing temperature may be explained without postulating stomatal action. In fact, the depth of the phase interface beneath the external surface of any leaf is determined by the rate at which water is fed to the phase interface and the rate at which vapour leaves it. The magnitude of each flux is (partly) determined by the extent of a transfer resistance. Those transfer resistances are each proportional to the inverse of a conductance: the hydraulic conductance of the vessels bringing water to the phase interface and the diffusivity of vapour in the leaf tissue above it, respectively. Both hydraulic conductivity and vapour diffusivity are known to enlarge with temperature; the former, however, more than the latter. Between  $10^\circ C$  and  $30^\circ C$  the hydraulic conductivity may well increase by some 40%, whereas a likely figure for vapour diffusivity is 10%. As the continuity equation for the  $H_2O$  flux demands the equilibrium between the water flux reaching the phase interface and the vapour flux leaving it, the phase interface *has* to get nearer to the external surface upon an increase of the temperature. This is observed as a decrease of the internal resistance. Indeed, porometer measurements by Mansfield (1965) put into evidence such behaviour, though he credited it to stomatal closure. On the other hand, some stomatal closure is indeed likely to take place at high temperatures (Stälfelt, 1962), due to some stress effect. The temperature at which these two opposing effects balance each other (the temperature for which the resistance is minimal) is, quite obviously, determined by physiological factors. The value found here ( $T_m = 24.5^\circ C$ ) is well within the range of values reported in the literature (Stälfelt, 1962; Avissar et al., 1985).

Having credited the decreasing part of the  $\bar{r}_i(T_o)$  function to the same process, whether at day or at night, it had to be assumed that the slightly different trends derived from the two data sets were due to other factors (as the extent of the temperature range). Hence, the daytime function was chosen as it was determined on a broader range.

It is worthwhile pointing out that it had to be expected that no effect of CO<sub>2</sub> concentration on the internal resistance should be observed at night. Any influence of it is thought to take place through stomatal action (Mansfield et al., 1981), thus no effect should be detectable when stomata are anyhow (almost) closed. The day-time trend observed here is weaker than it had been reported by Bruggink (1986), though in the same order of magnitude. It should be pointed out, however, that both Jarvis (1976) and Avissar et al. (1985), after postulating a trend for  $\bar{r}_i$  (CO<sub>2</sub>) as shown in fig. 2.12c, were unable to detect any, in Sitka spruce and tobacco, respectively. Indeed, it is quite likely that the extent of the response is (at least partly) determined by other factors, which is as stating that the present hypothesis of no synergism is the product of some wishful thinking. Then, extrapolation of the present CO<sub>2</sub> curve outside the range for which it was derived (100-1100 vpm) was considered unwarranted. It was postulated, therefore, that the resistance does not increase further for concentrations above the 1100 vpm, as it was indeed observed by Meidner and Mansfield (1968). This assumption, moreover, renders the trend of the  $\bar{r}_i$  (CO<sub>2</sub>) curve quite similar to the one displayed in fig. 2.12c.

As far as the effect of vapour pressure difference is concerned, it should be noted that there is practically no difference between the curves resulting from the day and nighttime data. The one for daytime data was thought to be more reliable, given the wider range of the observed vapour pressure differences. The increase of the internal resistance for a growing vapour pressure difference has probably two concurrent causes. On the one hand, stomata have been observed to close in reaction to exposure to a flow of drier air (Lange et al., 1971). On the other hand, on the basis of a rationale analogous to the one developed above, it could be argued that, if an increase of the rate of release of vapour from the phase interface is not balanced by a larger apportion of water to it, the phase interface has to recede, which is observed as an increase of the internal resistance. It cannot go unnoticed, however, that the relationship observed here between the canopy internal resistance and the vapour pressure difference is stronger than inferred from a review recently published by Choudhury and Monteith (1986). In fact, part of the problem may be caused by the heterogeneity of the quantities measured under the label 'leaf resistance': it is obvious that stomatal opening has to be a weaker function of vapour pressure difference than the internal resistance. Indeed, estimates by Dormans (1983) of the canopy internal resistance, based on an experimental technique analogous to the present one, seem also to suggest a strong influence of the vapour pressure difference. There may be other reasons for the present result, however. Löscher and Tenhunen (1981) showed, by observing stomatal aperture, that the closing in response to the vapour pressure difference was more pronounced for lower temperatures and larger CO<sub>2</sub> concentrations (their experiments were performed in the range 12 to 30°C and 0 to 400 vpm). This finding is a confutation of the assumption of 'no synergism' among the various factors, in the

first place. Indeed, it was found here too, that the extrapolation of  $\tilde{r}_i(e_o - e_a)$  above 0.8 kPa could lead to the overestimation of the total resistance. Accordingly, albeit arbitrarily, for vapour pressure differences larger than 0.8 kPa, it was assumed that  $\tilde{r}_i(e_o - e_a)$  does not enlarge any longer. Takakura et al. (1975) did propose a model for the internal resistance which does not need the assumption of no synergism. An equivalent to their method would be here to multiply  $r_{min}$  only by the largest of the various  $\tilde{r}_i$ , each time. Such a procedure, however, was not suitable for the optimization of the parameters, hence it was not considered. It is obvious that the application of Takakura's method now would not be warranted.

As previously mentioned, some modifications have been apported to the parameters as reported in tab. 3.3. It is worthwhile, therefore, reviewing the resulting equation for the canopy internal resistance:

$$r_i = 82.0 \cdot \frac{I_s + 4.30}{I_s + 0.54} (1 + 2.3 \cdot 10^{-2} (T_o - 24.5)^2) \cdot \tilde{r}_i(\text{CO}_2) \cdot \tilde{r}_i(e_o - e_a) \quad \text{s} \cdot \text{m}^{-1} \quad (3.51)$$

The functions  $\tilde{r}_i(\text{CO}_2)$  and  $\tilde{r}_i(e_o - e_a)$  are given, respectively, by:

$$\begin{aligned} \tilde{r}_i(\text{CO}_2) &= 1 & I_s &= 0 \text{ W} \cdot \text{m}^{-2} \\ &= 1 + 6.1 \cdot 10^{-7} (\text{CO}_2 - 200)^2 & \text{CO}_2 &< 1100 \text{ vpm} \\ &= 1.5 & \text{CO}_2 &\geq 1100 \text{ vpm} \end{aligned} \quad - \quad (3.52)$$

and

$$\begin{aligned} \tilde{r}_i(e_o - e_a) &= 1 + 4.3 \cdot (e_o - e_a)^2 & e_o - e_a &< 0.8 \text{ kPa} \\ &= 3.8 & e_o - e_a &\geq 0.8 \text{ kPa} \end{aligned} \quad - \quad (3.53)$$

In fig. 3.15 the daily course of the canopy internal resistance, thus calculated, is displayed together with the observed one, for three consecutive spring days. In general it may be said that the model reproduces quite well the large variations of the canopy internal resistance. The model is of comparable predictive value when applied to the other experimental runs (the multiple correlation coefficient,  $r^2$ , was between 0.51 and 0.84). Therefore, without attempting to deny that there is room for improvement, it is now time to check if all the parts, dealt with up to now, can at all be combined to give a consistent picture.

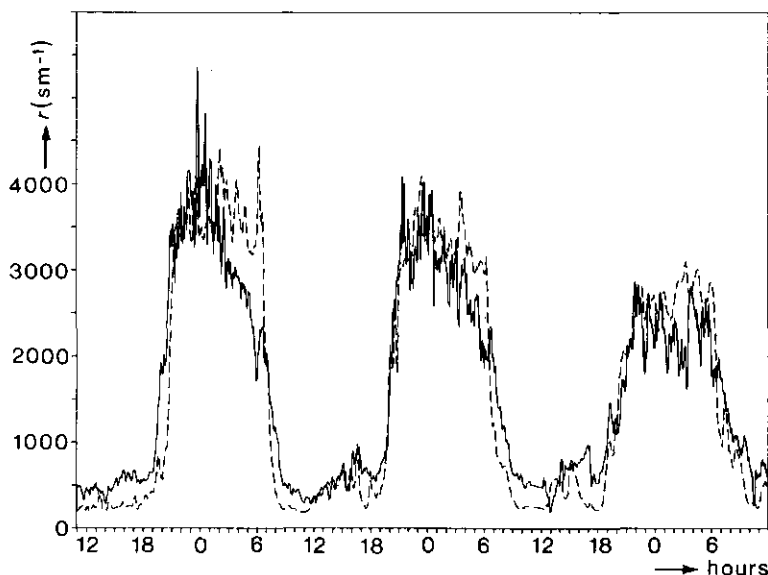


Fig. 3.15. Time course of the measured (—) and calculated (---) internal resistance for three days in the periode 1 to 4 May, 1985.

### 3.6 Temperature and transpiration of a greenhouse canopy

In the first section of this chapter it has been shown that, with a good deal of abstraction, it is possible to determine transpiration and temperature of a canopy through analytical equations quite similar to the ones derived – in chapter 2 – for a single leaf. The consequence of the abstraction has been that the entities for which the names of net radiation, internal and external resistance have been preserved, are not any longer the embodiment of familiar concepts, as they were for a wet flat plate. In § 3.2 and 3.5 models for the net radiation of a greenhouse canopy and its internal resistance, respectively, have been developed by applying semi-theoretical considerations to experimentally observed behaviours. A parametrization of the external resistance had been already developed in § 2.3, by similar means. The outcome of this modeling spree is that those abstract entities have been translated into (not necessarily transparent) functions of more straightforward (and measurable) quantities, as summarized in tab. 3.4.

However, when those functions are fitted into the equations for the transpiration and temperature of a canopy – eqs(3.4) and (3.5), respectively – the resulting equations are no longer analytical ones, i.e. they are suitable only for a numerical solution. In fact, net radiation as well as internal and external resistance have been found to be functions of (among others) the surface temperature of the canopy. This makes the transpiration rate into an explicit function of the latter. The

	$R_n$	$r_e$	$r_i$	$J$
to be known beforehand	$k_s, \rho_a, \rho_g$ $p, w, h$	$\ell$	$r_{min}, T_m$ $C_1 \dots C_5$	$\rho, c, d$
once a day	LAI			
with the same frequency of $T_o$ and LE	$I_s, T_p,$ $T_u, T_g$	$T_a, u$	$I_i, CO_2,$ $e_a$	

Table 3.4. Variables and parameters needed for the estimate of either transpiration or temperature of a greenhouse canopy, classified according to the frequency with which they have to be known, and the entities they determine.

easiest means to a numerical solution is, therefore, to determine the temperature of the canopy in the first place. This was achieved by an iterative procedure whereby the latest estimate of the canopy temperature was used to calculate the net radiation, the internal and external resistance and the thermal storage, respectively. These were then substituted into eq(3.5) to arrive at a new estimate. The iterations were stopped whenever the new estimate was within 0.001 K of the previous one; most of the time less than 50 steps were enough to get that far. Of course, if the canopy temperature is known, it may make no difference whether transpiration is calculated through eq(3.4) or eq(3.3). In the following, however, reference will be made more often to the combination equation (eq(3.4)) since it lends itself more easily to discussion, as the effect of the microclimate explicitly is taken into account there.

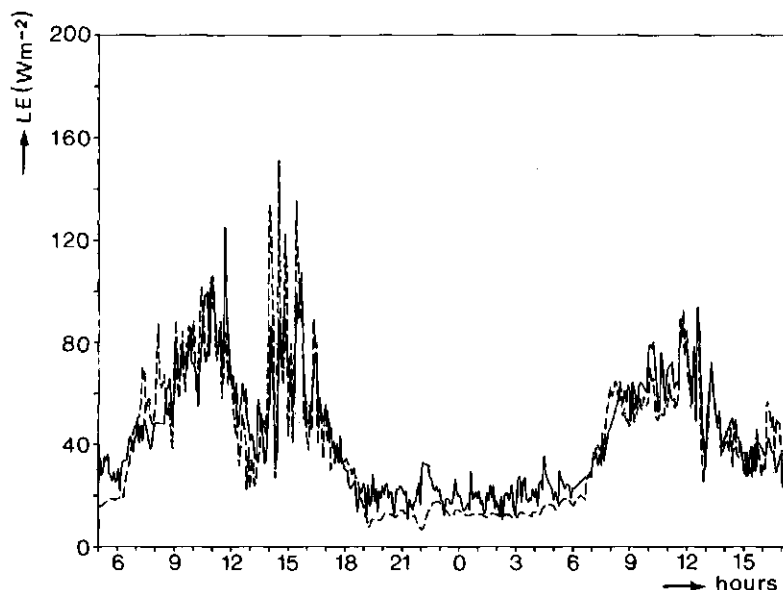


Fig. 3.16. Comparison of the time course of the measured (—) and calculated (---) transpiration (28-29 March, 1985).



In fig. 3.16 the time course of measured and estimated transpiration is shown for two consecutive spring days. Inspection of the results for other runs did show the estimate of the internal resistance to be the critical one: most deviations could be shown to be caused by a faulty assessment of the canopy internal resistance. This result was by no means unexpected, considering the observed order of magnitude of the two resistances. Hence, whereas the performance of the model is rather good (average  $r^2 = 0.79$ ), a significant improvement of its predictive ability is to be sought for through an improvement of our knowledge about the working of the internal resistance.

The ability of the present model to reproduce the 'mean' temperature of the canopy in presence of quite large variations as well, is clearly shown in fig. 3.17a.

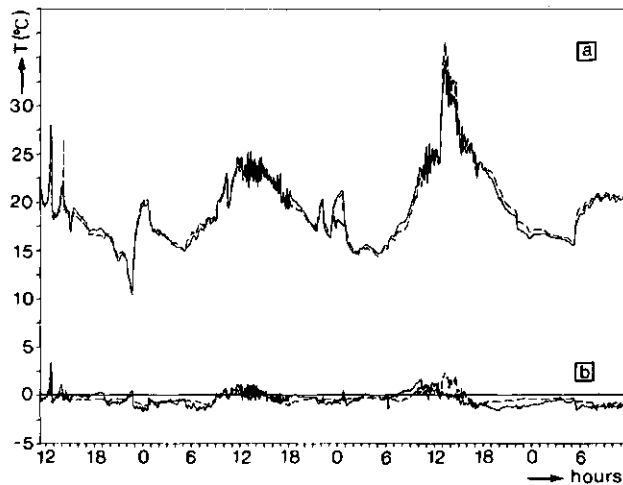


Fig. 3.17. Measured (—) and calculated (----) foliage temperature [a] and temperature excess [b] (2 to 5 April, 1985).

After reading § 3.4, however, one might wonder if all this labour did indeed deliver better estimates than the 'null hypothesis', i.e. the assumption that the mean temperature of the foliage equals the air temperature. The reader might be satisfied that a statistical test did confirm (with a confidence of more than 99%) the statement that the calculated temperature excess is a better estimate of the actual temperature excess (fig. 3.17b) than the 'null hypothesis' (shown by a straight line in fig. 3.17b). In fact, the model estimates of  $T_o$  always represented an improvement (sometimes marginal), on the already very high correlation between  $T_a$  and measured  $T_o$ . Therefore, while it cannot be denied that the ambient temperature provides an estimate of the mean canopy temperature which is accurate enough for many purposes, it has to be stressed that the model developed here is of a far better predictive value, as it accounts for the influence of many more factors.

## 4. TEMPERATURE AND TRANSPIRATION OF A GREENHOUSE CANOPY AS THE RESULT OF THE MICROCLIMATE

In this chapter the practical meaning of the relationship between the temperature and transpiration of a greenhouse crop and the microclimate to which it is exposed will be analyzed. The purpose of such an analysis is to show that, indeed, the transpiration rate of a crop may be controlled by an intelligent use of the existing greenhouse climate control systems. It will also be shown that the manipulations of the microclimate resulting from the purpose of controlling the transpiration rate could incorporate a lot of the commonly applied procedures for the (independent) control of the temperature and humidity of the ambient. From here on the term humidity will be used whenever reference is made in general to the vapour content of the ambient, without specific reference to any of the many parameters that one can use to quantify the 'humidity'.

The scope of the following section will be to assess the resulting temperature and transpiration of a greenhouse crop, as the one described in chapter 3, in response to a variation of the one or other parameter of the microclimate. The influence of the microclimate will be analyzed following a similar path as in § 2.5. Here too the variables typical of the climate will be regarded as independent of each other. In fact, the main purpose of this section is to provide an appraisal of the relative importance of the many parameters of the microclimate in determining the transpiration rate. This approach not only provides some useful insight, but also determines which parameters have to be known with the greatest accuracy and which ones could be guessed at, as well. As a matter of fact, the complexity of the resulting models for both transpiration and temperature has the consequence that the influence of the many variables cannot be assessed any longer in a simple way by means of partial differential equations. Therefore, and in order to make the following discussion somewhat more transparent, substantial reliance will be made on drawings.

In § 4.2, on the other hand, the influence (whether meant or not) of some common measures of climate control on the transpiration rate will be discussed more comprehensively. Finally, in the last part of this chapter, it will be shown that defining the transpiration rate as the parameter to be controlled, could largely simplify (and better define) the 'golden rules' for the control of the humidity within a greenhouse.

In the remaining part of this work the crop and the parameters typical of it (i.e. the ones appearing in the first row of tab. 3.4) will be regarded as given. Of course

they could easily be determined for other crops following the methods described in this work. However, no attempt will be made hereafter to speculate about other crops, training methods or row structures.

#### **4.1 Variation of canopy temperature and transpiration with the microclimate**

Here, each one of the variables listed on the last row of tab. 3.4 will be in turn assumed to undergo a slow variation. The effect of this variation on both temperature and transpiration of the canopy will be analyzed, for some combinations of other relevant parameters. Whenever not explicitly mentioned otherwise, the climate will be characterized thus: the temperature of the cover, of the ground and of the surface of the heating system is equal to the temperature of the ambient air; the air velocity within the house is  $9 \text{ cm}\cdot\text{s}^{-1}$  and the carbon dioxide concentration of the ambient air is 800 vpm; leaf area index is  $3 \text{ m}^2\cdot\text{m}^{-2}$ . It will be assumed that the incoming shortwave radiation is measured above the house, so that for the present circumstances the actual irradiation at the top of the canopy is 67% of it.

##### *4.1.1 Influence of the shortwave irradiation*

The relationship between the transpiration rate and the temperature of a greenhouse crop with the incoming shortwave radiation for some combinations of ambient temperature and relative humidity, is shown by fig. 4.1. The discontinuity of some of the lines of fig. 4.1a (the transpiration rate) follows from the present assumption that the internal resistance does not any longer intensify, for vapour pressure differences exceeding 0.8 kPa, and therefore should not be paid too much attention. Inspection of both components of fig. 4.1, confirms indeed that both temperature and transpiration of a canopy necessarily enlarge, if the canopy is exposed to more irradiation. Obviously, a lower relative humidity always results in a larger transpiration rate, the other conditions remaining the same. Moreover, as a constant relative humidity with an increasing temperature implies a larger saturation deficit, the importance of the relative humidity expands with the ambient temperature (fig. 4.1a).

Concerning the canopy temperature (fig. 4.1b), it may be surprising that the outbreak of daylight (as at dawn or upon withdrawal of an energy screen) entails a cooling of the foliage. This is a consequence of the drastic reduction of the internal resistance upon irradiation (fig. 3.14a), which causes the cooling part of the foliage temperature equation (3.5) to increase, whereas the radiative (warming) part of the same equation expands to a minor extent. Eq(3.40) – the ‘smoothed’ equation for the temperature of the foliage – may be readily manipulated to pro-

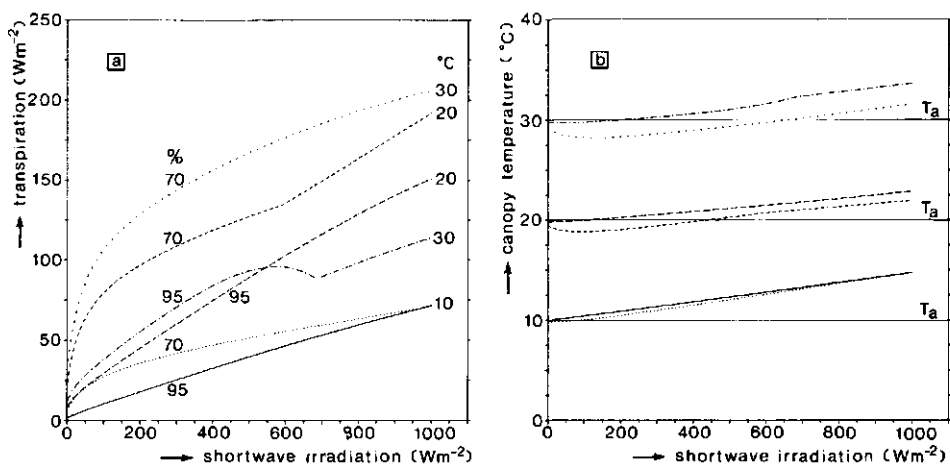


Fig. 4.1a. The transpiration rate as a function of the incoming shortwave radiation outside the house. The plots refer to three values of the ambient temperature ( $^{\circ}\text{C}$ , indicated on the right, in the Figure) and two relative humidities (% indicated on the left). Other conditions were:  $\text{LAI} = 3$ ;  $\text{CO}_2 = 800$  vpm;  $T_a = T_p = T_g = T_s$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ .

Fig. 4.1b. The temperature of the canopy as a function of the incoming shortwave radiation outside the house. Line types refer to the combinations of ambient temperature and relative humidity as indicated in Fig. 4.1a, the other conditions also being the same.

vide examples of this feature. In practice, this effect is counteracted by the use of executing the shift from the nighttime temperature set-point to its daytime value well before dawn. As it will be shown by fig. 4.3a (though it might also be deduced from fig. 4.1a), an increase of the ambient temperature at dark has no important effect on the transpiration rate. It results, however, in a much steeper increase of the latter as soon as radiation becomes available.

#### 4.1.2 Influence of the saturation deficit of the ambient air

The undisputed fact that the internal resistance of a canopy enlarges with the vapour pressure difference between the foliage and the ambient air, means that the dependence of both temperature and transpiration on the saturation deficit of the air cannot be as straightforward as it could be inferred from eqs(3.4) and (3.5), respectively. Choudhury and Monteith (1986) postulated that canopy transpiration could even decrease for the saturation deficit of the air exceeding a value that maximizes the transpiration. As far as the present writer is aware of, however, no experimental finding has been published which supports this hypothesis in an unambiguous way. Indeed, the latter is warranted only by the choice of representing  $\bar{r}_i (e_o - e_a)$  as a second grade polynomial. The present model (a parabola) would also suggest this conclusion (fig. 4.2a), were it not for the assumption that beyond a certain threshold the vapour pressure difference does not affect the internal resistance. It is clear that this point needs a lot more investigation before a conclusion about the actual trend of the transpiration rate in respect to the saturation

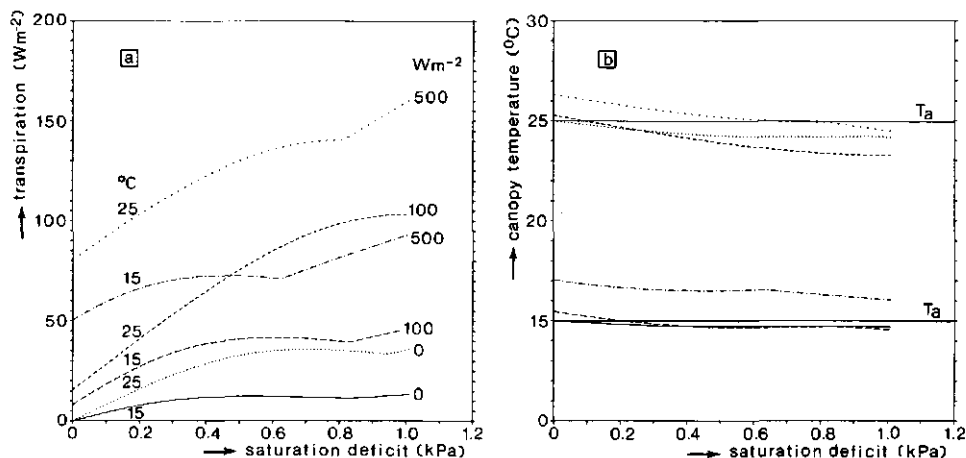


Fig. 4.2a. The transpiration rate as a function of the saturation deficit of the ambient. The plots refer to three values of the incoming shortwave radiation outside the house ( $\text{W}\cdot\text{m}^{-2}$ , indicated on the right, in the Figure) and two air temperatures ( $^{\circ}\text{C}$ , indicated on the left). Other conditions were:  $\text{LAI} = 3$ ;  $\text{CO}_2 = 800 \text{ vpm}$ ;  $T_u = T_p = T_g = T_a$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ .

Fig. 4.2b. The temperature of the canopy as a function of the saturation deficit of the ambient. Line types refer to the combinations of incoming shortwave radiation outside the house and ambient temperature as indicated in Fig. 4.2a, the other conditions also being the same.

deficit is allowed. It is beyond doubt, however, that both the transpiration and the temperature of a canopy (fig. 4.2b) are weaker functions of the ambient saturation deficit than the straight lines one could deduce from the corresponding equations alone. For instance, the consequence of de-humidification (increase of the saturation deficit without affecting the ambient temperature) could be inferred from fig. 4.2a. It is worthwhile pointing out that de-humidification is most efficient for almost saturated air, whereas an increase of the saturation deficit beyond say  $0.3 \text{ kPa}$ , is unlikely to affect the transpiration rate sensibly, certainly not in the dark and not in a rather cool ambient, say  $15^{\circ}\text{C}$ .

#### 4.1.3 Influence of the air temperature

An increase of the temperature of the air always makes more energy available at the surface, as it was observed in § 2.5.3, and it could be deduced from eq(3.35). The foliage, therefore, adapts to a new equilibrium temperature, dictated by its ability to release energy in the form of radiation or latent heat. Release of radiation is limited, in the present representation, by the device of letting the temperature of the cover, of the soil surface and of the pipe system follow the air temperature. Thus one might well expect the transpiration rate to pick up as the ambient gets warmer. Hence the effect of the ambient temperature on the transpiration rate of a canopy, as reproduced in fig. 4.3a might be somewhat surprising. In fact, the sharp decline in the transpiration rate for air temperatures exceeding a certain

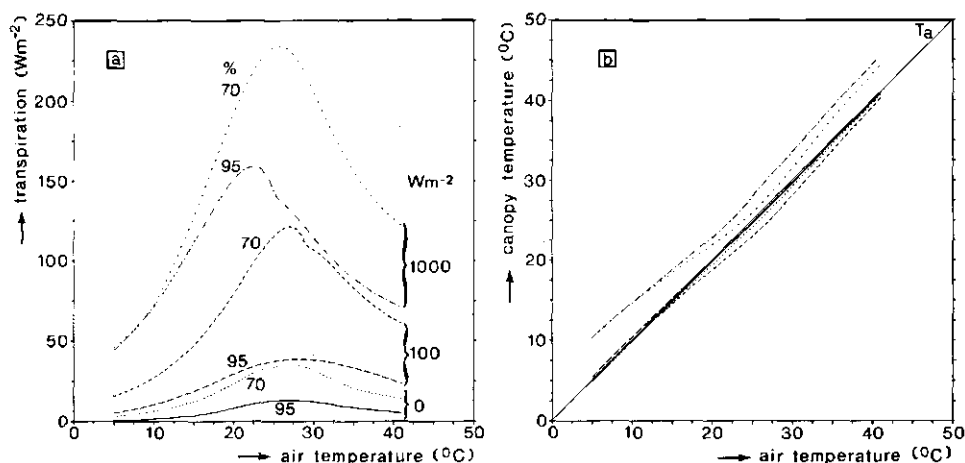


Fig. 4.3a. The transpiration rate as a function of the temperature of the ambient. The plots refer to three values of the incoming shortwave radiation outside the house ( $\text{W}\cdot\text{m}^{-2}$ , indicated on the right, in the Figure) and two relative humidities (% , indicated on the left). Other conditions were:  $\text{LAI} = 3$ ;  $\text{CO}_2 = 800 \text{ vpm}$ ;  $T_a = T_p = T_g = T_s$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ .

Fig. 4.3b. The temperature of the canopy as a function of the temperature of the ambient. Line types refer to the combinations of incoming shortwave radiation outside the house and relative humidity as indicated in Fig. 4.3a, also the other conditions being the same.

value – dependent on the conditions – is solely due to the observed increase of the canopy internal resistance at higher temperatures (fig. 3.14). This effect was credited to (partial) stomatal closure in response to stress (§ 3.5.2). It is worthwhile pointing out the fact that a similar figure, drawn for a constant apparent radiation temperature of the ambient was only marginally different.

The effective temperature of the canopy is shown by fig. 4.3b to be quite tightly coupled to the ambient temperature in most conditions, as it was predicted in § 3.4.2. Strong irradiation is shown to contribute most significantly to the temperature excess for extreme ambient temperatures. On the other hand, the relative humidity of the air plays a significant role, though only in the temperate zone. Choudhury (1983) could draw a quite similar conclusion ('among weather variables the air vapour pressure deficit appears to be the most important factor affecting the temperature excess of unstressed canopies') from his model of a corn canopy. It was already pointed out (§ 3.4.2) that the manipulation of the temperature of the ambient is the most straightforward means to influence the temperature of a greenhouse canopy. As a matter of fact, as the relationship shown by fig. 4.3a is most skewed in the range of temperatures typical of greenhouse management, manipulation of the ambient temperature may be also potentially relevant in the control of the vapour production of a greenhouse canopy, as it will be discussed at some length in § 4.3.

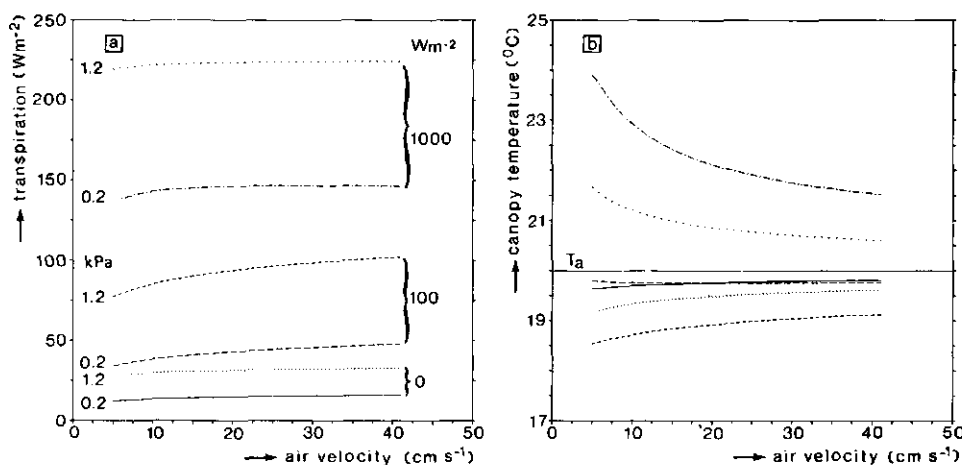


Fig. 4.4a. The transpiration rate as a function of the air velocity. The plots refer to three values of the incoming shortwave radiation outside the house ( $\text{W}\cdot\text{m}^{-2}$ , indicated on the right, in the Figure) and two saturation deficits of the ambient (kPa, indicated on the left). Other conditions were:  $\text{LAI} = 3$ ;  $\text{CO}_2 = 800 \text{ vpm}$ ;  $T_u = T_p = T_g = T_a = 20^{\circ}\text{C}$ .

Fig. 4.4b. The temperature of the canopy as a function of the air velocity. Line types refer to the combinations of incoming shortwave radiation outside the house and saturation deficit as indicated in Fig. 4.4a, the other conditions also being the same.

#### 4.1.4 Influence of the air velocity

As the canopy is assumed to consist of a uniform layer immersed in a uniform environment, in the present representation the air velocity influences only the external resistance of the canopy and not the distribution of temperature and humidity (possible, in a real greenhouse). Therefore, one can draw much from the discussion about the relationship between the external resistance and the temperature and transpiration of a single leaf (§ 2.5.4). The most important conclusion of that discussion was that neither the surface temperature, nor the transpiration could be expected to be strongly affected by the external resistance. Nor could they be by the air velocity, since there is, at most, a square root relationship between the former and the latter (eq(2.53)). Moreover, it was observed that an expansion of the external resistance could have opposing results for different microclimatic conditions. In fact, fig. 4.4a displays an example of the possibility that the transpiration rate is even (slightly) depressed by an increase of the air movement. The most important observation about fig. 4.4a, however, is that using a fan in order to stimulate the transpiration rate is unlikely to be worth the energy it consumes (although it could stimulate the transpiration rate by redistributing the vapour content in a possibly non uniform environment; Anonymous, 1987).

The relationship between the air movement and the temperature of the foliage (shown in fig. 4.4b) does not come as a surprise either, after considering the discussion of § 2.5.4. The other unexpected result of that discussion, namely that the temperature of the foliage could also be a non-monotonous function of the exter-

nal resistance, is represented in that figure as well, though not obviously. In fact, as it was shown in § 2.5.4, the temperature of the foliage has to approach the ambient temperature for very large wind speeds (negligible external resistance). The long-dashed line of fig. 4.4b, is therefore bound to invert its trend somewhere. Besides this more curious than important feature, fig. 4.4b seems to suggest that a fan could sensibly be used as a cooling device, in the presence of relevant temperature excesses and little air movement, without affecting much the water consumption of the crop (fig. 4.4a).

#### 4.1.5 Influence of the surface temperature of the heating system

It has been shown (§ 3.4.2) that the paramount effect of supplying energy by a warm-water-pipe system as the one dealt with here, is an indirect supply of sensible heat to the canopy. There may be other effects as well: stirring of the air (Stanghellini, 1983c and 1983d) and, of course, direct supply of radiation to the foliage. Only the last effect will be dealt with here, since the other two have been analyzed, although indirectly, in § 4.1.3 and 4.1.4, respectively. This section is, therefore, concerned with the rather unlikely scenario of a heating system releasing radiation only.

It should be stated beforehand that the outcome of the model on this point is largely dependent on the heating system dealt with and on its representation. There is plenty of room for discussion on the latter. In fact, in order to preserve

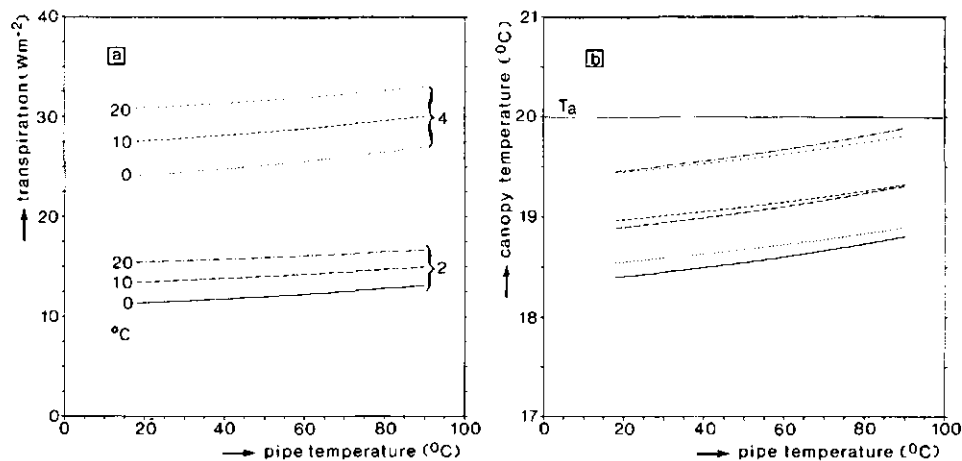


Fig. 4.5a. The transpiration rate as a function of the surface temperature of the heating pipes. The plots refer to three values of the temperature of the cover (°C, indicated on the left, in the Figure) and two leaf area indexes (indicated on the right). Other conditions were:  $I_s = 0 \text{ W·m}^{-2}$ ;  $T_g = T_a = 20^\circ\text{C}$ ;  $u = 9 \text{ cm·s}^{-1}$ ;  $e_a^* - e_a = 0.5 \text{ kPa}$ .

Fig. 4.5b. The temperature of the canopy as a function of the surface temperature of the heating pipes. Line types refer to the combinations of cover temperature and leaf area index as indicated in Fig. 4.5a, the other conditions also being the same.



the hypothesis of horizontal homogeneity, the ability to produce thermal radiation which may be intercepted by the canopy has been allocated, for the lower hemisphere, to the soil surface and the pipe system. The fraction allocated to each one is proportional to the projection of its area on the ideal horizontal lower surface of the canopy (in the present greenhouse it was 7% for the heating system and 93% for the soil surface). It is no wonder, therefore, that the canopy is not warmed much by the radiation it receives from the pipes (fig. 4.5b), and it is unlikely to produce a lot of vapour as a consequence of this (fig. 4.5a). In fact, even if one accepts the rule of thumb stating that a conventional heating system delivers half of its energy as radiation and half as sensible heat, it has to be realized that whereas the resistances of the canopy to the exchange of radiation and sensible heat are about equal (tab. 2.1 and fig. 2.10, respectively), there is more than a factor three between the exchange area of the two fluxes (tab. 3.2 and eq(3.2), respectively). It is then acknowledged that a different representation of the system could lead to a somewhat different slope of the lines displayed in figs. 4.5; it would not, however, change the present conclusion that the radiation it receives from the heating system is a minor fraction of the energy available to a greenhouse canopy. Hence one might wonder that, as far as the canopy is concerned, there is not much of a difference between a conventional, warm-water-pipes heating system and a warm air one.

From both figs. 4.5 (calculated for two values of LAI) one may deduce, furthermore, the extent to which it is accurate to state, as was done in 3.4.2, that the foliage temperature is (almost) independent of the leaf area, whereas the transpiration rate is (almost) proportional to it.

#### *4.1.6 Influence of the temperature of the cover and of the soil surface*

The two temperatures will be dealt with together, in this section, because as eq(3.14) attests, they appear in (almost) symmetric form in the model. The only difference is the (small) amount of radiation which is intercepted by the heating pipes lying between the soil and the canopy. As it has been discussed at some length here above, it is unlikely that this will make much of a difference. Only the radiative effect of a variation of the temperature of the cover or of the soil surface is analyzed, without considering the inevitable effect it would have on the temperature and humidity content of the air. The effect, as predicted by the present model (figs. 4.6), is more pronounced as the one of the temperature of the heating system, though not extreme. The application of an energy screen at night appears to let the foliage temperature grow by about half a degree for each ten degrees increase of the apparent cover temperature (fig. 4.6b). As that would also be the effect of floor heating, the latter is not necessarily a less efficient heating system than conventional ones. Observe that by accounting for only its radiative effect, the other likely consequences of the application of a screen (or of floor heating),

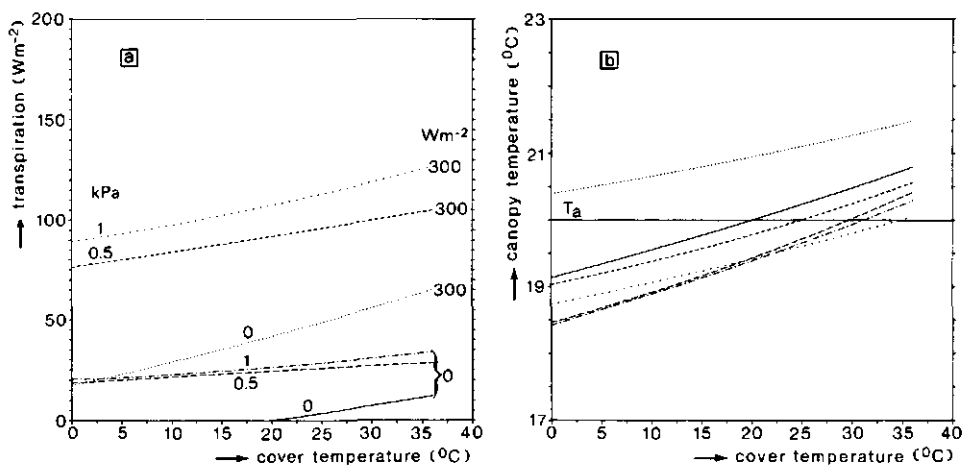


Fig. 4.6a. The transpiration rate as a function of the temperature of the cover. The plots refer to two values of the incoming shortwave radiation outside the house ( $\text{W}\cdot\text{m}^{-2}$ , indicated on the right, in the Figure) and three saturation deficits of the ambient (kPa, indicated on the left). Other conditions were:  $\text{LAI} = 3$ ;  $\text{CO}_2 = 800 \text{ vpm}$ ;  $T_p = T_g = T_a = 20^\circ\text{C}$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ .

Fig. 4.6b. The temperature of the canopy as a function of the temperature of the cover. Line types refer to the combinations of incoming shortwave radiation outside the house and saturation deficit of the ambient as indicated in Fig. 4.6a, the other conditions also being the same.

namely a lower temperature of the heating system and a smaller saturation deficit of the ambient have been neglected. The two last mentioned, however, would have opposite effects on the foliage temperature. Hence for a rough estimate as this one, those effects might be assumed to offset each other.

It is worthwhile observing, on the other hand, that the application of such an energy screen scarcely affects the transpiration rate whenever the ambient is not saturated (fig. 4.6a). Even the likely reduction of the saturation deficit does not appear to play a relevant role, and certainly not in the dark.

#### 4.1.7 Influence of the carbon dioxide concentration of the ambient air

The scope for the manipulation of either the transpiration or temperature of a greenhouse canopy through carbon dioxide enrichment appears to be limited (figs. 4.7a and 4.7b, respectively). In fact, the only possible influence the carbon dioxide concentration of the ambient would have on the transpiration rate could be exercised through a modification of the internal resistance. It was shown (in § 2.5.4 and 2.5.5, respectively) that a modification of either the external or the internal resistance would appear dampened in the transpiration rate. Indeed, it was no surprise to unearth (§ 4.1.4) that variations of the air movement (affecting only the external resistance) can seldom change the transpiration rate in a detectable way. From this point of view, the present observation that the transpiration rate is rather insensitive to the carbon dioxide concentration could be understood. This conclusion, albeit to a minor extent, is also a result of the (unexpectedly)

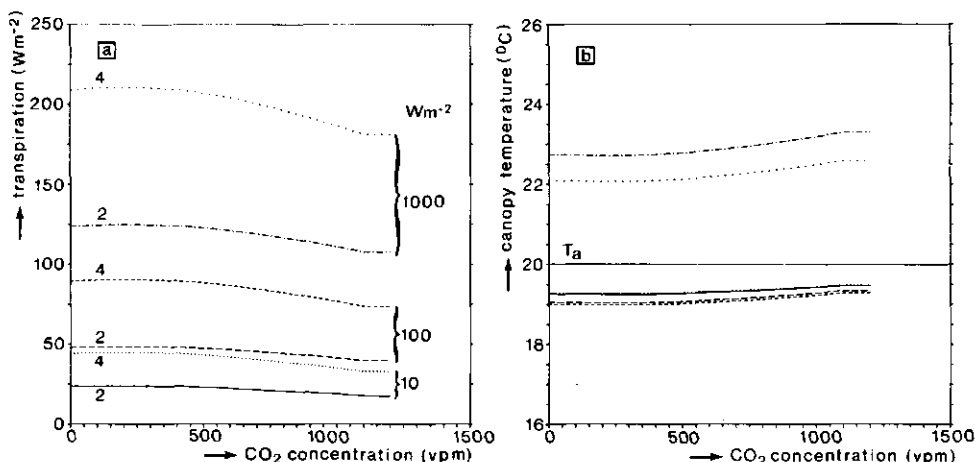


Fig. 4.7a. The transpiration rate as a function of the carbon dioxide concentration of the ambient. The plots refer to three values of the incoming shortwave radiation outside the house ( $W \cdot m^{-2}$ , indicated on the right, in the Figure) and two leaf area indexes (indicated on the left). Other conditions were:  $T_u = T_p = T_g = T_a = 20^{\circ}C$ ;  $u = 9 \text{ cm} \cdot \text{s}^{-1}$ ;  $e_a^* - e_a = 0.5 \text{ kPa}$ .

Fig. 4.7b. The temperature of the canopy as a function of the carbon dioxide concentration of the ambient. Line types refer to the combinations of incoming shortwave radiation outside the house and leaf area index as indicated in Fig. 4.7a, the other conditions also being the same.

weak relationship between the carbon dioxide concentration of the ambient and the internal resistance which has been observed here.

#### 4.1.8 Conclusion

A windfall of this discussion is that, as far as one is only interested in a reasonable estimate of the temperature and transpiration of a greenhouse crop, the eight parameters which have to be continuously monitored, as indicated in the last row of tab. 3.4, might be safely reduced to six. In fact, both the measurements of air velocity and of ambient carbon dioxide concentration could be substituted by reasonable estimates, without much loss of accuracy. The (weaker) hint that the knowledge of the temperature of the heating system might be unnecessary as well, has little advantage since in most modern greenhouses that temperature is measured anyway. Therefore, if it is considered that shortwave irradiation, temperature and humidity content of the air and temperature of the heating system are routinely monitored, wherever a climate control system is installed, the monitoring of only two other parameters is needed for the application of this model. These parameters are the temperature of the soil surface and that of the greenhouse cover. A strong argument can be made for the simulation of the former on the basis of the temperature of the air inside the house and of the thermal properties of the soil (Bot, 1983). On the other hand, there is much less scope for the simulation of the cover temperature, since – besides the knowledge of parameters

never exactly known – monitoring of the apparent temperature of the sky is then needed (Bot, 1983) which is no easier (nor cheaper) than the direct measurement of the cover temperature. However, some efforts should be devoted to the improvement of the present technique, as the reliability of a thermocouple exposed to sunlight is questionable.

The practical application of the model developed here demands the knowledge of a number of parameters typical of the crop one is dealing with. They could be supplied, for the most important greenhouse crops, by further research, for which the methods described here may form a blue-print. Furthermore, the observation that the transpiration rate per unit ground area is (almost) proportional to the leaf area index (in the present LAI range), implies that the transpiration rate of a unit leaf area is (almost) independent from the LAI. Therefore, whether or not daily gaugings of the leaf area are needed, is dependent on which application one requires for the appraisal of the transpiration rate. For instance: irrigation scheduling, ascertainment of the energy consumption of a greenhouse or adjusting the capacity of a de-humidifier all imply the knowledge of the transpiration rate per unit ground area, i.e. of the leaf area. On the other hand, whenever the transpiration is meant to be a plant process to be manipulated through the microclimate (as it will be suggested in the next section), one could be satisfied with the transpiration per unit leaf area as well, and no (cumbersome) gauging of the leaf area would then be necessary.

## **4.2 Transpiration: a re-appraisal of current procedures of climate management**

The research on the production of agricultural crops has since long shown that plant growth is clearly influenced by climate factors such as temperature, radiation, humidity, wind speed and CO<sub>2</sub> concentration. If there is an adequate supply of water and nutrients and if damaging factors as pests, diseases or weeds are absent then, for an optimal combination of the climate factors, the 'potential rate of growth' for a given crop may be achieved. When one or more of the climate factors limit the growth, at best only the 'maximum growth rate' for those conditions might be realized.

The whole business of greenhouse horticulture is ensuring the optimal combination of the climate parameters for the potential production of a given crop. It is clear however, that a marginal increase in the growth rate should not be paid for by a large increase in the consumption of (supplied) energy. Most current procedures of manipulation of the environmental conditions of greenhouse crops are an acknowledgement of this fact, and a lot of the research on crop production has found its most obvious application in advanced horticulture in greenhouses.

Systems for the automatic manipulation of the greenhouse climate are widely used in the Dutch horticultural industry and systems of increasing complexity find their way into the market. The temperature within the house (ambient) is somehow controlled in practically all greenhouses in The Netherlands, whereas almost all systems do apply some form of control of the ambient humidity. The drain of energy is reduced by the application of energy screens (especially at nighttime), and the supply of radiation is regulated by the use of either artificial irradiation or shading screens. Addition of carbon dioxide to the ambient is a widespread practice. Some growers have installed fans in order to stimulate the exchange of heat and mass between the canopy and the ambient and to ensure a better homogeneity of the ambient. However, 'lack of detailed knowledge of the processes determining the growth of these crops limits the fine-tuning which is technically possible' (Rabbinge, 1986).

Transpiration is indeed known to be one of the processes correlated to growth and there may be several reasons for this relationship. In fact, the microclimate factors known to affect uptake of carbon dioxide are largely the same as the ones shown to determine transpiration. Moreover, the efforts devoted to the research about the measure and the interpretation of the stem flow (e.g. Van Meurs and Gieling, 1981) attest that the connection among transpiration, water uptake and growth is perceived as relevant.

However, the existence on a longer term of a relationship between production and transpiration, does not mean that good greenhouse management would be maximization of transpiration at every instant. It is well known for instance, that during a bright day following a long period of gloomy weather, one should reduce the evaporative demand of the ambient in order to avoid the risk of stress for the crop (Van Onna, 1985). There are also conditions (especially at nighttime) when it would be desirable to increase the transpiration rate. One would like, however, to keep it short of rates which would indeed represent a spilling of energy. Moreover, it is acknowledged that large, sudden variations of the transpiration rate may negatively affect the growth of the crop. It is clear, therefore, that influencing the transpiration rate could be quite often the (implicit) target of the manipulation of the microclimate. The nomograms of § 4.1 have an obvious application here: they allow the quantification of the necessary variation of a parameter in order to bring about a required variation of the transpiration rate. In order to show how one could make use of the present work to improve the quality of the manipulation of the climate, with respect to the transpiration rate, the most common climate control procedures will be reviewed hereafter and some comments will be given. In § 4.3 some examples, and how this work could be applied, will be analyzed in more detail.

#### *4.2.1 Manipulation of the ambient temperature*

The control of the ambient temperature is usually performed with the aim of

keeping it as near as possible to one, prefixed value: the set-point of heating (i.e. if the temperature falls short of that value, heating has to be provided). Normally the ambient temperature is allowed to exceed that value by a few degrees, before some form of cooling is applied; the value of the temperature for which this happens is called the set-point of ventilation. The width of the temperature band where no action is performed (i.e. the difference in degrees between the two mentioned set-points) is set beforehand, though it may be allowed to vary, in some conditions. Most commonly, two values may be introduced for the set-point of heating depending on whether it is night or day.

In the daytime, moreover, the heating set-point may be increased further, if the available shortwave radiation exceeds a threshold value. This latter proviso is a translation of the requirement that the temperature should not limit the growth whenever there is adequate supply of radiation. More recent research, however, suggests that, though the assimilation is largely affected by the temperature, light and heat need not necessarily be supplied at the same time (Klapwijk, 1987).

#### *4.2.2 Manipulation of the humidity of the ambient*

The purpose of the humidity control is manifold. Generally, every attempt is made in order to avoid condensation on parts of the crop, as most people do not enjoy working in a wet canopy. Fruits should be dry when picked, moreover, and plant diseases are known to thrive in condensation. The purpose of somehow manipulating the transpiration rate is also acknowledged (it should never become too small nor, in some conditions, too large; Rovers, 1985).

It is customary that the saturation deficit of the ambient is kept above a threshold value which is normally a two-value function (day and night). Since a de-humidifier is seldom available, the control of humidity has to take place through some combination of heating and ventilation. If the ambient temperature exceeds the set-point of heating, then ventilation alone may be sufficient to reduce the vapour content of the ambient, if the air outside has a lower humidity content. Heating may otherwise have to be provided whilst ventilating (Zandbelt, 1984).

The most commonly applied procedure is to avoid the heating system getting cooler than a 'minimum' value of 'pipe temperature' whatever the ambient temperature may be; hence a new set-point for the ambient temperature is unknowingly defined. It is commonly suggested that the use of the 'minimum pipe temperature' has other useful consequences, namely: to increase both the thermal radiation available to the canopy and the air movement within it. The analysis of § 4.1.4 and 4.1.5 should have made clear that the usefulness of those consequences is not that obvious.

Another procedure often used for reducing the humidity of the ambient is 'droogstoken', i.e. to supply heating for some time, forcing the ambient temperature above the ventilation set-point – raised for this purpose.

Nevertheless, these procedures scarcely result in a permanent decrease of the

vapour content of the ambient air, because of the resulting higher rates of transpiration (Matthews and Saffell, 1986). One could wonder, therefore, whether it makes any sense establishing beforehand which saturation deficit ought to be attained. Indeed, the requirement that the humidity content aimed at should be (automatically) chosen in function of the actual microclimate (Goeijenbier, 1985) reveals a certain awareness that the transpiration rate has no simple relationship with the ambient humidity. It is worthwhile pointing out here that the ambient humidity is used as a parameter (in whatever form) in order to decide about the application of measures which, most commonly, only indirectly affect the humidity. It is the firm conviction of the present writer, therefore, that the transpiration rate would be no worse a parameter on which to base the decisions about the manipulation of the microclimate. Indeed, it would be a much more direct (and effective) way of achieving the desired adaptation of the set-points. Showing that and how this suggestion could be applied in practice is the object of § 4.3.

#### *4.2.3 Manipulation of the shortwave irradiation of a canopy*

The most usual means of affecting the irradiation of a greenhouse canopy is by either switching on an artificial irradiation system or by applying a shading screen. Irradiation systems normally supply an irradiation which is comparable with a shortwave radiation outside the house of less than  $50 \text{ W} \cdot \text{m}^{-2}$ . It has already been pointed out that for each combination of irradiation and humidity there is an ambient temperature which maximizes the transpiration (fig. 4.3a). One might then wonder, that in this case it could be most appropriate to try to make the best of the little irradiation by choosing the optimum transpiration as a criterion. A way of achieving this would be to adapt the set-points of the ambient temperature accordingly, as will be shown in § 4.3.2.

On the other hand, a shading screen is often used when the shortwave irradiation exceeds a threshold value. This is in order to avoid the canopy becoming too warm or, as mentioned, the transpiration rate becoming too large. It could be suggested that raising the ambient humidity could achieve the purpose of limiting the transpiration rate as well. It may be inferred (from figs. 4.2b and 4.3b) that this would not dramatically increase the temperature of the canopy.

#### *4.2.4 Manipulation of the exitance of a canopy*

The use of an energy screen increases the apparent temperature of the greenhouse cover, thereby reducing the longwave radiation emitted by the canopy. This effect results always in a higher temperature (fig. 4.6b) and would induce a larger transpiration rate of the canopy (fig. 4.6a). Nevertheless, the application of such a screen should be expected to reduce the saturation deficit of the ambient, since a lot of the vapour which would otherwise condense on the cover is no longer disposed of. Hence most climate control programs provide for an incomplete closure of the screen cover, the extent of which is determined according to

the ambient humidity. This practice, however, largely reduces the amount of energy actually saved, due to the convective losses (Vegter, 1983).

In fact, the increase of the apparent cover temperature and the decrease of the saturation deficit would affect the transpiration rate in opposite ways, and the net effect is not easily forecast. It has already been stated that it would be more sensible to establish the humidity aimed at in function of the actual conditions; a practical example here might stress this point. Let us assume for instance, that the application of a good energy screen increases the apparent temperature of the cover from 5 to 15°C, while the saturation deficit of the ambient (controlled at a temperature  $T_a = 20^\circ\text{C}$ ) decreases from 1 to 0.5 kPa. Then the transpiration rate should slightly expand, as it might be deduced from fig. 4.6a. One could of course find examples to the contrary just as easily. The whole point here, however, was to demonstrate that the relationship humidity-transpiration is not as trivial as it is generally regarded to be, and hence the safest way to manipulate the transpiration rate is to set up to manipulate the parameter 'transpiration rate'.

#### *4.2.5 Other manipulations of the microclimate*

Addition of carbon dioxide to the ambient has been mentioned above as a widely available manipulation of the microclimate as well as the use of fans for the circulation of air. Both systems, however, have been shown (§ 4.1.7 and 4.1.4, respectively) hardly to affect the transpiration rate. There appears to be little scope, therefore, for the use of either system for the purpose of controlling the transpiration rate. Accordingly, both the addition of carbon dioxide to the ambient and the circulation of air will not be dealt with further in the present work.

### **4.3 Examples**

Most manipulations of the microclimate can be performed only indirectly. To warm up the ambient air, for example, the temperature of the water at the inlet of the heating system is raised. This has some consequence more than the meant warming up of the air. Indeed, the surface temperature of the heating system is obviously affected; less obvious is the change of the ambient humidity; and the air movement in the house is most likely stimulated (Stanghellini, 1983d). Luckily, both the surface temperature of the heating system and the air movement within the house, have been shown (figs. 4.5a and 4.4a, respectively) scarcely to affect the transpiration rate. The intertwining of the temperature and vapour content of the ambient, however, cannot be wished away. Therefore, the mutual influence of the temperature and humidity manipulations will have to be accounted for, albeit qualitatively.

In the following, the relative humidity will be used more often than saturation



deficit as a parameter of the vapour content of the ambient, because of the need of a unique parameter when considering a large spectrum of temperatures: a saturation deficit of 1 kPa is hardly possible at 10°C, whereas at 40°C the air would be quite moist with the same saturation deficit.

In order to go further with this discussion, it is worthwhile realizing that of all the parameters listed in tab. 3.4 as necessary for an accurate appraisal of the transpiration rate, the first group (the species-specific parameters) is considered here as given and not a subject of speculation. Furthermore, the transpiration rate has been shown to be (almost) proportional to the leaf area index (§ 3.4.3 and fig. 4.5a) hence the relative influence of the microclimate is not coupled to the leaf area. Moreover, of the eight parameters of the microclimate appearing in tab. 3.4, three (the air velocity, the ambient concentration of carbon dioxide and the

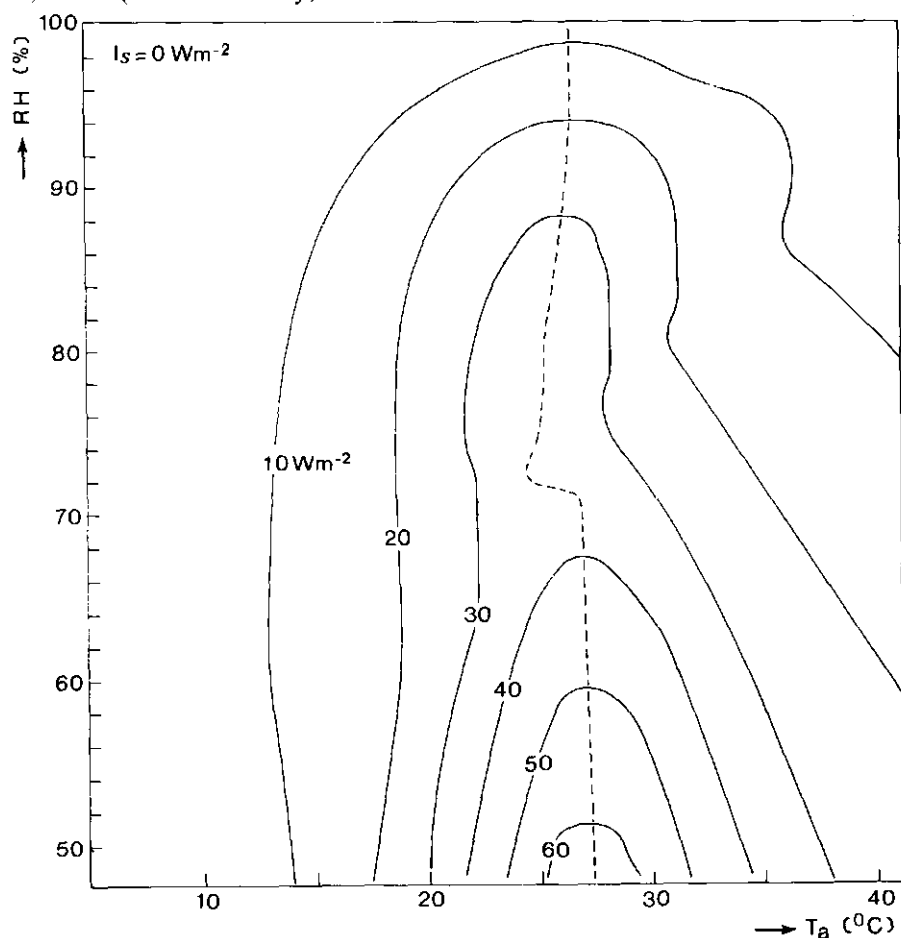


Fig.4.8. The transpiration rate ( $\text{W}\cdot\text{m}^{-2}$ ) as a function of the temperature and relative humidity of the ambient, for no incoming shortwave radiation outside the house. The other conditions were assumed to be:  $\text{LAI} = 3$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ ;  $T_u = T_p = T_g = T_a$ .

surface temperature of the heating system) have been shown to be of scarce consequence (figs. 4.4a; 4.7a and 4.5a, respectively). The relevance of two more (the apparent radiation temperature of the cover and of the soil surface) is not very large either (fig. 4.6a) and for the sake of the following discussion, the apparent radiation temperature of the ambient (cover, soil surface and pipe system) will be assumed to be equal to the temperature of the air.

The transpiration rate is thus primarily determined by the shortwave irradiation, the ambient temperature and its humidity. Accordingly, for each irradiation level, a diagram such as the one reproduced in fig. 4.8 could provide for an approximate appraisal of the actual transpiration rate. The isolines of the transpiration rate are shown there for all combinations of ambient temperature and relative humidity, for a crop as the one dealt with in this work, and a leaf area index of three. As the transpiration rate is almost proportional to LAI, an analogous diagram for another LAI might easily be deduced. On the other hand, it would not be that straightforward to deduce an analogous diagram for another crop, since both the internal and external resistance, as well as the radiation exchanges would be different.

If one imagines that the actual microclimate is represented by a point in such a diagram, then the effect of procedures affecting only the ambient temperature

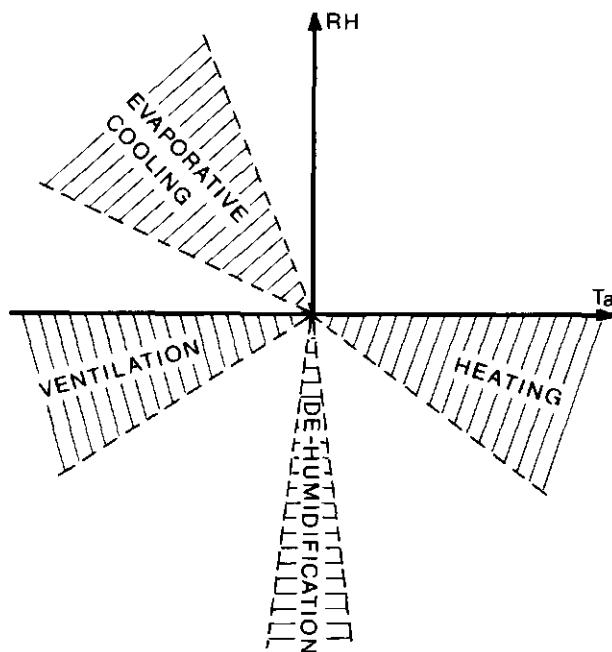


Fig. 4.9. If the present state of the microclimate is represented by the origin in this  $(T_a, RH)$  plane, then the point representing the state after a climate manipulation will be in the corresponding sector.

and its humidity would be represented by a displacement of the point representing the microclimate, in the diagram. In fig. 4.9, the simultaneous variations of  $T_a$  and RH produced by the most typical climate manipulations is suggested by the direction towards which the point representing the microclimate would move.

#### 4.3.1 *Optimal supply of heat at night*

The purpose of heating at night is, in the first place, to avoid damage to the canopy, due either to very low temperatures or to diseases related to a very high humidity. It is further acknowledged that in order to ensure a good development of the canopy at its various stages, the nighttime transpiration rate should not become too small (De Koning, 1985). One could well infer that the no-damage requirements gradually translate into the transpiration requirement since the 'good development of the canopy' is unlikely to be a step function of either the temperature or the humidity. Anyway, the current received wisdom in greenhouse management ensures that the transpiration requirement sets a much stronger constraint on the microclimate than the no-damage requirements do. Therefore, with the willingness to overlook a lot of additional factors, one might as well state that the purpose of nighttime climate manipulations is to maintain a given transpiration rate at least. Besides being species-specific, the minimal transpiration rate is likely to be dependent on the phenological stage of the crop, and on its leaf area. The fact that the climate set-points commonly applied (and deduced from a lot of biological and agricultural research) are dependent on the crop and its stage, suggests that they indeed might be translated into 'transpiration set-points'.

It is then possible to deduce from a diagram as the one shown in fig. 4.8, which combinations of ambient temperature and relative humidity are compatible with the required transpiration rate. Let us assume that one finds out that the actual microclimate entails that the transpiration rate falls short of the required level, i.e. the transpiration has to be 'stimulated'. It should be appreciated thus that the actual circumstances dictate the most efficient way to achieve this (as fig. 4.8 attests). In order to clarify this important point, let us assume, for instance, that the nighttime 'transpiration set-point' is  $15 \text{ W}\cdot\text{m}^{-2}$ . Then, from fig. 4.8, it may be deduced that it makes no sense trying to push the relative humidity below about 85%, when the ambient temperature is lower than about  $20^\circ\text{C}$ , since the transpiration rate would not pick up, anyway. Moreover, one could observe that with high relative humidities (of say more than 85%) within the house (normally related to warm nights outside), it could be worthwhile raising the heating set-point, even if this does not necessarily lower the relative humidity. Conversely, with relative humidities exceeding 95%, there is no temperature for which our hypothetical transpiration set-point could be realized. The relative humidity *has* therefore to be reduced. Ventilation will do only if the air within the house contains more vapour than the air outside does. One procedure certain to depress the relative humidity within the house anyway, is pushing the ambient temperature above the

value which maximizes the transpiration rate for those conditions. The coupling between ambient temperature and transpiration is reversed then, causing a drop of the relative humidity.

As it is quite a sensible attitude to be suspicious of models yielding results contrary to the conventional wisdom, this writer likes to point out that the humidity manipulation measures known as ‘minimum pipe temperature’ and ‘droogstoken’ have been respectively described here above. It is worthwhile stressing, however, that more has been provided here than simply a theoretical framework for procedures already applied in practice. Indeed, this work yields a yet missing (and much needed) measure for the application of those procedures.

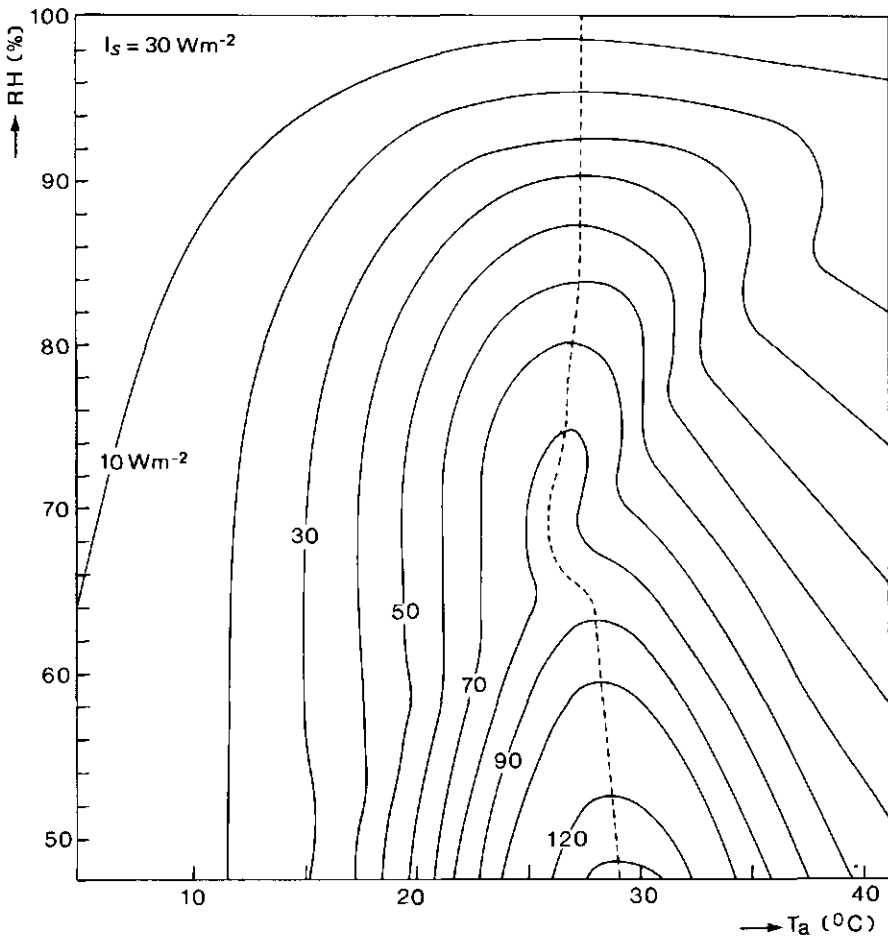


Fig.4.10. The transpiration rate ( $\text{W}\cdot\text{m}^{-2}$ ) as a function of the temperature and relative humidity of the ambient, for an incoming shortwave radiation outside the house of  $30 \text{ W}\cdot\text{m}^{-2}$ . The other conditions were:  $\text{LAI} = 3$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ ;  $\text{CO}_2 = 200 \text{ vpm}$  (i.e.  $\bar{r}_i(\text{CO}_2) = 1$ );  $T_a = T_p = T_g = T_a$ .

#### 4.3.2 Making the best out of little irradiation

It has already been suggested that with low irradiation levels, some measure may be actively sought to maximize the growth. It will be assumed – for the sake of this discussion – that this is equivalent to maximize the transpiration rate. The diagram to be used in this case is reproduced in fig. 4.10. It can be observed that, in general, it is true that the maximum attainable transpiration rate increases to the extent to which the relative humidity drops. However, it should be appreciated that it is worthwhile trying to reduce the latter only if the ambient temperature is close to the value which maximizes the transpiration rate for that humidity. This is due to the transpiration rate being almost no function of the relative humidity for ambient temperatures much smaller than that value.

Moreover, it should be noted that the diagram shown in fig. 4.10 shows a region which proves to be an ideal target for the purpose of maximizing the transpiration rate at a not-too-high cost. That region is namely the plateau with a transpiration rate of about  $80 \text{ W}\cdot\text{m}^{-2}$ , centered on  $\text{RH} = 70 (\pm 5)\%$  and  $T_a = 26 (\pm 1.5)^\circ\text{C}$ . Indeed, the transpiration rate could be pushed above  $80 \text{ W}\cdot\text{m}^{-2}$  ( $\sim 120 \text{ g}\cdot\text{m}^{-2}$  per hour) only at a very high cost: the ambient temperature should be increased much further while the relative humidity should be considerably lowered.

#### 4.3.3 Containment of the transpiration rate

The avoidance of stress, i.e. trying to ensure that the crop has always enough water available to meet the transpiration rate, is a quite important aspect of agricultural management. With respect to traditional agriculture, greenhouse horticulture has the advantage that when not enough water can be supplied (for instance with a non optimal development of the root system or, more obviously, in arid conditions) one could try to manipulate the climate in order to reduce the potential transpiration rate. One obvious way to achieve this is to apply a shading screen, as fig. 4.1a clearly shows.

In the afore-mentioned case of the outbreak of sun after a gloomy weather period, however, one might be quite unwilling to forgo a much awaited increase in the photosynthesis. One would then need to adapt the management of temperature and humidity. An example will make this point clear. Let us assume that the gloomy weather was characterized by an irradiation of  $30 \text{ W}\cdot\text{m}^{-2}$ , while temperature and relative humidity inside the house were about  $22^\circ\text{C}$  and  $80\%$ , respectively. From fig. 4.10 it may be deduced that the transpiration rate was then about  $60 \text{ W}\cdot\text{m}^{-2}$ . In fig. 4.11 the situation is given for an irradiation of, say,  $250 \text{ W}\cdot\text{m}^{-2}$ . Indeed, for the same set-points of temperature and humidity, the transpiration shoots up to about  $110 \text{ W}\cdot\text{m}^{-2}$ . If one assumes that the crop is unable to sustain that rate, then one might as well reduce the ambient temperature and let the relative humidity rise to  $T_a = 18^\circ\text{C}$  and  $\text{RH} = 85\%$ , for instance.

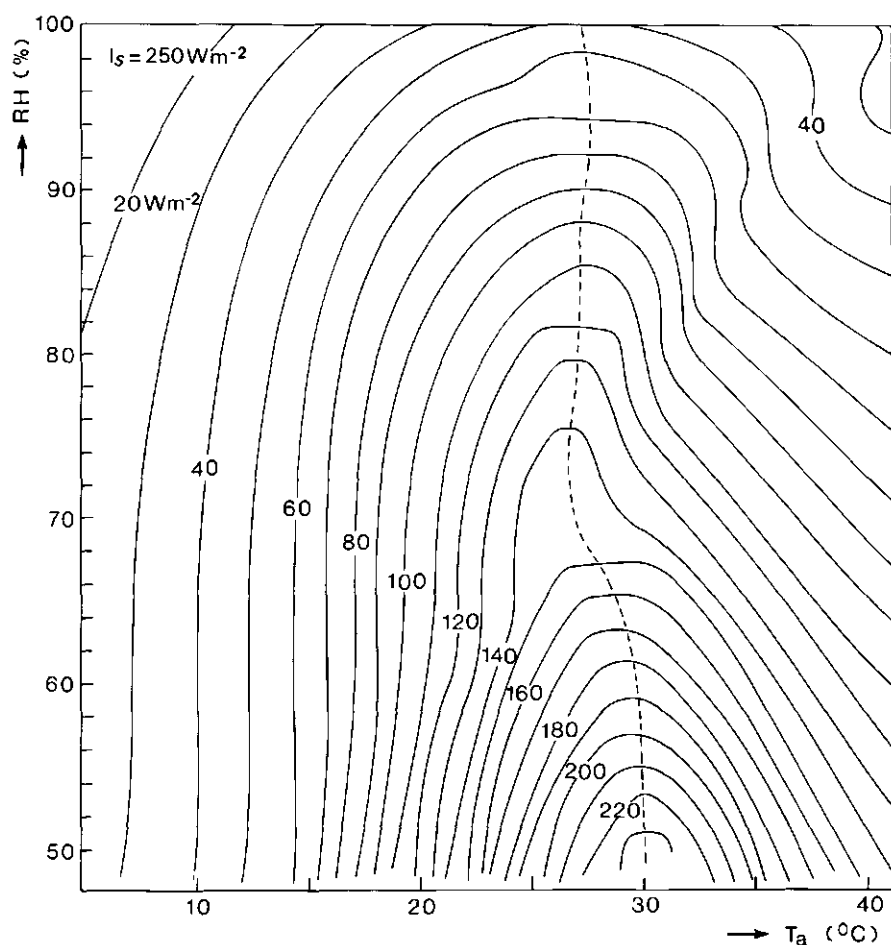


Fig.4.11. The transpiration rate ( $\text{W}\cdot\text{m}^{-2}$ ) as a function of the temperature and relative humidity of the ambient, for an incoming shortwave radiation outside the house of  $250 \text{ W}\cdot\text{m}^{-2}$ . The other conditions were:  $\text{LAI} = 3$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ ;  $\text{CO}_2 = 200 \text{ ppm}$  (i.e.  $\bar{f}_i(\text{CO}_2) = 1$ );  $T_u = T_p = T_g = T_a$ .

#### 4.3.4 Cooling

Some form of cooling is practiced whenever ventilation is ineffective in keeping the ambient temperature within an 'acceptable' level. Cooling is then performed by sprinkling the upper side of the cover with water, for instance. A measure of the influence this could have on both the temperature and transpiration rate might be deduced from figs. 4.6, though this would provide an underestimate, since the certain cooling of the ambient is not accounted for, in those figures. The common practice of opening the roof windows a little while sprinkling, moreover, ensures that much of the moist, cool air flowing along the roof enters the house. This is a modified form of a cooling procedure known as 'fan and pad', whereby the am-

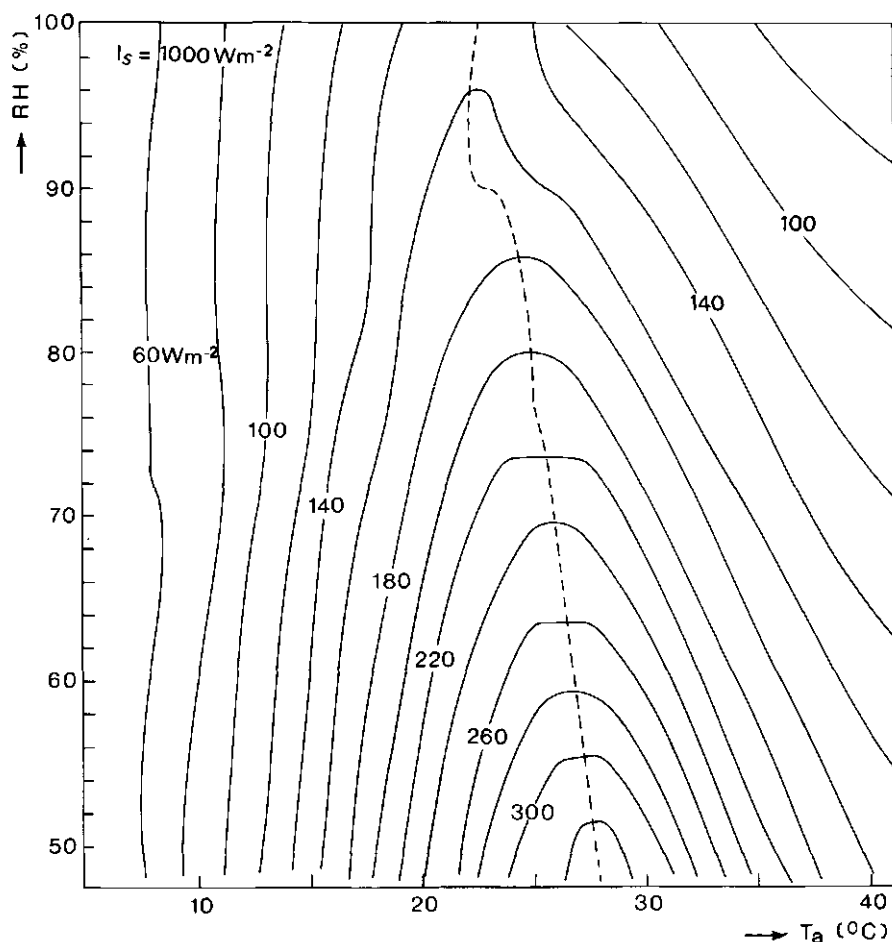


Fig.4.12. The transpiration rate ( $\text{W}\cdot\text{m}^{-2}$ ) as a function of the temperature and relative humidity of the ambient, for an incoming shortwave radiation outside the house of  $1000 \text{ W}\cdot\text{m}^{-2}$ . The other conditions were:  $\text{LAI} = 3$ ;  $u = 9 \text{ cm}\cdot\text{s}^{-1}$ ;  $\text{CO}_2 = 200 \text{ vpm}$  (i.e.  $f_i(\text{CO}_2) = 1$ );  $T_u = T_p = T_g = T_a$ .

bient is cooled by ventilation with air circulated through wet pads (evaporative cooling). Since then the saturation deficit of the ambient is drastically reduced, one might wonder whether such a measure can effectively mitigate the temperature of the foliage (Landsberg et al., 1979; Monteith, 1981a; Van Bavel et al., 1981). For a crop as tightly coupled to the ambient as the one we are dealing with, one could deduce (from fig.4.3b) that evaporative cooling of the ambient does reduce the temperature of the canopy, although to a lesser degree than the air temperature. However, as the diagram reproduced in fig. 4.12 shows, evaporative cooling scarcely affects the transpiration rate.

Therefore, since 'tomatoes can easily bear a temperature of  $40^\circ\text{C}$ , if humidity is not a problem' (Klapwijk, 1987) one might indeed wonder 'whether greenhouses

are cooled for the benefit of the crop or of the workers' (Garzoli, 1985). On the other hand, in order to avoid stress (with low humidities), one should reduce the transpiration rate. In this case, shading appears to be the most efficient way of achieving this, although spraying of the crop might be effective too.

#### **4.4 Summary**

The sensitivity analysis performed in the beginning of this chapter (§ 4.1) has shown that the microclimate exerts its influence on the transpiration rate of a greenhouse crop primarily through three factors: the available shortwave radiation, the temperature of the ambient and its humidity. The temperature of the surfaces exchanging thermal radiation with the canopy also contributes to the transpiration rate, albeit to a minor extent.

Further, the common practices for the handling of the greenhouse climate have been reviewed (§ 4.2). It has been pointed out that many of these practices betray the object of manipulating the transpiration rate of the crop, whether this fact is acknowledged or not. Indeed, that this could often be quite a reasonable purpose had been stated in the introduction to that section. Hence the opinion resumed in the title of this book: that if the management of the crop transpiration was acknowledged to be the intended goal of many procedures for the manipulation of the greenhouse climate, then the transpiration rate (and not the ambient humidity) ought to be defined as the yardstick for the application of those procedures. In § 4.3 some examples were used to make this point. Indeed, it was shown that defining a 'transpiration set-point' as the criterion on which to base decisions regarding the manipulation of the microclimate could incorporate the many rules of thumb presently used, into a more quantitative framework. That would deliver a far more straightforward management of the microclimate; it could even avoid some spilling of energy by unnecessary attempts to reduce the humidity in the greenhouse.



## 5. CONCLUSION

It was stated in the beginning of this thesis that the quality of greenhouse management would be improved if the transpiration of crops could be manipulated through wise control of the microclimate. Such 'wise' control is possible only as long as the influence the microclimate exerts on the transpiration of crops is understood. This knowledge was described to be of some use in three areas where advances in technology are now taking place. In the first place, to improve the efficiency of the control of humidity in modern (well insulated) greenhouses, as it is known that reduction of the ambient humidity is a process which may eliminate any saving due to better insulation. In addition, to deliver a better picture of the interaction between a canopy and the greenhouse environment which is needed for a good simulation of the greenhouse climate. Finally, it was pointed out that the development of better greenhouse management systems requires that the climate set-points be fixed according to a desired trend of crop processes. Transpiration was mentioned as one of the processes one might wish to manipulate. For this purpose, the way transpiration is affected by the microclimate has got to be known. Of course an accurate method of assessing the transpiration of a crop could also be of use in the development of better water gift schemes.

The relationship between the microclimate and the transpiration of a greenhouse crop has been ascertained in this work. A physical model of a greenhouse canopy has been shown to yield accurate appraisals of the transpiration rate of that canopy, during time intervals as short as a few minutes. In order to make up for the awkwardness of accurately representing such a complex system as a canopy, the crop was modeled as a single layer of a porous medium, the composing material being opaque for longwave radiation and semi-transparent for radiation in the shortwave range. This layer was supposed to be immersed in a homogeneous ambient, characterized by a set of parameters defining the 'microclimate'. Transfer of heat between the canopy and the ambient, takes place through an exchange area equal to the total (both sides) leaf area, across an 'external' resistance. The transfer of vapour is impeded by an additional resistance, the 'internal' one. The microclimate concurs with some features of the canopy in establishing the magnitude of both these resistances. Then, once the microclimate is given, this set of assumptions was shown to be consistent with *one* value of temperature – the effective temperature of the canopy which, in fact, is defined by the present represen-

tation. Furthermore, the transpiration rate was shown to be fixed once the effective temperature of the canopy is known.

An experimental set-up had to be devised in order to determine the parameters of the sub-model for the radiation exchange, as the presence of the heating system makes the use of experimental methods commonly applied for field crops, impossible. Hence, the transmittance and the reflectance of the canopy were determined by means of measurements of shortwave radiation fluxes. Their parametrization as a function of the leaf area index, as required by the turbid medium representation, allowed the appraisal of the absorption coefficients of the canopy, for short as well as long wave radiation.

The external resistance of a greenhouse canopy was assessed by means of a new experimental technique. The resulting values for the external resistance were shown to be satisfactorily explained by a theoretical model whereby the transfer of heat could be derived by writing the vectorial combination of the velocities due to forced and natural convection.

Also, it was shown that an experiment consistent with the model can successfully be executed in order to evaluate the internal resistance of a greenhouse crop growing in natural conditions. The behaviour of the internal resistance of such a canopy was then parametrized as a function of the microclimate, according to a semi-empirical model.

Another experiment allowed for the appraisal of the relevance of the storage of thermal energy in the foliage, in relation to the magnitude of the other energy fluxes. It was concluded that, as far as the foliage (and not the whole crop) is concerned, stationary equations provide estimates of both the temperature and the transpiration rate, which are accurate enough on a time interval of at least a few minutes.

All these sub-models were validated with measurements. They were then included in the theoretical framework developed beforehand, and the resulting transpiration model was confronted with an independent data set. The model was shown to reproduce satisfactorily the measured transpiration rate of a greenhouse tomato crop and to provide quite a good estimate of the 'mean' temperature of it; both on a time scale of a few minutes. The most important (and sometimes surprising) results of a sensitivity analysis of the model as well as of some theoretical speculations performed beforehand may shortly be summarized here:

- Though the transpiration rate is formally a linear function of the irradiation (and of the ambient saturation deficit), there is no hope that such a relationship could provide accurate appraisals of the transpiration rate at any time.
- An increase of the air movement could dampen as well as stimulate the transpiration rate; whatever the effect, however, it is likely to be small.
- Longwave radiation from the elements of a conventional pipe heating system does not contribute significantly to the transpiration.

- There is a non obvious relationship between the transpiration rate and the ambient temperature.

It was then suggested that the transpiration rate thus determined, might be quite an attractive parameter for the control of the climate within a greenhouse. The accepted existence of a relationship between the water use of a crop and its production had been previously brought as an argument to support this statement. By means of a couple of examples, it was shown that, indeed, many of the commonly applied 'golden rules' of greenhouse climate manipulation betray the purpose of controlling the transpiration process. Explicit use of transpiration as a control criterion (a 'transpiration set-point') would be more elegant, as the many parameters which are now independently taken into account would be joined into only one. A more practical advantage, however, would be that more quantitative rules could be deduced, by this means, with regard to the application of these manipulations. Indeed, not only has it been shown through various examples that this approach is feasible, but that it could also be much more efficient. For instance, working with a 'transpiration set point' instead of separate temperature and relative humidity set-points could sometimes avoid unnecessary (and often expensive) attempts at reducing the relative humidity within the house.

Of course, in order to ensure a more general applicability of the method developed here, the results of two kinds of investigations are needed for at least the most common greenhouse crops. In the first place, the necessary species-specific parameters have to be determined, as it was done in the present work in the case of a tomato crop. Besides, a knowledgeable application of transpiration as a climate control parameter, has to be based on a good deal of biological research to establish which is a desirable (or acceptable) transpiration rate for an agricultural crop, during its various phenological stages.

## SUMMARY

In this thesis a method for the appraisal of the vapour production of greenhouse crops as a function of the microclimate is developed and tested. The method is shown to be of practical use for the purpose of controlling the transpiration of a greenhouse crop by manipulating the greenhouse climate. The humidity management in well insulated greenhouses (given the associated high costs) as well as the development of 'expert systems' for the climate control, are mentioned as areas where this method could find its most useful applications.

After a survey of the potential for the manipulation of the greenhouse climate offered by the systems currently available, it is made clear that more knowledge about the relationship microclimate-crop transpiration would allow a more efficient exploitation of that potential. As transpiration is one of the ways a crop can exchange energy with its environment, the energy balance method is pointed out as being the one most likely to deliver an appraisal of the relationship between the transpiration rate of a greenhouse crop and the microclimate characterizing its environment.

In chapter two the energy balance approach is applied to the simplest component of a canopy: an 'idealized' leaf. After defining the properties of such an ideal leaf surface and of its environment, both the energy balance equation of such a leaf and the equations for the transfer of sensible and latent heat between the leaf and the ambient are derived. It is then shown that it is enough to postulate the existence (somewhere within the leaf) of a surface saturated at its temperature (the phase interface), to deduce analytical equations for both the temperature and the transpiration rate of such a leaf. Those equations, however, require the transfer resistances for heat and vapour either to be given or to be known functions of the microclimate. An experimental technique for the appraisal of the resistance to heat transfer (external resistance) of leaves immersed in a greenhouse canopy has been developed at this purpose. Subsequently, a model based on the combination of forced and natural convection is shown to yield reasonable predictions of the actual magnitude of the external resistance. The internal resistance of the leaf is defined as the resistance to vapour transfer created by the leaf layer contained between the phase interface and the external surface of the leaf. Then, the influence of each one of the parameters which appears to be relevant in determining the transpiration rate is shortly discussed. It is shown, for instance, that the transpira-

tion could be estimated using simple formulae based on only one parameter of the microclimate (such as irradiation, temperature or saturation deficit), only under very restrictive conditions. The effect of the external resistance is elucidated and a couple of surprising peculiarities are unearthed. An enlargement of the external resistance is shown not necessarily to reduce the transpiration rate, nor to have an obvious effect on the temperature of the leaf. In a number of natural conditions anyway, a variation of the external resistance hardly causes the transpiration rate to change. Furthermore, the internal resistance appears only in the ratio internal to external resistance, in both the temperature and transpiration equations. It is then pointed out that any variation of the internal resistance plays a role only to the extent to which that ratio is affected.

In chapter three the method developed for one leaf is applied to a greenhouse canopy. This requires some degree of abstraction as neither the available net radiation nor the internal and external resistances of a canopy have an evident meaning. In fact, the crop is represented as a single layer of a porous medium. The transfer of sensible and latent heat between the canopy and the ambient takes place via an exchange area equal to the total (both sides) leaf area, across two resistance (internal and external) which are defined by the present representation. As far as the net radiation is concerned, a semi-theoretical model for the transfer of radiation in a greenhouse crop is developed, whereby the canopy layer is regarded as a turbid medium, characterized by one value of effective temperature. The parameters of this model, namely: the extinction coefficient for shortwave radiation, the reflectance of a dense stand with similar properties, and the reflectance of the soil surface, are experimentally determined. An experimental technique was also developed in order to determine the internal resistance of a greenhouse canopy growing in 'natural' conditions. The resulting internal resistance is parametrized as a function of some factors of the microclimate. Another experiment allowed the thermal capacity of the same canopy to be ascertained; that capacity is small enough for the storage of thermal energy within the foliage (and not the whole canopy) to be negligible in nearly all conditions of practical relevance. When all these sub-models are assembled into the theoretical framework provided in the beginning of chapter three, the resulting estimates of both the transpiration rate and the temperature of the foliage are shown to be quite reliable (on a time basis of a few minutes). It is further pointed out that both the transpiration rate of a canopy and the temperature of its foliage are in simple relationship with those of a single 'idealized' leaf. The transpiration rate is almost proportional to the leaf area and the temperature of the foliage nearly independent of it.

From the sensitivity analysis carried out in the beginning of chapter four it is deduced that the microclimate exerts its influence on the transpiration rate of a greenhouse crop primarily through three factors: the available shortwave radiation, the temperature of the ambient, and its humidity. The temperature of the

surfaces exchanging thermal radiation with the canopy also contributes to the transpiration rate, albeit to a minor extent. Then, after reviewing the common practices for the handling of the greenhouse climate, it is suggested that many of these practices betray the object of manipulating the transpiration rate of the crop, whether this fact is acknowledged or not. It is then stated that if the management of the crop transpiration were recognized to be the intended goal of many procedures for the manipulation of the greenhouse climate, then the transpiration rate (and not the ambient humidity) had better be defined as the yardstick for the application of those procedures. This point is made by means of some practical examples, whereby it is shown that defining a 'transpiration set-point' as the criterion on which to base decisions about the manipulation of the microclimate could incorporate the many rules of thumb presently used, into a more quantitative framework. This would deliver a far more straightforward management of the microclimate; it could even avoid some spilling of energy caused by unnecessary attempts to reduce the humidity in the greenhouse.

# SAMENVATTING

## GEWASVERDAMPING

hulpmiddel om vat te krijgen op het kasklimaat

In dit proefschrift wordt een methode ontwikkeld en op bruikbaarheid getoetst om de gewasverdamping in kassen kwantitatief te beschrijven in afhankelijkheid van het heersende microklimaat. Aangetoond wordt, dat de aanpak praktische mogelijkheden biedt om de verdamping door het gewas in tuinbouwkassen te beheersen via regeling van het kasklimaat. De bij dit onderzoek ontwikkelde methoden lijken bij uitstek geschikt om te worden toegepast bij het verminderen van de hoge kosten die moeten worden gemaakt om vochthuishouding in goed geïsoleerde kassen te beïnvloeden of bij de invoering van 'expert systems' voor klimaatregeling.

Na een kritisch overzicht van de thans beschikbare mogelijkheden om het kasklimaat te beïnvloeden wordt duidelijk gemaakt, dat een grondiger inzicht in de relatie tussen gewasverdamping en microklimaat in de kas kan leiden tot een efficiënter gebruik van de beschikbare middelen en methoden. De verdamping is een van de belangrijke posten in de energiebalans van het gewas in relatie met zijn omgeving. Nadere bestudering van de energiebalans lijkt daarom de meest aangewezen methode om de relatie tussen gewasverdamping en omgevingscondities nauwkeuriger te overzien. Om tegemoet te komen aan de moeilijkheid om een complex system als een gewas te beschrijven, is gekozen voor een stapgewijze aanpak.

In hoofdstuk twee wordt de energiebalans onderzocht voor een eenvoudig te beschrijven component van het gewas, te weten een geïdealiseerd blad. De eigenschappen van een dergelijk geïdealiseerd blad en van zijn naaste omgeving worden nauwkeurig vastgelegd. Daarna worden de energiebalans van het blad en de transporten van voelbare en latente warmte tussen blad en omgeving in vergelijkingen gebracht. Om de vergelijkingen voor de warmteoverdracht en de verdamping simultaan te kunnen oplossen wordt het fasescheidingsvlak geïntroduceerd. Dit is een vlak, gesitueerd onder het bladoppervlak, waarin de waterdampspanning gelijk is aan de verzadigingsdruk die behoort bij de (onbekende) temperatuur van het vlak. Voordat de waterdampflux het buitenoppervlak van het blad bereikt moet hij de (inwendige!) weerstand overwinnen tussen fasescheidingsvlak

en buitenoppervlak. Naast deze conceptuele veronderstelling is natuurlijk ook kennis vereist omtrent de uitwendige overdrachtsweerstand voor warmte en vocht tussen bladoppervlak en omgeving in afhankelijkheid van het gegeven microklimaat in de kas. Daarom is een experimentele techniek ontwikkeld om in een kas deze uitwendige weerstand van een blad temidden van het gewas te kunnen vaststellen. Aangetoond is dat een rekenmodel waarbij gedwongen en vrije convectie simultaan optreden een redelijk goede overeenstemming geeft met de aldus gevonden experimentele waarden.

Vervolgens wordt de invloed besproken van elk der parameters die van belang zijn voor het bepalen van de gewasverdamping. Het blijkt daarbij onder meer, dat slechts onder zeer beperkte omstandigheden de verdamping kan worden gevonden uit een eenvoudige relatie met niet meer dan één parameter van het microklimaat (zoals instraling, temperatuur of verzadigingsdeficit). De invloed van de uitwendige weerstand is onderzocht, waarbij enkele onverwachte bijzonderheden aan het licht komen. Zo blijkt het, dat vergroting van de externe weerstand niet onvermijdelijk hoeft te leiden tot een lagere gewasverdamping en dat dit evenmin een uitgesproken effect op de bladtemperatuur hoeft mee te brengen. Anders geformuleerd betekent dit voor de praktijk, dat onder natuurlijke omstandigheden de gewasverdamping nauwelijks wordt beïnvloed door variaties van de uitwendige weerstand. Als de inwendige weerstand zowel in de formule voor de bladtemperatuur als in die voor de verdamping uitsluitend voorkomt in de vorm van een quotient van inwendige en uitwendige weerstand, geconcludeerd wordt dat veranderingen in de inwendige weerstand slechts van invloed zijn in zoverre zij er toe leiden dat juist dat quotient wordt beïnvloed.

In hoofdstuk drie wordt de aanpak die ontwikkeld werd voor het enkelvoudige blad geschikt gemaakt voor toepassing op een compleet gewas. Dit vereist een zekere mate van abstractie, aangezien bij een gewas noch voor de beschikbare netto straling, noch voor de inwendige of uitwendige weerstand een direct aanwijsbare fysische interpretatie valt aan te geven. Teneinde toch tot een beschrijving te komen wordt het gewas voorgesteld als één enkele laag van een poreus medium met uniforme eigenschappen. De overdracht van voelbare en latente warmte tussen gewas en omgeving vindt plaats via een uitwisselingsoppervlak dat gelijk gesteld wordt aan het totaal aanwezige (dubbelzijdige) bladoppervlak. De inwendige en uitwendige weerstand worden op basis van deze aanname voor het uitwisselingsoppervlak gedefiniëerd. Wat betreft de netto straling wordt er een half-theoretisch model ontwikkeld voor de stralingsoverdracht van en naar het gewas, waarbij de gewaslaag wordt opgevat als een verstrooiend medium dat kan worden gekenmerkt door één uniforme waarde voor de effectieve temperatuur. De parameters van dat model – te weten de extinctiecoëfficiënt voor kortgolvlige straling, de reflectiecoëfficiënt van een gesloten gewas met overeenkomstige eigenschappen en de reflectiecoëfficiënt van het onderliggende grondoppervlak – zijn experimenteel bepaald. Ook werd een experimentele techniek ontwikkeld om de inwen-



dige weerstand te bepalen van een gewas dat onder 'natuurlijke' omstandigheden groeit in een tuinbouwkas. De gevonden waarden voor de inwendige weerstand kunnen worden geparametriseerd als functie van een aantal microklimaatfactoren. Een ander experiment maakte het mogelijk de warmtecapaciteit van dit zelfde gewas vast te stellen. De capaciteit blijkt zodanig klein te zijn dat de warmteopslag in de bladeren in vrijwel alle gevallen van praktisch belang redelijkerwijze verwaarloosd kan worden (vanzelfsprekend geldt dit alleen voor de bladeren en niet zonder meer voor het gewas als geheel). Wanneer al deze modelveronderstellingen worden ingebracht in het totale model voor het gewas blijken de hiermee bepaalde waarden voor gewasverdamping en temperatuur van het gebladerte, genomen over een tijdspanne van enkele minuten, alleszins aanvaardbaar te zijn. De aandacht wordt er nog op gevestigd, dat zowel de gewasverdamping als de temperatuur van het gebladerte in eenvoudige relatie staan tot de overeenkomstige grootheden voor het enkelvoudige geïdealiseerde blad. Dit komt omdat de gewasverdamping nagenoeg evenredig blijkt te zijn met het bladoppervlak, terwijl de temperatuur van het gebladerte daar vrijwel onafhankelijk van is.

Het hoofdstuk vier begint met een gevoeligheidsanalyse, waaruit blijkt dat het microklimaat in de kas zijn invloed op de gewasverdamping vooral doet gelden via drie grootheden. Dit zijn de aanwezige kortgolelige straling, de temperatuur van de omgevende lucht en de luchtvochtigheid. In mindere mate heeft daarnaast ook de temperatuur van de kasdek en de bodemoppervlak invloed op de verdamping. Vervolgens wordt besproken hoe in de praktijk het kasklimaat wordt gehanteerd. Hierbij wordt aangegeven dat vele van de praktijkmaatregelen (bewust of onbewust) in feite zijn gebaseerd op manipulatie van de gewasverdamping. Onderkende dat beheersing van de gewasverdamping inderdaad het beoogde doel is van menige procedure bij het hanteren van het kasklimaat, wordt gesteld dat de verdampingssnelheid van het gewas, meer dan de luchtvochtigheid, te prefereren is als maatstaf bij deze procedures. Dit gezichtspunt is doorgenomen aan de hand van enige praktijkvoorbeelden. Hierbij wordt aangetoond, dat na het vastleggen van een 'transpiratie-setpoint' als criterium bij het manipuleren van het microklimaat vele thans gebruikelijke vuistregels tot een meer kwantitatief samenhangend schema zouden kunnen worden samengevoegd. Dit zou een veel meer rechtstreekse aanpak opleveren van de klimaatbeheersing in kassen. Het zou zelfs kunnen verhinderen dat er energie verloren gaat als gevolg van pogingen nodeloos de luchtvochtigheid in de kas te verlagen.

# RESUMEN

## TRANSPIRACION DE CULTIVOS EN INVERNADERO una ayuda para el manejo del microclima

En este libro se acaban de desarrollar las relaciones cuantitativas entre la transpiración de un cultivo y el microclima en invernaderos.

La precisión de las relaciones constituyentes el modelo se pudo comprobar por comparación con mediciones. Luego se destacó la transcendencia práctica de este método para controlar la transpiración del cultivo por el trámite del microclima. Cabe destacar que las ecuaciones presentadas en este libro permiten afinar el control de la humedad en invernaderos y, por ende, reducir los costos de ese control. Esas mismas relaciones permitirían aprovechar sistemas 'expertos' para controlar procesos más complejos, por ejemplo el riego y el crecimiento del cultivo.

A través de una descripción somera de las oportunidades que brindan los sistemas de control del microclima en invernaderos, se pudo destacar que las relaciones entre microclima y transpiración son terminantemente necesarias para el aprovechamiento eficiente de estos sistemas. La transpiración es una componente muy importante del balance de energía del sistema cultivo-invernadero. Por ende se desarrolló por pasos intermedios una descripción teórica del balance de energía de ese sistema.

En el primer paso se desarrolló y analizó el esquema físico-matemático de las interrelaciones entre una hoja y su medio. Se plantearon las características de esa hoja y las relaciones entre ellas en el marco termodinámico del balance de energía. Para resolver el conjunto de ecuaciones, inclusive la ecuación de transferencia de vapor, hubo que definir la superficie de separación entre líquido y vapor. Esta superficie de evaporación se encuentra definida por ser la presión de vapor igual a la presión de vapor saturado a la temperatura de esa superficie.

El flujo de transpiración hacia afuera de la hoja queda establecido por un gradiente (la diferencia de presión del vapor entre aire y superficie de evaporación) y dos resistencias: una resistencia interna entre las superficies de evaporación y de la hoja y una resistencia externa entre la superficie de la hoja y el aire lejos de la misma. Desde luego hizo falta desarrollar y aplicar una técnica para medir esa resistencia externa. Estas mediciones permitieron de comprobar un modelo teórico de esa resistencia en un régimen de transferencia de calor mixta (libre y forzada).

En la segunda etapa del desarrollo se logró generalizar el modelo simple de una hoja a todo el cultivo. La compleja estructura del cultivo hace que sea sumamente complicado relacionar las resistencias interna y externa con algún elemento del cultivo. Sin embargo las técnicas experimentales aprovechadas permitieron determinar las características físico-matemáticas de un modelo simple del cultivo. Este quedó esquematizado en una capa porosa homogénea. El intercambio de calor y vapor procede a través de una superficie igual al área total de las hojas del cultivo. Para calcular la radiación neta del cultivo, este se planteó ser una capa semitransparente, de temperatura homogénea. Los coeficientes de las ecuaciones en el modelo de transferencia de radiación se determinaron por mediciones.

Para determinar la resistencia interna del cultivo en invernadero hizo falta desarrollar otra técnica de medición. Sin embargo esta permitió establecer el impacto de variaciones microclimáticas sobre la resistencia interna.

Bastante nuevo es el método desarrollado para determinar la capacidad térmica de las hojas del cultivo. Se logró establecer que la parte dinámica de las ecuaciones de transpiración y temperatura del cultivo es bastante pequeña para que no necesite considerarse.

El conjunto de las ecuaciones, establecidas por desarrollo teórico en combinación con mediciones, constituye el modelo de la interrelación entre microclima y transpiración. Por comparación con mediciones de transpiración (cada 5 min.) de un cultivo de tomate en invernadero, se logró comprobar la precisión más que satisfactoria de ese modelo.

Los resultados más trascendentes que se han logrado son:

- relaciones simples entre un parámetro solo del microclima y la transpiración se pueden aplicar bajo hipótesis muy restrictivas;
- el aumento de la velocidad del aire, y por ende una menor resistencia externa, no implica necesariamente un aumento de la transpiración. Entonces la variabilidad del movimiento del aire en el invernadero no influye mucho sobre la transpiración del cultivo;
- la transpiración y la temperatura de la superficie de evaporación quedan afectadas por el cociente entre resistencia interna y externa. Esta, entonces, establece una escala para determinar el impacto actual de variaciones de la resistencia interna;
- los parámetros del microclima que más directamente influyen sobre la transpiración son: irradiación solar, temperatura y humedad del aire en el invernadero;

- la temperatura del techo del invernadero y de la superficie del suelo no influyen mucho sobre la transpiración. Aun menor es el aporte de la emisión térmica de un sistema tradicional de calefacción.

El control de la humedad en invernaderos implica, muy a menudo, el control de la transpiración del cultivo. En este libro se pretende destacar que el control del microclima tendría que apuntar hacia la transpiración directamente.

Para comprobar esta conclusión se desarrollaron unos ejemplos de aplicación práctica del modelo. Los ejemplos en su conjunto permiten destacar que varias reglas prácticas de control se pueden deducir de un control apuntado a la transpiración por medio del modelo que aquí se acaba de presentar. La gran ventaja del mejor fundamento físico de este control es la reducción de costos por la eliminación de procedimientos prácticos pero ineficientes de control de la humedad en el invernadero.

# SOMMARIO

## TRASPIRAZIONE DI COLTURE IN SERRA

un aiuto nella gestione del microclima

In questa tesi viene sviluppato un metodo per descrivere quantitativamente la traspirazione di una coltura in serra, in funzione del microclima; l'affidabilità del metodo viene dimostrata sulla base di dati sperimentali. In seguito, viene discusso come quest'approccio offra la possibilità pratica di regolare la traspirazione di una coltura in serra attraverso il controllo del microclima. I metodi sviluppati per questa ricerca sono adeguati per applicazioni miranti a diminuire gli elevati costi connessi col controllo dell'umidità in serre ben isolate o per l'applicazione di 'expert systems' per la gestione (a breve e lungo termine) di alcuni processi all'interno della serra, come irrigazione, crescita, microclima.

Dopo una rivista delle enormi possibilità oggi esistenti per influenzare il clima in serra, viene chiarito che una adeguata comprensione della relazione esistente fra la traspirazione di una coltura ed il microclima può condurre ad un uso più efficiente dei mezzi e metodi disponibili. La traspirazione è uno dei termini più importanti del bilancio di energia di una coltura in relazione al suo ambiente. Uno studio accurato del bilancio di energia appare perciò l'approccio più indicato per una conoscenza accurata della relazione fra la traspirazione di una coltura e l'ambiente in cui questa è immersa. Il compito di descrivere in termini fisico-matematici uno strato di vegetazione viene affrontato in questo lavoro in maniera graduale.

Il bilancio di energia di un componente semplice della vegetazione (una foglia alquanto astratta) viene analizzato in primo luogo. Le qualità di una foglia siffatta e dell'ambiente in cui questa si trova, vengono definite. Da queste definizioni segue la possibilità di enunciare in forma di equazioni sia il bilancio di energia della foglia che lo scambio di calore e vapore tra quest'ultima e l'ambiente. Per poter risolvere il sistema formato da queste equazioni, è stata introdotta la definizione di separazione di fase: una superficie, al di sotto della superficie esterna della foglia, caratterizzata dall'essere satura alla propria (incognita) temperatura. Per essere rilasciato dalla foglia, il vapore che attraversa questa superficie deve vincere la resistenza (interna) opposta dallo strato compreso fra la separazione di fase e la superficie esterna della foglia. Anche lo strato di aria a contatto con la foglia offre

naturalmente una resistenza (esterna) al trasporto di calore e vapore. Viene quindi sviluppata una tecnica sperimentale originale per quantificare la resistenza esterna di foglie in una normale coltura in serra. In seguito viene dimostrato che un modello per il trasporto di calore che tenga conto dell'effetto simultaneo della convezione libera e forzata è in grado di riprodurre i valori misurati della resistenza esterna con una accuratezza accettabile.

L'adattamento ad una vegetazione del modello concettuale così creato per una superficie semplice, richiede un livello di astrazione ancora maggiore. Per una vegetazione, in effetti, non è possibile fornire un corrispondente concreto al concetto di resistenza, sia interna che esterna, né è banale quantificare lo scambio di energia radiante. Ciò nonostante, allo scopo di pervenire ad una rappresentazione, la vegetazione viene considerata come uno strato di un materiale poroso uniforme. Lo scambio di calore e vapore con l'ambiente avviene attraverso una superficie assunta uguale alla area totale (due parti) delle foglie presenti. Per il calcolo del flusso radiativo netto, d'altra parte, viene sviluppato un modello per cui lo strato vegetato è considerato come uno strato semi-trasparente, caratterizzato da un valore (incognito) di temperatura; i parametri di quel modello vengono determinati sperimentalmente. Una tecnica sperimentale viene sviluppata anche per determinare la resistenza interna di una vegetazione coltivata 'naturalmente' in serra. L'effetto del microclima sulla resistenza interna è stato successivamente quantificato. Un ultimo esperimento ha reso possibile determinare la capacità termica del fogliame. Si è concluso che la capacità termica è sufficientemente piccola perché la parte dinamica della soluzione della temperatura e della traspirazione del fogliame possa essere trascurata (questa conclusione è limitata al fogliame e non dovrebbe essere applicata alla vegetazione nel suo complesso).

Le stime (di traspirazione e temperatura della vegetazione), prodotte dalla ricomposizione di questi sub-modelli nella cornice teorica sviluppata all'inizio, vengono dimostrate riprodurre in maniera sufficientemente accurata i valori di traspirazione e temperatura (misurati ogni cinque minuti) di una coltura di pomodoro in una serra commerciale.

I risultati più importanti (e talvolta più sorprendenti) derivati da una analisi di sensibilità del presente modello, si possono così riassumere:

- Solo in casi particolarissimi la traspirazione può essere stimata accuratamente attraverso relazioni basate su non più di un parametro del microclima (come irradiazione, temperatura o umidità)
- Un aumento della velocità del vento (cioè una diminuzione della resistenza esterna) non necessariamente comporta un aumento della traspirazione. In pratica questo significa che le variazioni del movimento di aria in una serra hanno poca influenza sul rateo di traspirazione della coltura.

- Poichè la resistenza interna compare (sia nell' equazione per la traspirazione che in quella per la temperatura) esclusivamente sotto forma di quoziente con la resistenza esterna, quest' ultima costituisce una specie di unità di misura per stabilire l' influenza di una variazione della resistenza interna in condizioni differenti.
- I parametri del microclima di fondamentale importanza nel determinare la traspirazione sono: la radiazione globale disponibile, la temperatura ed il contenuto di umidità dell' ambiente.
- La temperatura della copertura (o dello schermo, se presente) e della superficie del terreno hanno una influenza più limitata sulla traspirazione della coltura. La radiazione termica emessa da un sistema di riscaldamento convenzionale non ha un effetto praticamente rilevante.

La regolazione dell' umidità in serra avviene, in pratica, secondo regole che (esplicitamente o implicitamente) spesso mirano a manipolare la traspirazione della coltura. In questa tesi si sostiene che, se si ammette questo, la stima della traspirazione reale e non l' umidità dovrebbe essere considerata il criterio per la gestione del microclima sotto quest' aspetto. Questo punto di vista è sostenuto da alcuni esempi pratici attraverso i quali si dimostra che l' introduzione di un ipotetico 'set point' per la traspirazione potrebbe ricondurre in uno schema unitario quantitativo molte delle 'regole d' oro' oggi in uso per il controllo del clima in serra. Un siffatto schema oltre ad essere, ovviamente, necessario per l' applicazione di sistemi computerizzati di controllo del microclima, può anche offrire il vantaggio di ridurre i costi di gestione, poichè ridurrebbe l' incidenza di azioni (costose) miranti alla riduzione dell' umidità.

# REFERENCES

- ALLEN Jr., L., 1974. Model of light penetration into a wide-row crop. *Agron. J.*, 66: 41-47.
- ANONYMOUS, 1987. Gebruik recirculatieventilatoren. *Vakblad voor de Bloemisterij*, 42 (2): 42-43.
- ASTON, A.R., 1984. Evaporation from eucalypts growing in a weighing lysimeter: a test of the combination equations. *Agric. For. Meteorol.*, 31: 241-249.
- ASTON, A.R., 1985. Heat storage in a young eucalypt forest. *Agric. For. Meteorol.*, 35: 281-297.
- AVISSAR, R., P. AVISSAR, Y. MAHRER and B.A. BRAVDO, 1985. A model to simulate response of plant stomata to environmental conditions. *Agric. For. Meteorol.*, 34: 21-29.
- AZAM-ALI, S.N., 1984. Environmental and physiological control of transpiration by groundnut crops. *Agric. For. Meteorol.*, 33: 129-140.
- BAILEY, B.J., 1985. Microclimate, physical processes and greenhouse technology. *Acta Horticulturae*, 174: 35-42.
- BIRTA, L.G., 1977. A parameter optimization module for CSSL-based simulation software. *Simulation*, 28(4): 113-121.
- BÖRNER, H., 1965. Über den Wärme und Stoffübergang an umspulten Einzelkörper bei Überlagerung von freier und erzwungener Strömung. *VDI (Ver. Deut. Ing.)*, Forschungsh. No. 512.
- BOT, G.P.A., 1983. Greenhouse climate: from physical processes to a dynamic model. Ph.D. Dissertation, Agricultural University, Wageningen,: 240 pp.
- BOWEN, L.S., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Phys. Rev.*, 27: 779-787.
- BREUER, J.J.G., 1987. Jaarbelastingsduurkromme en energiebesparing voor de nederlandse glastuinbouw. Een studie naar relevante invloeden. Institute of Agricultural Engineering (IMAG), Wageningen, Rapport 90: 67 pp.
- BROWN, H. and F. ESCOMBE, 1900. Static diffusion of gases and liquids in relation to the assimilation of carbon and translocation in plants. *Phil. Trans. Royal Soc., London*, B 193: 223-291.
- BRUGGINK, G.T., 1986. In: Jaarverslag 1985. Vakgroep Tuinbouwplantenteelt, Agricultural University, Wageningen: 48.
- CANNON, J.N., W.B. KRANTZ, F. KREITH and D. NAOT, 1979. A study of transpiration from porous flat plates simulating plant leaves. *Int. J. Heat Mass Transfer*, 22: 469-483.
- CHALLA, H., 1985. Report of the working party 'Crop Growth Models'. *Acta Horticulturae*, 174: 169-174.
- CHAMBERLAIN, A.C., 1974. Mass transfer to bean leaves. *Boundary-Layer Meteorol.*, 6: 477-486.
- CHEN, J., 1984. Mathematical analysis and simulation of crop micrometeorology. Ph.D. Dissertation, Agricultural University, Wageningen: 116 pp.



- CHOUDHURY, B.J., 1983. Simulating the effects of weather variables and soil water potential on a corn canopy temperature. *Agric. Meteorol.*, 29: 169-182.
- CHOUDHURY, B.J., and S.B. IDSO, 1985a. Evaluating plant and canopy resistances of field-grown wheat from concurrent diurnal observations of leaf water potential, stomatal resistance, canopy temperature, and evapotranspiration flux. *Agric. For. Meteorol.*, 34: 67-76.
- CHOUDHURY, B.J. and S.B. IDSO, 1985b. An empirical model for stomatal resistance of field-grown wheat. *Agric. For. Meteorol.*, 36: 65-82.
- CHOUDHURY, B.J. and J.L. MONTEITH, 1986. Implications of stomatal response to saturation deficit for the heat balance of vegetation. *Agric. For. Meteorol.*, 36: 215-225.
- COLUMELLA, L.J.M., 65. *De Re Rustica. liber XI: 3, 52.* Edition: R. Calzecchi Onesti, 1977. Giulio Einaudi, Torino.
- COOPER, A.J., 1959. Observations on the growth of the leaves of glasshouse tomato plants between March and August. *J. Hort. Sci.*, 34: 104-110.
- CORVER, F.J.M., 1984. Productie van het tomatengewas in het Venlowarenhuis. Institute of Agricultural Engineering (IMAG), Wageningen, Intern. Rep.
- CORVER, F.J.M., 1985. Productie van het tomatengewas in het Venlowarenhuis. Institute of Agricultural Engineering (IMAG), Wageningen, Intern. Rep.
- COULSON, K.L., 1975. Solar and terrestrial radiation. Methods and measurements. Academic Press, New York: 112.
- CURRAN, J.C., 1979. Regional mean Bowen ratios deduced from diurnal changes of temperature and humidity. *J. Hydrol.* 40: 113-121.
- De GRAAF, R., 1978. Onderzoek naar de waterhuishouding, in het bijzonder het waterverbruik bij een teelt van stooktomaten in 1977. Proefstation voor de groenten- en fruitteelt onder glas, Naaldwijk, Intern. versl., 36: 34 pp.
- De GRAAF, R., 1985. Nieuwe automatische watergeefsystemen: keuzemogelijkheden vergeleken. *Tuinderij*, 65(28): 68-71.
- De GRAAF, R., and J. Van den ENDE, 1981. Transpiration and evapotranspiration of the glasshouse crops. *Acta Horticulturae*, 119: 147-158.
- De JONG, T., 1985. Metingen aan- en simulatie van het kasklimaat. M.Sc. Dissertation, Agricultural University, Wageningen: 8-12.
- De KONING, A.N.M., 1985. Voordeliger tomaten telen? *Tuinderij*, 65(14): 16-17.
- De WIT, C.T., 1965. Photosynthesis of leaf canopies. *Agric. Res. Rep.*, n. 663, Pudoc, Wageningen: 57 pp.
- DOORENBOS, J. and W.O. PRUITT, 1977. Guidelines for predicting Crop Water Requirements. Food and Agriculture Organization of the United Nations, Rome, Irrigation and Drainage paper n. 24 : 144 pp.
- DOORENBOS, J. and A.H. KASSAM, 1979. Yield response to water. Food and Agriculture Organization of the United Nations, Rome, Irrigation and Drainage paper n. 33: 193 pp.
- DORMANS, F.J.S.M., 1983. Metingen aan en simulatie van gewasverdamping in een geschermd kas. M. Sc. Dissertation, Agricultural University, Wageningen: 5.14-5.21.
- EHRLER, W.L., F.S. NAKAYAMA and C.H.M. Van BAVEL, 1965. Cyclic changes in water balance and transpiration of cotton leaves in a steady environment. *Physiol. Plant.*, 18: 766-775.
- FUCHS, M. and G. STANHILL, 1980. Row structure and foliage geometry as determinants of the interception of light rays in a sorghum row canopy. *Plant, Cell and Environment*, 3: 175-182.

- GAASTRA, P., 1959. Photosynthesis of crop plants as influenced by light, carbon dioxide, temperature and stomatal diffusion resistance. Meded. Landbouwhogeschool, Wageningen, 59 (13): 68 pp.
- GAASTRA, P., 1963. Climatic control of photosynthesis and respiration. In: L.T. EVANS ed., *Environmental Control of Plant Growth*. Academic Press, New York: 113-140.
- GARZOLI, K., 1985. Discussion of poster group B 'Physical Models and the Greenhouse Climate'. *Acta Horticulturae*, 174: 167-168.
- GASH, J.H.C. and J.B. STEWART, 1975. The average surface resistance of a pine forest derived from Bowen ratio measurements. *Boundary-Layer Meteorol.*, 8: 453-464.
- GATES, D.M., 1968. Transpiration and leaf temperature. *Ann. Rev. Plant Physiol.*, 19: 211-238.
- GAUSMAN, H.W., W.A. ALLEN, C.L. WIEGAND, D.E. ESCOBAR, R.E. RODRIGUEZ and A.J. RICHARDSON, 1973. The leaf mesophylls of twenty crops, their light spectra, and optical and geometrical parameters. United States Dept. of Agriculture (USDA), Technical Bulletin 1465.
- GAY, A.P. and R.G. HURD, 1975. The influence of light on stomatal density in the tomato. *New Phytologist*, 75: 37-46.
- GOEIJENBIER, P., 1985. Beperkingen bij meten en regelen van vocht. *Groenten en Fruit*, 41(15): 44-47.
- GOUDRIAAN, J., 1977. Crop micrometeorology: a simulation study. *Simulation Monographs*, Pudoc, Wageningen: 249 pp.
- GRACE, J., 1981. Some effects of wind on plants. In: J. GRACE, E.D. FORD and P.G. JARVIS eds., *Plants and their Atmospheric Environment*. Blackwell Scientific Publications, Oxford: 31-56.
- GRACE, J. and J. WILSON, 1976. The boundary layer over a *Populus* leaf. *J. Exptl. Bot.*, 27: 231-241.
- GREGORY, F.G. and H.L. PEARSE, 1937. The effect on the behaviour of stomata of alternating periods of light and darkness of short duration. *Ann. Bot. N.S.*, 1 (1): 3-10.
- HAMAKER, Ph. and R. DE GRAAF, 1978. Onderzoek naar de waterhuishouding bij de teelt van paprika's en komkommers in het najaar. Institute for Land and Water Management Research (ICW), Wageningen, Nota 1030: 32 pp.
- HASEBA, T., 1973. Water-vapour transfer from leaf-like surfaces within canopy models. *J. Agric. Meteorol.*, Tokyo, 29: 25-33.
- HASHIMOTO, Y., T. MORIMOTO and S. FUNADA, 1982. Image processing of plant information in the relation between leaf temperature and stomatal aperture. *Proc. 9th IMEKO World Congress*, vol. V/III: 318-325.
- HIPPS, L.E., G. ASRAR and E.T. KANEMASU, 1985. A theoretically-based normalization of environmental effects on foliage temperature. *Agric. For. Meteorol.*, 35: 113-122.
- HOPMANS, P.A.M., 1971. Rhythms in stomatal opening of bean leaves. Meded. Landbouwhogeschool, Wageningen, 71 (3): 86 pp.
- HUNT, L.A., I.I. IMPENS and E.R. LEMON, 1968. Estimates of the diffusion resistance of some large sunflower leaves in the field. *Plant Physiol.*, 43: 522-526.
- IDSO, S.B., 1968. Comments on the paper by Richard Lee, 'The hydrologic importance of transpiration control by stomata'. *Water Resources Res.*, 4(3): 665-666.
- IDSO, S.B., 1982. Non-water-stressed baselines: a key to measuring and interpreting plant water stress. *Agric. Meteorol.*, 27: 59-70.
- IDSO, S.B., 1983. Stomatal regulation of evaporation from well-watered plant canopies: a new synthesis. *Agric. Meteorol.*, 29: 213-217.

- IDSO, S.B., 1984. Book reviews. *Agric. For. Meteorol.*, 32: 339-341.
- IDSO, S.B., R.J. REGINATO, K.L. CLAWSON and M.G. ANDERSON, 1984. On the stability of non-water-stressed baselines. *Agric. For. Meteorol.*, 32: 177-182.
- IQBAL, M. and J.A. STOFFERS, 1975. Natural convection heat transfer in covered plant canopies. *Agric. Meteorol.*, 15: 97-111.
- JARVIS, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. Royal Soc. London, B* 273: 593-610.
- JARVIS, P.G., 1981. Stomatal conductance, gaseous exchange and transpiration. In: J. GRACE, E.D. FORD and P.G. JARVIS eds., *Plants and their Atmospheric Environment*. Blackwell Scientific Publications, Oxford : 175-204.
- JARVIS, P.G., W.R.N. EDWARDS and H. TALBOT, 1981. Models of plant and crop water use. In: D.A. ROSE and D.A. CHARLES-EDWARDS eds., *Mathematics and Plant Physiology*. Academic Press, London: 151-194.
- JONES, H.G., 1983. *Plants and Microclimate*. Cambridge University Press, Cambridge : 323 pp.
- KASANAGA, H. and M. MONSI, 1954. On the light transmission of leaves, and its meaning for the production of matter in plant communities. *Jap. J. Bot.*, 14: 304-324.
- KATERJI, N. and A. PERRIER, 1985. Détermination de la résistance globale d'un couvert végétal à la diffusion de vapeur d'eau et des ses différentes composantes. Approche théorique et vérification expérimentale sur une culture de luzerne. *Agric. For. Meteorol.*, 34: 105-120.
- KIMBALL, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage of 430 prior observations. *Agron. J.*, 75: 779-788.
- KIMBALL, B.A., 1986. A modular energy balance program including subroutines for greenhouses and other latent heat devices. United States Dept. of Agriculture (USDA), *Agric. Res. Service, ARS-33*: 356 pp.
- KLAPWIJK, D., 1987. Lichtafhankelijk stoken? *Groenten en Fruit*, 42(26): 40-43.
- KÖRNER, Ch., J.A. SCHEEL and H. BAUER, 1979. Maximum leaf diffusive resistance in vascular plants. *Photosynthetica*, 13 (1): 45-82.
- KOZAI, T., 1985. Ideas of greenhouse climate control based on knowledge engineering techniques. *Acta Horticulturae*, 174: 365-373.
- KREITH, F., 1976. *Principles of Heat Transfer*. Intext Press Inc., New York: 656 pp.
- KREITH, F., and W.D. SELLERS, 1975. General principles of natural evaporation. In: D.A. de VRIES and N.H. AFGAN eds., *Heat and Mass Transfer in the Biosphere*. Scripta Book Company, Washington, 1: 207-224.
- KUIPER, P.J.C., 1961. The effects of environmental factors on the transpiration of leaves, with special reference to stomatal light response. *Meded. Landbouwhogeschool, Wageningen*, 61 (7): 49 pp.
- LANDSBERG, J.J., B. WHITE and M.R. THORPE, 1979. Computer analysis of the efficacy of evaporative cooling for glasshouses in high energy environments. *J. Agric. Engng. Res.*, 24: 29-39.
- LANG, A.R.G. and G.S.G. SHELL, 1976. Sunlit areas and angular distributions of sunflower leaves for plants in single and multiple rows. *Agric. Meteorol.*, 16: 5-15.
- LANGE, O.L., R. LÖSCH, E.D. SCHULZE and L. KAPPEN, 1971. Response of stomata to changes in humidity. *Planta*, Berlin, 100: 76-86.
- LEE, R., 1967. The hydrological importance of transpiration control by stomata. *Water Resources Res.*, 3(3): 737-752.
- LEE, R., 1968a. Reply. *Water Resources Res.*, 4(3): 667-669.
- LEE, R., 1968b. Reply. *Water Resources Res.*, 4(6): 1389-1390.

- LEMMON, K., 1962. The covered Garden. Museum Press Ltd., London: 14.
- LIM, A.T., 1969. A study of convective heat transfer from plant leaf models. M.Sc. Dissertation, Duke University, Dept. of Mech. Engineering, Durham, N.Car.: 102 pp.
- LIN, C.C., 1970. The Theory of Hydrodynamic Stability. Cambridge University Press, London.
- LINACRE, E.T., 1964. A note on a feature of leaf and air temperature. *Agric. Meteorol.*, 1: 66-72.
- LISS, P.S. and A.J. CRANE, 1984. Man-made Carbon Dioxide and Climatic Change. Geo Books, Norwich: 127 pp.
- LÖSCH, R. and J.D. TENHUNEN, 1981. Stomatal response to humidity – phenomenon and mechanism. In: P.G. JARVIS and T.A. MANSFIELD, eds., *Stomatal Physiology*. Cambridge University Press, Cambridge: 137-161.
- LYON, C.J., 1948. A factor method for the area of tomato leaves. *Plant Physiol.*, 23: 634-635.
- MANN, J.E., G.L. CURRY, D.W. De MICHELE and D.N. BAKER, 1980. Light penetration in a row-crop with random plant spacing. *Agron. J.*, 72: 131-142.
- MANSFIELD, T.A., 1965. Studies in stomatal behaviour XII. Opening in high temperature in darkness. *J. Exptl. Bot.*, 16: 721-731.
- MANSFIELD, T.A., A.J. TRAVIS and R.G. JARVIS, 1981. Responses to light and carbon dioxide. In: P.G. JARVIS and T.A. MANSFIELD eds., *Stomatal physiology*. Cambridge University Press, Cambridge: 119-135.
- MARTIALIS, M.V., 93. *Epigrammi. Liber VIII, Ep. 14*. Edition: G. Ceronetti, 1964. Giulio Einaudi, Torino.
- MATTHEWS, R.B. and R.A. SAFFELL, 1986. Computer control of humidity in experimental glasshouses. *J. Agric. Engng. Res.*, 33: 213-221.
- McNAUGHTON, K.G. and T.A. BLACK, 1973. A study of evapotranspiration from a Douglas fir forest using the energy balance approach, *Water Resources Res.*, 9: 1579-1590.
- MEIDNER, H. and T.A. MANSFIELD, 1968. *Physiology of Stomata*. McGraw-Hill, London: 179 pp.
- MEIJER, J., G.P.A. BOT, C. STANGHELLINI and A.J. UDINK ten CATE, 1985. Development and application of a sensitive, high precision weighing lysimeter for use in greenhouses. *J. Agric. Engng. Res.*, 32: 321-336.
- MENENTI, M., 1984. Evaporation in Deserts. Institute for Land and Water Management Research (ICW), Wageningen, Rep. 10 (special issue): 202 pp.
- MONTEITH, J.L., 1963. Gas exchange in plant communities. In: L.T. EVANS ed., *Environmental Control of Plant Growth*. Academic Press, New York: 95-112.
- MONTEITH, J.L., 1965. Evaporation and environment. In: *The State and Movement of Water in Living Organisms*, 19th Symp. Soc. Exp. Biol.: 205-234.
- MONTEITH, J.L., 1969. Light interception and radiative exchange in crop stands. In: J.D. EASTIN ed., *Physiological Aspects of Crop Yield*. Am. Soc. of Agronomy, Madison, Wisc.: 89-111.
- MONTEITH, J.L., 1972. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecol.*, 9: 747-766.
- MONTEITH, J.L., 1975. *Principles of Environmental Physics*. Edward Arnold, London: 241 pp.
- MONTEITH, J.L., 1981a. Evaporation and surface temperature. *Quart. J. Roy. Meteorol. Soc.*, 107(451): 1-27.

- MONTEITH, J.L., 1981b. Coupling of plants to the atmosphere. In: J. GRACE, E.D. FORD and P.G. JARVIS eds., *Plants and their Atmospheric Environment*. Blackwell Scientific Publications, Oxford: 1-29.
- MONTEITH, J.L., G. SZEICZ and P.E. WAGGONER, 1965. The measurement and control of stomatal resistance in the field. *J. Appl. Ecol.*, 2: 345-355.
- MORESHET, S. and C.S. YOCUM, 1972. A condensation type porometer for field use. *Plant Physiol.*, 49: 944-949.
- MORRIS, L.G., F.E. NEALE and J.P. POSTLETHWAITE, 1957. The transpiration of glasshouse crops and its relationship to the incoming solar radiation. *J. Agric. Engng. Res.*, 2: 111-122.
- MYNENI, R.B. and I. IMPENS, 1985a. A procedural approach for studying the radiation regime of infinite and truncated foliage spaces. Part I. Theoretical considerations. *Agric. For. Meteorol.*, 33: 323-337.
- MYNENI, R.B. and I. IMPENS, 1985b. A procedural approach for studying the radiation regime of infinite and truncated foliage spaces. Part II. Experimental results and discussion. *Agric. For. Meteorol.*, 34: 3-16.
- NEILSON, R.E. and P.G. JARVIS, 1975. Photosynthesis in Sitka Spruce (*Picea sitchensis* (Bong.) Carr.). VI. Response of stomata to temperature. *J. Appl. Ecol.*, 12: 721-745.
- NEWTON, J.E. and G.E. BLACKMAN, 1970. The penetration of solar radiation through leaf canopies of different structure. *Ann. Bot.*, 34: 329-348.
- NG, P.A.P. and P.G. JARVIS, 1980. Hysteresis in the response of stomatal conductance in *Pinus sylvestris* needles to light: observations and a hypothesis. *Plant, Cell and Environment*, 3: 207-216.
- NOBEL, P.S., 1974. *Introduction to Biophysical Plant Physiology*. W.H. Freeman and Co., San Francisco: 406-407.
- NORMAN, J.M., 1975. Radiative transfer in vegetation. In: D.A. de VRIES and N.H. AFGAN eds., *Heat and Mass Transfer in the Biosphere*. Scripta Book Company, Washington., 1: 187-205.
- NORMAN, J.M. and J.M. WELLES, 1983. Radiative transfer in an array of canopies. *Agron. J.*, 75: 481-488.
- PARKHURST, D.F., P.R. DUNCAN, D.M. GATES and F. KREITH, 1968a. Convection heat transfer from broad leaves of plants. *J. Heat Transfer (Trans. ASME)*, 90: 71-76.
- PARKHURST, D.F., P.R. DUNCAN, D.M. GATES and F. KREITH, 1968b. Wind-tunnel modelling of convection from plant leaves. *Agric. Meteorol.*, 5: 33-47.
- PEARMAN, G.I., H.L. WEAVER and C.B. TANNER, 1972. Boundary layer heat transfer coefficients under field conditions. *Agric. Meteorol.*, 10: 83-92.
- PENMAN, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Meteorol. Soc. A*, 193: 120-145.
- PERRIER, A., 1976. Étude et essai de modélisation des échanges de masse et d'énergie au niveau des couverts végétaux: profils micro-climatiques, évapotranspiration et photosynthèse nette. Ph.D. Dissertation, University of Paris VI: 240 pp.
- PLINIUS, S.G., 77. *Naturalis Historia. Liber XIX*: 19,4 and 23,5. Edition: Ajasson de Grandsagne, 1829-1833. Bibliotheque Latine- Francaise. C.L.F. Panckoucke, Paris.
- PORTER, A.M., 1937. Effect of light intensity on the photosynthetic efficiency of tomato plants. *Plant Physiol.*, 12(2): 225-252.
- PRIESTLEY, C.H.B., 1966. The limitation of temperature by evaporation in hot climates. *Agric. Meteorol.*, 3: 241-246.
- RABBINGE, R., 1986. The bridge function of crop ecology. *Neth. J. Agric. Sci.*, 34: 239-251.

- RASCHKE, K., 1960. Heat transfer between the plant and the environment. *Ann. Rev. Plant Physiol.*, 11: 111-126
- RASCHKE, K., 1975. Stomatal action. *Ann. Rev. Plant Physiol.*, 26: 309-340.
- ROBERTS, J.M., C.F. PYMAR, J.S. WALLACE AND R.M. PITMAN, 1980. Seasonal changes in leaf area, stomatal and canopy conductances and transpiration from bracken below a forest canopy. *J. Appl. Ecol.*, 17: 409-422.
- ROSENBERG, N.J., 1974. *Microclimate: the biological Environment*. John Wiley and Sons, Inc., New York: 315 pp.
- ROSS, A.A., 1946. Studies of growth correlations in the tomato. *Queensland J. Agric. Sci.*, 3: 121-156.
- ROSS, J., 1975. Radiative transfer in plant communities. In: J.L. MONTEITH, ed., *Vegetation and Atmosphere*, Academic Press, London: 13-55.
- ROSS, J., 1981. *The Radiation Regime and Architecture of Plant Stands*. Dr W. Junk Publishers, The Hague: 391 pp.
- ROVERS, J.A., 1985. Tomatenplanten moeten lang en optimaal produceren. *Tuinderij*, 65 (1): 30-31.
- RIJTEMA, P.E., 1965. An analysis of actual evapotranspiration. *Agric. Res. Rep.* 659. Pudoc, Wageningen: 107 pp.
- SCHENK, J. and C.J. STIGTER, 1975. *Omgevingsnatuurkunde van de bovengrondse delen van de plant. Heterosiscursus 'Omgevingsnatuurkunde van grond en gewas'*, Landbouwhogeschool, Wageningen, voordracht 9.
- SCHEUPP, P.H., 1980. Heat and moisture transfer from flat surfaces in intermittent flow: a laboratory study. *Agric. Meteorol.*, 22: 351-366.
- SEGINER, I., 1984. On the night transpiration of greenhouse roses under glass or plastic cover. *Agric. Meteorol.*, 30: 257-268.
- SENECA, L.A., 63. *Epistulae morales ad Lucilium. Liber XIX-XX: Ep. 13 (122)*. Edition: E. Romagnoli, 1934. Collezione Romana. Soc. An. Notari, Villa Santa (Milano).
- SHEPERD W., 1972. Some evidence of stomatal restriction of evaporation from well-watered plant canopies. *Water Resources Res.*, 8(4): 1092-1095.
- SHIRAISHI, M., Y. HASHIMOTO and S. KURAISHI, 1978. Cyclic variations of stomatal aperture observed under the scanning electron microscope. *Plant and Cell Physiol.*, 19(4): 637-645.
- SHUTTLEWORTH, W.J., 1976. A one-dimensional theoretical description of the vegetation-atmosphere interaction. *Boundary-Layer Meteorol.*, 10: 273-302.
- SIMMONS, R.C., 1970. Heat and water vapour transfer of real and artificial leaves. B.Sc. Dissertation, University of Nottingham, School of Agriculture.
- SIVAKUMAR, M.V.K. and S.M. VIRMANI, 1984. Crop productivity in relation to interception of photosynthetically active radiation. *Agric. For. Meteorol.*, 31: 131-141.
- SLATYER, R.O., 1977. Altitudinal variation in the photosynthetic characteristic of Snow gum, *Eucalyptus pauciflora* Sieb. ex Spreng. IV. Temperature response of four populations grown at different temperatures. *Aust. J. Plant Physiol.*, 4: 583-594.
- SLATYER, R.O. and J.F. BIERHUIZEN, 1964. Transpiration from cotton leaves under a range of environmental conditions in relation to internal and external diffusive resistances. *Aust. J. Biol. Sci.*, 17: 115-130.
- SLOB, W.H., 1982. Climatological values of solar irradiation on the horizontal and several inclined surfaces at De Bilt. Dutch Roy. Meteorol. Institute (KNMI), De Bilt, Scient. Rep. W.R. 82-7: 19 pp.
- SORBELLO-HERRENDORF, V., 1981. Plant resistance to water flow. M.Sc. Dissertation, Agricultural University, Wageningen: 42 pp.

- SPARROW, E.M. and J.L. GREGG, 1956. Laminar free convection from a vertical plate with uniform surface heat flux. *J. Heat Transfer (Trans. ASME)*, 78: 435-440.
- SQUIRE, G.R. and C.R. BLACK, 1981. Stomatal behaviour in the field. In: P.G. JARVIS and T.A. MANSFIELD eds., *Stomatal Physiology*. Cambridge University Press, Cambridge: 223-245.
- STÄLFELT, M.G., 1955. The stomata as a hydrophotic regulator of the water deficit of the plant. *Physiol. Plant.*, 8: 572-593.
- STÄLFELT, M.G., 1962. The effect of temperature on the stomatal cells. *Physiol. Plant.*, 15: 772-779.
- STANGHELLINI, C., 1983a. Radiation absorbed by a tomato crop in a greenhouse. Institute of Agricultural Engineering (IMAG), Wageningen, Res. Rep. 83-5: 23 pp.
- STANGHELLINI, C., 1983b. Evaporation of a greenhouse crop and its relationship to the supply of heat. Institute of Agricultural Engineering (IMAG), Wageningen, Res. Rep. 83-6: 31 pp.
- STANGHELLINI, C., 1983c. Forcing functions in greenhouse climate and their effect on transpiration of crops. Institute of Agricultural Engineering (IMAG), Wageningen, Res. Rep. 83-4: 55 pp.
- STANGHELLINI, C., 1983d. Calculation of the amount of energy released by heating pipes in a greenhouse and its allocation between convection and radiation. Institute of Agricultural Engineering (IMAG), Wageningen, Res. Rep. 83-3: 20 pp.
- STANGHELLINI, C., 1985. Transpiration and temperature of greenhouse crops, in relation to internal and external resistances. *Acta Horticulturae*, 174: 87-95.
- STANGHELLINI, C., 1987. The role of internal and external resistances in scheduling irrigation of a greenhouse crop. *Acta Horticulturae*, Irrigation and Water Gift: in press.
- STANHILL, G., M. FUCHS, J. BAKKER and S. MORESHET, 1973. The radiation balance of a glasshouse rose crop. *Agric. Meteorol.*, 11: 385-404.
- STANHILL, G. and J. SCHOLTE ALBERS, 1974. Solar radiation and water loss from glasshouse roses. *J. Am. Soc. Hort. Sci.*, 99 (2): 107-110.
- STEWART, J.B. and A.S. THOM, 1973. Energy budgets in pine forests. *Quart. J. Roy. Meteorol. Soc.*, 99: 154-170.
- STIGTER, C.J., 1972. Leaf diffusion resistance to water vapour and its direct measurement I. Introduction and review concerning relevant factors and methods. *Meded. Landbouwhogeschool, Wageningen*, 72 (3): 47 pp.
- STIGTER, C.J., J. BIRNIE and B. LAMMERS, 1973. Leaf diffusion resistance to water vapour and its direct measurement II. Design, calibration and pertinent theory of an improved leaf diffusion resistance meter. *Meded. Landbouwhogeschool, Wageningen*, 73 (15): 55 pp.
- STOFFERS, J.A., 1975. Radiation absorption of canopy rows. *Acta Horticulturae*, 46: 91-95.
- SUNDERLAND, R.A., 1968. Experiments on momentum and heat transfer with artificial leaves. B.Sc. Dissertation, University of Nottingham, School of Agriculture: 75 pp.
- TAKAKURA, T., K.A. JORDAN and L.L. BOYD, 1971. Dynamic simulation of plant growth and environment in the greenhouse. *Trans. Am. Soc. Agric. Eng. (ASAE)*, 14: 964-971.
- TAKAKURA, T., J. GOUDRIAAN and W. LOUWERSE, 1975. A behaviour model to simulate stomatal resistance. *Agric. Meteorol.*, 15: 393-404.
- TANTAU, H.J., 1985. Greenhouse climate control using mathematical models. *Acta Horticulturae*, 174: 449-459.

- THOFELT, L., H. RUFELT and P.A. BRATTEMO, 1984. A note on the influence of a windbreak on plant temperature. *Agric. For. Meteorol.*, 32: 1-11.
- THOM, A.S., 1968. The exchange of momentum, mass, and heat between an artificial leaf and the airflow in a wind-tunnel. *Quart. J. Roy. Meteorol. Soc.*, 94: 44-55.
- THOM, A.S., 1972. Momentum, mass and heat exchange of vegetation. *Quart. J. Roy. Meteorol. Soc.*, 98: 124-134.
- UDINK ten CATE, A.J., 1983. Modeling and (adaptive) control of greenhouse climates. Ph.D. Dissertation, Agricultural University, Wageningen: 159 pp.
- UDINK ten CATE, A.J., G.P.A. BOT and J. Van DIXHOORN, 1978. Computer control of greenhouse climates. *Acta Horticulturae*, 87: 265-272.
- Van BAVEL, C.H.M., 1966. Potential evaporation: the combination concept and its experimental verification. *Water Resources Res.*, 2 (3): 455-467.
- Van BAVEL, C.H.M., 1968. Further to the hydrological importance of transpiration control by stomata. *Water Resources Res.*, 4 (6): 1387-1388.
- Van BAVEL, C.H.M., J. DAMAGNEZ and E.J. SADLER, 1981a. The fluid roof solar greenhouse: energy budget analysis by simulation. *Agric. Meteorol.*, 23: 61-76.
- Van BAVEL, C.H.M., E.J. SADLER and J. DAMAGNEZ, 1981b. Cooling greenhouse crops in a Mediterranean summer climate. *Acta Horticulturae*, 115: 527-536.
- Van den MUIJZENBERG, E.W.B., 1980. A history of greenhouses. Institute of Agricultural Engineering (IMAG), Wageningen: 435 pp.
- Van der VARST, P.G.I. and J.D.G. POSTEL, 1972. Bepaling bladoppervlak van tomatenplanten. Instituut voor Tuinbouwtechniek (ITT), Wageningen, Rapport 46: 36 pp.
- Van KEULEN, H. and H.H. Van LAAR, 1986. The relation between water use and crop production. In: H. Van KEULEN and J. WOLF eds., *Modelling of Agricultural Production: weather, soils and crops*. Pudoc, Wageningen: 117-129.
- Van MEURS, W.T.M., 1980. The climate control computer system at the IMAG, Wageningen. *Acta Horticulturae*, 106: 77-83.
- Van MEURS, W.T.M. and T.H. GIELING, 1981. A research strategy to solve air humidity problems in greenhouses, caused by the use of energy-saving measures. *Acta Horticulturae*, 115: 359-364.
- Van ONNA, B., 1985. Weersovergangen tijdig opvangen. Vooral de vochthuishouding kan problemen geven. *Tuinderij*, 65(12): 20-21.
- Van 't OOSTER, B., 1983. Metingen aan en simulatie van het klimaat in een geschermd kas. M.Sc. Dissertation, Agricultural University, Wageningen: 56-58.
- VEGTER, B., 1983. Programma's nog niet altijd naar wens. *Vakblad voor de Bloemisterij*, 38 (26): 26-29.
- VERWAAJEN, P.W.T., T.H. GIELING and W.T.M. Van MEURS, 1985. Measurement and control of the climate in a greenhouse, where a heated concrete-floor is used as low temperature energy source. *Acta Horticulturae*, 174: 469-475.
- Von ELSNER, B., 1982. Das Kleinklima und der Wärmeverbrauch von geschlossenen Gewächshäusern. Institut für Technik in Gartenbau und Landwirtschaft, Universität Hannover: 197 pp.
- VOGEL, S., 1970. Convective cooling at low airspeeds and the shapes of broad leaves. *J. Exptl. Bot.*, 21 (66): 91-101.
- WAGGONER, P.E. AND W.E. REIFSNYDER, 1968. Simulation of the temperature, humidity and evaporation profiles in a leaf canopy. *J. Appl. Meteorol.*, 7: 400-409.
- WANG, X.A., 1982. An experimental study of mixed, forced and free convection heat transfer from a horizontal flat plate to air. *J. Heat Transfer (Trans. ASME)*, 104: 139-144.



- WHITFIELD, D.M., 1986. A simple model of light penetration into row crops. *Agric. For. Meteorol.*, 36: 297-315.
- WIGLEY, G. and J.A. CLARK, 1974. Heat transport coefficients for constant energy flux models of broad leaves. *Boundary-Layer Meteorol.*, 7: 139-150.
- YAGLOM, A.M., 1977. Comments on temperature flux-profile relationships. *Boundary-Layer Meteorol.*, 11: 89-102.
- YAMOAKA, Y., 1958. Total transpiration from a forest. *Trans. Am. Geophys. Union*, 39: 266-272.
- ZANDBELT, A.J., 1983. Selectief regelen van luchtvochtigheid. *Vakblad voor de Bloemisterij*, 38(48): 44-45.
- ZANDBELT, A.J., 1984. Vochtregelen met de klimaatcomputer. *Tuinderij*, 64(30): 22-25.
- ZHAO, J., B. JENKINS, R.H. SHAW and I. SEGNER, 1985. Heat and water vapour balance of greenhouse plant leaves under convective and infrared heating. *Am. Soc. Ag. Engng.*, St Joseph MI, Paper No 85-4052: 32 pp.