BARD

FINAL REPORT
PROJECT NO. I-390-82

**Optimization of Greenhouse Ventilation for
Humidity Control and Energy Conservation**

I. Seginer, R.H. Shaw, U.M. Peiper

1987

000000011648

24415

2000 10

30 April 1987

BARD
POBox 6
Bet Dagan 50250, ISRAEL

BARD project No. I-390-82

OPTIMIZATION OF GREENHOUSE VENTILATION FOR HUMIDITY CONTROL AND ENERGY CONSERVATION

Investigators

Institution

Ido Segner	Technion, Haifa 32000, Israel
Roger H. Shaw	University of California, Davis, CA 95616, USA
Uri M. Peiper	Agricultural Research Organization, Bet Dagan 50250, Israel

התאחדות המחקר והפיתוח
לחקר ופיתוח תעשיית
הבנייה והקונסטרוקציה
ב"מ-83

Project starting date: 1 November 1983

Type of report: **FINAL**

Principal Investigator

Institution's Authorizing Official

$$\frac{630.72}{\text{BAR/SEG}} : 631.544 : 728.9 : 531.6$$

2nd copy

Technion, Israel Institute of Technology
Agricultural Engineering Department

University of California - Davis
Land, Air and Water Resources Department

Agricultural Research Organization, Israel
Agricultural Engineering Institute

**OPTIMIZATION OF GREENHOUSE VENTILATION FOR HUMIDITY CONTROL AND ENERGY
CONSERVATION**

Final Research Report, BARD Project I-390-82

Covering the Period 1 November 1983 to 30 April 1987

Prepared by

Ido Seginer,
Roger H. Shaw,
Uri M. Peiper,

Principal Investigator, Technion
Cooperating Investigator, UCD
Cooperating Investigator, ARO

Submitted to BARD, POBox 6, Bet Dagan 50250, Israel

Haifa, Davis and Bet Dagan, April 1987

TABLE OF CONTENTS

page

Authors' affiliation	v
Abstract	vi
1. Introduction	
I. Seginer	
1. Problem and objectives	1- 1
2. Approach	1- 2
3. Overview of report	1- 3
2. In-situ determination of transfer coefficients for heat and water vapor in a small greenhouse	
I. Seginer, D. Kantz	
Abstract	2- 1
1. Introduction	2- 1
2. Model	2- 3
3. Experimental procedure	2- 5
4. General description of results	2- 6
5. Transfer coefficients	2- 9
6. An approximate formula for the inside relative humidity . .	2-13
7. Discussion and conclusion	2-14
References	2-16
3. Transfer coefficients of several polyethylene greenhouse covers	
I. Seginer, D. Kantz, U.M. Peiper, N. Levav	
Abstract	3- 1
Notation	3- 2
1. Introduction	3- 3
2. Experimental procedure	3- 5
3. Model and analysis	3- 7
4. Results	3-12
5. Comparison with commercial greenhouses	3-17
6. Discussion and conclusion	3-18
References	3-21
Appendices	3-22
Tables	3-24
Figures	3-25
4. Nocturnal water balance under several polyethylene greenhouse covers	
I. Seginer, D. Kantz	
Abstract	4- 1
Notation	4- 2
1. Introduction	4- 3
2. Model	4- 4
3. Experimental procedure	4- 5
4. Results	4- 7
5. Steady-state relationships	4- 9

6. Transient analysis	4-12
7. Conclusions	4-14
References	4-16
Tables	4-17
Figures	4-19
 5. Heat and water vapor balance of greenhouse plant leaves under convective and infrared heating	
J. Zhao, B. Jenkins, R.H. Shaw, I. Seginer	
Abstract	5- 1
1. Introduction	5- 1
2. Literature review	5- 2
3. Theoretical background	5- 3
4. Methods and procedure	5- 7
5. Results and discussion	5-10
References	5-12
Tables	5-15
Figures	5-18
 6. Night time transpiration and evaporation in greenhouses	
I. Seginer, D. Kantz, N. Levav, U.M. Peiper	
Abstract	6- 1
Notation	6- 1
1. Introduction	6- 2
2. Procedure	6- 3
3. Results	6- 6
4. Discussion	6-10
References	6-13
Tables	6-14
Figures	6-17
 7. Identification of onset of condensation on leaves	
R.H. Shaw, N. Cherry, W. Gao	
Abstract	7- 1
1. Introduction	7- 2
2. Psychrometry and hygrometry	7- 3
3. Materials and methods	7- 8
4. Results	7-10
5. Summary and conclusion	7-12
References	7-13
Figures	7-14
 8. Experimental evaluation and mathematical model of an hygroscopic greenhouse dehumidifier	
U.M. Peiper, N. Levav, F. Geoola, I. Seginer	
Abstract	8- 1
Notation	8- 2
1. Introduction	8- 3
2. Construction and operation of the system	8- 3
3. Operating principles	8- 4

4. Simulation	8- 5
5. Measurement procedure	8- 7
6. Results and discussion	8- 7
Figures	8-13

9. Maintenance of desirable nighttime temperature and humidity in greenhouses

I. Seginer, D. Kantz

Abstract	9- 1
Notation	9- 2
1. Introduction	9- 3
2. Model	9- 4
3. Calculations	9- 9
4. Results	9-11
5. Discussion and conclusion	9-15
6. References	9-19
Figures	9-21

10. Conclusion

I. Seginer

1. Cooperation	10- 1
2. Research achievements	10- 2
3. List of publications	10- 5

AUTHORS' AFFILIATION

Cherry N.	UC Davis, USA	LAWR Department
Gao, W.	UC Davis, USA	LAWR Department
Geoola, F.	ARO, Israel	Agricultural Engineering Institute
Jenkins, B.	UC Davis, USA	Agricultural Engineering Department
Kantz, Dvora	Technion, Israel	Agricultural Engineering Department
Levav, Nahum	ARO, Israel	Agricultural Engineering Institute
Peiper, Uri M.	ARO, Israel	Agricultural Engineering Institute
Seginer, Ido	Technion, Israel	Agricultural Engineering Department
Shaw, Roger H.	UC Davis, USA	LAWR Department
Zhao, J.	UC Davis, USA	LAWR Department

OPTIMIZATION OF GREENHOUSE VENTILATION FOR HUMIDITY CONTROL AND ENERGY CONSERVATION

I. Seginer, R.H. Shaw, U.M. Peiper

ABSTRACT

Greenhouse fungus diseases thrive in high humidity environments. To maintain low humidity in greenhouses at night, light forced ventilation is traditionally applied, but this increases the heating energy requirement of the greenhouse. Recently, a new active device to reduce humidity has been introduced: the dehumidifier. It absorbs water vapor in hygroscopic brine and may replace ventilation and save some heating energy.

The objective of this study was to supply the environmental engineer with computational tools to better design and operate greenhouses. The emphasis was on minimizing energy requirement to maintain a desirable nighttime level of humidity in a greenhouse.

A steady state greenhouse model, composed of several uniform elements, such as canopy and ceiling, was formulated. Fluxes of energy and water among the elements were expressed by formulas which included transfer coefficients. Most of these coefficients could be and were extracted from experimental data obtained in the study, mostly on a small experimental greenhouse. The most general model included a crop as the vapor source, a two layer cover, heater, ventilation fan and dehumidifier. Convective and radiative fluxes were treated separately.

Several convective transfer coefficients (such as that between the greenhouse air and the ceiling), as well as radiative shape factors (such as that between the cover and the sky) were evaluated. The canopy resistance to vapor transfer at night, for a range of greenhouse crops, has also been determined.

Finally, the various experimentally determined coefficients were introduced into a steady state simulation model. The model was then used to evaluate the energy required to maintain desired temperature and humidity inside a greenhouse, when the outside weather and the properties of the greenhouse are known. The results of this activity can be used to decide which environmental control devices should be used, and determine their proper level of operation.

INTRODUCTION

Ido Seginer

1. Problem and objectives

Greenhouse fungus diseases thrive in high humidity environment. To maintain low humidity in greenhouses at night, light forced ventilation can be applied, but this increases the heating energy requirement of the greenhouse. To optimize humidity control, the cost of ventilation must be weighed against the risk of infection and the cost of fungicides. Unfortunately, not enough information is available at this time on the risk of infection. Therefore, the engineering problem is limited to maintaining a recommended environment at the minimum possible cost. The engineer can use passive or active devices to control the greenhouse environment. Passive devices include different cover materials, double layer covers, thermal capacitance, etc. Active devices include, traditionally, heating and ventilation. Most heating systems rely on convection to heat the air. The air then heats the crop. Other heating systems, such as soil heating or radiative heating have also been tried. Recently a new active device to reduce humidity has been introduced: the dehumidifier. It absorbs water vapor in hygroscopic brine and may replace ventilation and save some heating energy. The engineering problem is to make the right choice of air conditioning means for the situation at hand.

The overall objective of the research (as stated in the proposal) was to reduce energy requirement for the maintenance of appropriate internal climate in greenhouses. The specific original objectives were:

1. Adapt and develop measuring techniques to estimate heat and vapor fluxes in a greenhouse, at both the immediate vicinity of the plant and on an overall scale.
2. Identify main sources of vapor during night, and determine experimentally the effect of soil mulching, greenhouse cover, different heating systems and various modes of ventilation, on the condensation and humidity during night and transition (day to night, night to day) time.

3. Model the dynamics of evapotranspiration and condensation in a greenhouse, including stomatal and cuticular effects.

4. Develop guidelines and control algorithms for the ventilation of heated greenhouses.

Most of these objectives have been achieved, as will be detailed in the CONCLUSION section.

2. Approach

The basic approach to the problem was to develop a rather simple greenhouse model, which could be calibrated and then used to explore various design and operation possibilities through simulation.

Various models were used in various phases of the study. All, however, were versions of a basic model, which viewed the greenhouse as composed of several homogeneous static elements, plus some active environmental control devices. The static elements were as follows: floor or crop (no soil), inside air, two layers of cover, outside air and sky. Each was characterized by a single temperature and humidity. The formulation of energy and water vapor transfer between these elements required certain transfer coefficients.

Most of the effort in this project was devoted to the experimental evaluation of the various convective and radiative transfer coefficients of the system. This required devising experimental situations where energy and vapor fluxes could be measured together with the relevant temperature or vapor pressure differences. Dividing a measured flux by the relevant potential difference yielded the desired transfer coefficient. Some of the experimental situations were artificial in the sense that they could not be achieved in a commercial greenhouse. Some experimental effort was devoted to comparisons of measuring devices (e.g. psychrometers and dew-point hygrometers) and checks of their accuracy (e.g. by closing water vapor balances).

When enough information on the characteristics of the structure, the crop and the environmental control equipment was available, these were

incorporated in a simulation model, which was used to predict the performance of the system under various assumed conditions. This model could calculate the levels at which the equipment has to be operated to maintain certain inside conditions, given the outside weather conditions and the properties of the greenhouse and crop.

3. Overview of report

The report consists of 10 chapters, of which the first and last are an overall INTRODUCTION and an overall CONCLUSION. The other chapters discuss specific activities of the project and comprise the main body of the report.

The various chapters were written as independent individual papers, to facilitate eventual publication. As a result, some repetition has been unavoidable. Cross referencing among the chapters is similar to referencing any other published material. While each chapter has its own abstract, the overall ABSTRACT opening the report is an attempt to bring the whole material into one frame.

Chapters 2 to 4 deal with the nighttime performance of empty greenhouses, and are ordered chronologically. They all discuss experimental studies, designed to evaluate in-situ various transfer coefficients of the system.

Chapter 2 is a prototype study, based on a steady-state model, which includes energy and water balances of a single-layer cover greenhouse. The model was used to evaluate coefficients of a greenhouse into which water vapor was introduced artificially. Chapter 3 deals in a similar manner with a greenhouse over which four different covers were tested. Two of these covers were single layer covers and the other two were double layer covers. Regular and infra-red absorbing polyethylene sheets were used with each configuration. No vapor was introduced into the greenhouse in this study. Chapter 4, again, uses an artificial source of water vapor, this time under four different single layer polyethylene covers. Some attention is given to the transient stage, where the vapor contents of the inside air changes significantly with time. The coefficients evaluated in Chapters 2 to 4 are used to compare the conservation properties of various covers and are later (Chapter 9) incorporated into a composite model which includes a crop.

Chapters 5 to 7 deal with the transpiration of greenhouse plants and with

the onset of condensation on such plants.

Chapter 5 applies an energy balance model to formulate the response of a crop canopy to the greenhouse environment. The results can be used to predict nighttime canopy temperature and transpiration rate of a chrysanthemum crop. The differences between convective and radiative heating are considered. Chapter 6 describes a study with several vegetable and pot plants under convective heating. The leaf resistances obtained in this study can be used in simulations of commercial greenhouses. Chapter 7 explores the possibility of detecting onset of condensation on leaves. The question here is mainly the accuracy and representativeness of temperature and humidity measurements in the greenhouse.

Chapter 8 reports on some tests of a commercial dehumidifier, whose purpose is to replace ventilation (which is energy wasteful) as a means for reducing greenhouse humidity.

Chapter 9 is a calculational study, which uses data collected in all previous chapters to study the alternatives available for maintaining acceptable conditions in a greenhouse at night. In particular, the replacement of ventilation by a dehumidifier is discussed.

CONCLUSION

I. Seginer

1. Cooperation

Cooperation took place between investigators of three institutions: UCD (USA), Technion (Israel) and ARO (Israel).

As stated in the proposal, the focus of the UCD activities was on the immediate plant environment. Chapter 5, dealing with heat and water vapor balance of leaves, provided data on the leaf and aerodynamic resistance of chrysanthemum plants, which, together with data collected at Technion (Chapter 6), was later used in a simulation model (Chapter 9). During the second year, when the study of Chapter 5 was performed, the principal investigator spent his sabbatic leave at UCD. Chapter 7, dealing with the detection of onset of condensation was also performed by UCD.

The cooperation between Technion and ARO was mainly on the commercial scale study, where ARO was the major contributor. Results of this study were incorporated in Chapters 3, 6 and 8. Chapter 3 includes a section on spot measurements in several commercial greenhouses, Chapter 6 reports on evapotranspiration measurements under semi-commercial conditions, and Chapter 8 describes the performance of a commercial dehumidifier.

In addition to the direct cooperation, which resulted in co-authoring 4 of the chapters, there was a continuous exchange of ideas. This included the visit of Roger Shaw in Israel to decide on the contents and form of the final report, as well as using the experience gained in UCD to improve humidity measurements in Israel.

2. Research achievements

This study is basically quite straightforward and not too sophisticated. The main effort was put into the experimental work, which required some new techniques. The experiments provided information needed for the simulation model of Chapter 9, which may be regarded as the tool which emerged from the

study. The achievements may be divided into three groups: new methodology, new data, and new understanding (at least to us).

New methodology

1. Two methods have been developed to measure nighttime canopy resistance (both are extensions of known approaches): a weighing method and a water balance method (Chapters 5 and 6). The weighing method can be used only for potted plants. The water balance method can be used for a homogeneous crop growing in soil, provided that condensation on the ceiling is prevented by dehumidification, and that soil evaporation is either prevented or included in the measured evapotranspiration. The measurement of evapotranspiration in commercial greenhouses, over single nights, by the water balance method, can be achieved with portable research equipment. This may be considered a contribution on the research level.

2. Splitting the heat transfer process into convective and radiative components, and taking several representative measurements, made it possible to evaluate in-situ film convective transfer coefficients, radiative transmissivities and certain radiative shape factors (Chapters 2, 3 and 4). These results can be combined reliably in various ways to describe greenhouses with different covers in different climates. The model thus obtained can be used to calculate the night time behavior of various types of conventional greenhouses. This improved, yet simple model, may be used by engineers to calculate more accurate energy consumption.

3. Artificially introducing vapor into an empty greenhouse, made it possible to measure the rate at which vapor condenses on the ceiling (Chapter 4). This may eventually be used in dynamic models of greenhouses. At the moment it is a contribution to experimental methodology.

New data

1. Data on nighttime canopy resistance are rare, partly due to the difficulty of measuring accurately small vapor fluxes and humidity gradients. The results of this study provide new information on 8 greenhouse crops (Chapter 6). The accuracy of the data seems to be sufficient for simulation studies. The range of values among crops was found to be very large, roughly from 500 s/m to 5000 s/m per both sides of single leaves.

2. A significant body of information on overall transfer coefficients of greenhouses is already available. Much less information is available on particular transfer coefficients measured in situ. In the present study several convective film coefficients and radiative transmissivities for polyethylene covers were evaluated (Chapters 2, 3 and 4). These may be used in somewhat more detailed models for design and operation purposes.

3. This report provides data, hitherto unavailable, on the performance of a new commercial greenhouse dehumidifier (Chapter 8).

New understanding

1. It is suggested that the appropriate measure of humidity in the greenhouse is a relative humidity constructed by dividing the actual vapor pressure of the greenhouse air by the saturation vapor pressure at leaf temperature. When convective heating is used, this measure is higher than the relative humidity of the greenhouse air. The opposite is true under radiative heating (Chapter 5).

Usually there cannot be both transpiration and condensation on the canopy at the same time. Unless there is another source of vapor at a higher temperature (such as sometimes the soil), it is unlikely that condensation will occur on a canopy in a heated greenhouse (Chapter 9).

2. The nighttime water balance of a greenhouse was expressed in terms of sources (canopy, soil) and sinks (condensation, ventilation, absorption). This is not new by itself, but made possible the ordered evaluation of source importance and sink alternatives. In particular, ceiling condensation is a most effective sink in mid-winter and under single layer covers. Ventilation and absorption dehumidifiers are most beneficial in mild weather and under double layer covers. The relative advantage of dehumidifiers over ventilation is when the ratio of sensible to latent heat (Bowen ratio) to be removed by ventilation is high (Chapter 9).

3. The need for nighttime ventilation increases as the conductance of the canopy to water vapor increases. At low transpiration rates condensation on the ceiling may be sufficient as a vapor sink, but as transpiration increases, a point is reached where ventilation must be applied. From this point on the required ventilation increases linearly with the vapor

conductance of the canopy (Chapter 9).

Comparison with original goals

Most of the objectives of this research were actually achieved. There were a few aspects to which more time or less time was devoted than originally intended. Referring to the objectives listed in the INTRODUCTION, the following comments are appropriate.

Objective 1. Measuring techniques were adopted and developed as intended (Chapters 2, 4, 5, 6 and 7).

Objective 2. Several crops were investigated to determine their vapor conductance (Chapters 5 and 6). Only one evaluation of the contribution of wet soil and the effect of mulching it was made (Chapter 6). Various greenhouse covers were tested, as intended (Chapters 3 and 4), and a comparison was made between convective and radiative heating (Chapter 5). Ventilation was not varied experimentally as much as thought originally to be required. The transition period between day and night was explored only briefly (Chapter 5).

Objective 3. The dynamic (transient) nature of the phenomena was not explored as much as intended, mostly because of their second order effect. Some work was performed on the opening and closing of stomata during transition between day and night (Chapter 5). Evaluation of the characteristic time of adjustment to changes in evaporation was also undertaken (Chapter 4).

Objective 4. Guidelines for the ventilation of heated greenhouses under quasi steady state conditions have been developed (Chapter 9). No transient control algorithms have been developed.

Benefit to agriculture

Greenhouse models, like any other models, can be developed endlessly. The present state of the composite model (as used in Chapter 9) seems, however, to be suitable for engineering applications. It may be used for both design and operation purposes under quasi steady state night conditions.

In addition to its usefulness as a tool, the model improves our understanding of the water balance of a greenhouse. This enables a better judgment of suggestions to improve the inside climate or reduce their cost.

3. List of publications

Published

Seginer I., Kantz D. 1986. In situ determination of transfer coefficients for heat and water vapour in a small greenhouse. J. of Agricultural Engineering Research 35:39-54 (Chapter 2)

Zhao J., Jenkins B., Shaw R.H., Seginer I. 1985. Heat and water vapor balance of greenhouse plant leaves under convective and infrared heating. ASAE paper 85-4052 (Chapter 5)

Submitted

Seginer I., Kantz D., Peiper U., Levav N. Transfer coefficients of several polyethylene greenhouse covers (Chapter 3)

In preparation

Chapters 4, 6, 9.