ENVIRONMENTAL SIMULATION OF A GREENHOUSE SYSTEM IN KENYA

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DECLARATION

I declare that this is my original work and has not been submitted for a degree in any other University.

Date...6th Sep. 2004...

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DEDICATION

Dedicated to the memories of my late parents,

Jeremiah and Margaret

Agullo.

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Januarius Ondiek Agullo,
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ABSTRACT

Greenhouse systems are becoming important as more Kenyans venture into horticultural farming. The environment of a greenhouse is an important factor that determines the quality of horticultural produce. This study was done in this area with respect to Kenyan conditions.

The broad objective of the study was to develop a model to be used to simulate the environment of a greenhouse system in Kenya. The specific objectives of the study were to: Identify the pertinent physical parameters which affect the environment of a greenhouse system; use parameters identified to develop a mathematical model for simulation of environment of a greenhouse system; use computer simulation to solve the model developed; and verify and then validate the computer simulation model developed, using experimental data collected from a physical model greenhouse.

The pertinent physical parameters identified from established works were: Solar heat gain; furnace heat; heat from equipment; plant respiration; photosynthesis; evapotranspiration; thermal radiation exchange between the greenhouse and its surroundings; conduction through the greenhouse floor; conduction through the greenhouse cover; ventilation; infiltration and ex-filtration through cracks; and condensation.

A one dimensional mathematical model was developed based on energy balances on six elements of the greenhouse system which were: Cover; air; vegetation; soil surface; first soil layer and second soil layers. Non-linear differential equations were used to represent mathematically the interactions between the six elements.

A dynamic computer simulation program (GREENSIM) was developed in DELPHI-5 environment for numerical solution of the simultaneous differential equations using the fourth-order Runge-Kutta method. The inputs into the computer simulation program included: Global solar radiation, the external temperature and relative humidity, and average external wind speed. The outputs were: Cover, air and soil surface temperatures and relative humidity of the air in the greenhouse.

The computer simulation model developed was verified and then validated using a five days data collected during July 2003, from a naturally ventilated, polyethylene covered, single even-span greenhouse situated at University of Nairobi Field Station, Kabete Campus. Good agreements were obtained between the simulated and measured values. The correlation coefficient (R^2 value) between the measured and simulated cover temperature, interior air temperature, soil surface temperature and relative humidity were: 0.92; 0.96; 0.76; and 0.80 respectively. Sensitivity analyses done showed that global solar radiation, vents area, initialization and wind speed had influence on the model output.

The computer model can be used to test the effects of changing design parameters on the environment of a greenhouse. It can also be used to predict and analyse the behaviour of microclimate of a particular design of greenhouse under different climatic conditions, without need for expensive experimentation, so long as meteorological information about the particular area is known. It is a tool which can be used for rational decision making about the most appropriate design of a greenhouse system.

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LIST OF SYMBOLS

Roman alphabet

A	area, m^2
C	specific heat, $J\ kg^{-1}\ °C^{-1}$
C_d	discharge coefficient, dimensionless
C_w	wind effect coefficient, dimensionless
E	effectiveness of the opening, dimensionless
e_a	actual air vapour pressure, Pa.
e_{as}	vapour pressure at saturation at the air temperature, Pa
e_{vs}	air vapour pressure at saturation at leaf temperature, Pa
F_{12}	geometrical shape factor for exchange of diffuse radiation between surfaces 1 and 2
F_{cn}	sky clearness factor of the sky, dimensionless
g	gravity constant, $m\ s^{-2}$
G	ventilation rate, $m^{-3}\ s^{-1}$
G_T	ventilation due to temperature difference, $m^{-3}\ s^{-1}$
G_w	ventilation rate due to wind, $m^3\ s^{-1}$
h	coefficient of heat transfer, $W\ m^{-2}\ °C^{-1}$
H	heat flux, $W\ m^{-2}$
J	Joule
I	net global solar radiation, $W\ m^{-2}$
K	Kelvin
k	thermal conductivity, $W\ m^{-1}\ °C^{-1}$
k_h	hydraulic conductivity, $cm\ min^{-1}$
L	latent heat of condensation, $J\ kg^{-1}$
M	mass, kg
m	metre
Nu	Nusselt number
Q	energy in, J
R	thermal radiation, W
R^2	coefficient of determination
r_e	average external resistance to sensible heat transfer between crop and air, $s\ m^{-1}$
r_f	stomatal resistance of the leaf, $s\ m^{-1}$

RH	relative humidity, %
S_p	heat is stored by the crop per unit leaf area, W m^{-2}
T	temperature, K or °C
t	time, s or hr
U(t)	m-dimensional vector of input variables
U	wind / air velocity, m s^{-1}
V_e (z,t)	root extraction term, cm^3 min^{-1}
V_g	volume of greenhouse, m^3
V_w	Wind speed, m s^{-1}
w	humidity ratio
W	Watt
Y(t)	n-dimensional vector of state variables
Y_i	initial state at the initial time, t_i
ΔP	total pressure difference, Pa
ΔP_T	pressure difference due to temperature difference, Pa
ΔP_w	pressure difference due to wind, Pa
ΔT	interior-exterior air temperature difference, K
Z	height, m
z	soil depth, m

Greek alphabet

ε	emittance of thermal radiation
б	Stefan-Boltzmann constant, 5.67x 10^{-8} W m^{-2} K^{-4}
τ	transmittance of thermal radiation
θ	soil volumetric moisture content
γ	psychometric constant, 66.7 Pa K^{-1}
δ	slope of the saturated vapour pressure curve, Pa K^{-1}, k Pa K^{-1}
ξ	pressure drop coefficient, dimensionless
α	opening angle, degree
ℓ	mean characteristic length
ρ	density, kg m^{-3}
Δ	difference

Subscripts

a	air
ai	inside air
ao	outside air
c	cover
ca	canopy
cd	conduction
c-go	from cover to outside ground
ci	inside of cover
co	outside of cover
cond	condensate
cond-go	from condensate to outside ground surface
cond-sky	from condensate to the sky
conv	convective
c-sky	from cover to sky
cv	convection
eq	equipment
evtr	evapotranspiration
f	fluid
G	ventilation
gi	inside ground surface of greenhouse
gi-c	from inside ground to cover
gi-cond	from inside ground to condensate
gi-sky	from inside ground surface to sky
go	outside ground surface
lk	leakage
lt	latent heat
m	mean
ma	machines
o	outside
ol	outlet
op	ventilation opening
ph	photosenthesis
r	respiration
rad	radiation

s	solid
s1	first soil layer
s2	second soil layer
so	soil
sr	solar radiation
ss	soil surface
tr	thermal radiation
trp	transpiration
v-ai	vegetation to air
v-c	vegetation to cover
v-v	vegetation to vegetation
W	water

LIST OF ABBREVIATIONS

ASAE	American Society of Agricultural Engineering
ASCL	Advanced Continuous Simulation Language
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
CFD	Computation Fluid dynamics
DEBE	Department of Environmental and Biosystems Engineering
FORTRAN	Formula Translation
J. agr. engng	Journal of Agricultural Engineering
N	N number of data points
SD	Standard Deviation
SEM	Standard Error of Mean
Temp.	Temperature
Trans.	Transactions
UoN	University of Nairobi

1. INTRODUCTION

1.1 Background

Kenya is a leading exporter of cut flowers and related floricultural products in Africa (Kenya Flower Council, 2002). The flowers form a key part of Kenya's rapidly growing horticultural industry, the fastest growing sector of the economy and the second in importance in the nation's foreign exchange earnings. Exports in the year 2001 exceeded 38,000 metric tons and earned Kenya over $110 million (Kenya Flower Council, 2002).

Horticultural crops like flowers are very sensitive to variation in the weather conditions and thus have to be grown under controlled environmental conditions. Greenhouses are used to control and modify many of the environmental factors that affect growth of plants (Seginer, 2002). In controlled environment, crops can be produced for specific market dates and the quality maintained by eliminating many of the variations and hazards that are associated with weather. The temperature can be regulated with varying degrees of precision; damage from wind is avoided; injury from plant and insects is reduced; growing media moisture content and fertility levels can be adjusted to meet plant requirements. The precision with which the environment is regulated is determined by the ability of the farmer to manage the greenhouse equipment and controls (Mastalerz, 1977).

In Kenya, greenhouses are mostly naturally ventilated, as this is cheaper in terms of the maintenance costs in comparison to forced ventilation greenhouses (Musembi, 2002). If there are environmental controls, they are mostly operated manually in contrast to western countries where controls have been automated. The major cladding material for greenhouses in Kenya is the polyethylene film. The architectural design found in Kenya include: the detached or single span greenhouses, the ridge and furrow greenhouses and the curved arch ridge and furrow houses (Musembi, 2002).

The basic reason for using greenhouses is to control the temperature at which the plants grow. However, in Kenya, due to the fact that it is in the tropical zone, the temperatures within the microclimate of greenhouses sometimes go beyond the optimal levels during hot seasons. Temperatures as high as 38 °C are at times experienced within the greenhouses in Kenya (Musembi, 2002). This is beyond the desirable level for most crops which stand at 28 °C. For crops to survive such a temperature the management is forced to give hormonal injections thus raising the cost of production (Musembi, 2002).

When outdoor temperatures are low it is relatively easy to control the day temperature within the required limits, but as the seasonal temperature increases precise control of the day temperature becomes more difficult (Musembi, 2002).

The degree of temperature rise above the ambient levels is determined by the amount of radiant energy transmitted through the covering material. It is also dependent on the amount stored within the structure, lost through the covering and that used for evapotransipiration (Mastalerz, 1977; Seginer, 2002).

The basic factors that determine the amount of available solar radiant energy and consequently affect the radiant flux density within the greenhouse include the position of the sun in the sky at various times of the year, the location of the greenhouse, the degree of the cloud cover, and the characteristics of the covering material which is the final factor (Mastalerz, 1977). The radiant energy flux density and the duration of solar radiant energy are function of latitude and time of the day. The latitude of the greenhouse site and the season of the year govern the angle at which the sunrays strike the earth. This angle influences the flux density of the solar radiant energy. The number of hours also changes with the latitude and the season of the year (Mastalerz, 1977).

Many factors affect the radiant flux within the greenhouse. Decisions made at the time of construction, affect the radiance. These decisions include the type of structure, shape and pitch of the roof, orientation to the sun, location of equipment within the greenhouse and the type of cladding material. Where a greenhouse is already built, understanding of the effect of the above factors is required. Else, at the time of constructions, the chosen architectural style, structural components and orientation of the greenhouse should be selected for optimum total radiant energy (Mastalerz, 1977).

1.2 Statement of the Problem

At present, there has been no significant work done on functional design of greenhouses in Kenya. The criteria for evaluating the proper functional and environmental design are lacking. The greenhouse environment research findings done on other parts of the world, mostly temperate climatic zones, may not be applicable for the local conditions without modifications, for example in tropical and subtropical climatic conditions present in Kenya. The solution to this problem is research that is specific to Kenyan conditions. This not only helps in the research being more relevant to Kenya's unique problems, but also helps the personnel involved in the research to gain a deeper understanding of greenhouse systems.

The environment within a greenhouse can be simulated by development of tools like a computer program that solves mathematical equations formulated to represent the physical system. Construction and management decisions can then be based on the results of the simulations.

The mathematical model developed is formulated to describe the physical system by making some assumption about the physical system (Loewer *et al.*, 1994). For a greenhouse, the pertinent parameters that can be modelled include:

- Outside air temperature
- Solar radiant flux as affected by seasons and altitude.
- Greenhouse geometry
- Wind and thermal buoyancy
- Heat transfer through structural materials and cladding material of the greenhouse and the soil
- Evapotranspiration and
- Orientation of the greenhouse.

A computer simulation model consisting of input data, computer program and output information can be developed to digitally represent a system such as a greenhouse. The input data should be easily measurable parameters like, outside temperature, wind speed, greenhouse orientation, soil thermal properties and greenhouse cladding material characteristics. The output data should be parameters that directly affect the growth of crops within the greenhouse for example, temperatures of elements of the greenhouse system (air, crop and soil surface) and relative humidity of the greenhouse air.

1.3 Justification

Temperature is important for the development of greenhouse crops (Sase *et al.*, 2002). As stated by Mastalerz (1977), it influences the rates of photosynthesis, respiration, and other metabolic processes; day and night temperatures affect the balance between the yield and quality floricultural crops; timing of crop maturity is regulated largely by temperature; many species have particular temperature requirements for flower initiation and development; unusual temperatures may result in the development of abnormal and malformed flowers; the post harvest life of flowers depends mainly on temperature levels; soil temperatures influence the availability, absorption, and utilization of mineral elements and water; seed germination and the rooting of cuttings depend upon suitable temperatures in the propagating medium; and transpiration rates are influenced largely by leaf temperatures, air temperature and relative humidity of the greenhouse air. The driving force of transpiration is vapour pressure difference between the saturation vapour pressure at the leaf temperature and the vapour pressure of the air adjacent to the leaf.

Relative humidity is also important in relations to the incident of several foliar diseases (Seginer and Kantz 1989; Wang and Bourlard, 2000). Many fungal diseases of greenhouse plants thrive in high humidity, a condition that is characteristic of tight greenhouses in mild nocturnal weather. Where crops are sensitive to fungal diseases, growers aim not only to keep their greenhouses at appropriate temperature, but also at low humidity levels (Seginer and Kantz 1989).

Temperatures and humidity may be too low or too high, thus the necessity to bring them back to the desired levels. The greenhouse environmental conditions desired by a given plant are also a function of its stage of growth. Plants respond to temperature at all stages of growth; consequently, temperatures should be maintained at optimum levels whenever possible. Kenyan designers and users of greenhouse systems due to the complexity of the microclimate of a greenhouse thus need a tool to help in making appropriate decisions which directly affect the greenhouse environment.

A model is helpful in that, once developed, it can be used to simulate the environment of a greenhouse of all characteristics. The mathematical equations formulated and incorporated into a computer program to represent the physical model are used to test the effect of different levels of the exogenous variables on the system (Loewer *et al.*, 1994). This enables a designer or a farmer to gain insight in the system. The model can then be used to forecast the response of the greenhouse environment to external factors thus evaluating the implications of the input data on prevailing conditions. With a few data entries to initialise the computer simulation program, the designer or the farmer is able to simulate the thermal environment of any typical greenhouse house he might be interested in for all months and all hours of the year enabling him to take necessary action. Profitability of the greenhouse farming is thus ensured.

1.4 Objectives

The broad objective of this study was to develop a model for simulation of the environment of a greenhouse system in Kenya.

The specific objectives of the study were to:

1. Identify the pertinent physical parameters which affect the environment of a greenhouse system
2. Use parameters identified in (1) above to develop a mathematical model for simulation of the environment of a greenhouse system
3. Use computer simulation to solve the model developed in (2) above
4. Verify and then validate the computer simulation model developed in (3) above using experimental data collected from a physical model greenhouse.

2. LITERATURE REVIEW

2.1 Greenhouse System

A system can be defined as a collection of one or more related objects (Murthy et al., 1990). An object is a physical entity with specific characteristics or attributes. The objects can be either interacting or non-interacting in some sense (Murthy et al., 1990). In real world the objects of a physical system most of the time interact such that any change in state of one object result into change in state of the whole system.

The greenhouse system can be considered to consist of the crop, the cladding material used on the roof and the walls, the soil or ground conditions and the equipment within the greenhouse. Any change in one of the objects will result into a given set of feedbacks from the other objects. For example, when the cladding material of a greenhouse is changed from glass to polyethylene, the flow of energy into and out of the greenhouse system is affected by the different thermal properties. Consequently, the states of other objects in the system adjust automatically.

Greenhouse systems are constructed to help control and modify many of the environmental factors affecting the growth of plants (Sase *et al.*, 2002). Within a greenhouse one can control the temperatures, the humidity and the moisture content of the soil to the desired levels. Diseases that affect the plants are also reduced. However, the precision with which the environment is controlled is determined by good system design and installation and understanding of the system characteristics (Mastalerz, 1977).

The environment of a greenhouse is much influenced by the energy flow within the system (see Figure 2.1). Of great importance to greenhouse crops is the solar energy. Solar radiation is used for the important process of photosynthesis. It is thus important that solar radiation into the greenhouse is optimised to the requirements of the plants, at the same time ensuring that temperature rise, due to the same is controlled. Most greenhouses are equipped with heating, cooling and ventilation equipment for control of temperature and humidity of the environment (Duncan *et al.* 1981; Mastalerz, 1977). However, where such equipments are not installed temperature is controlled by natural ventilation through proper design of vent openings.

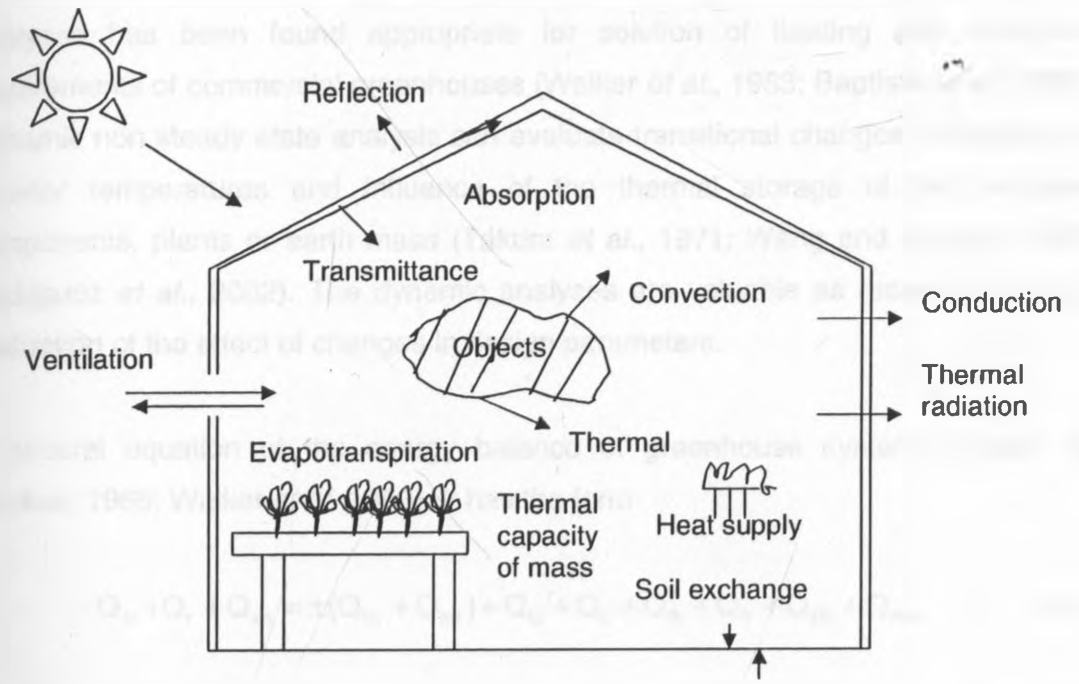


Figure 2.1: A Schematic illustration of the primary energy flows in a greenhouse (Duncan *et al.*, 1981)

2.2 Analysis and Simulation of Greenhouse Environment

Several studies have been done to simulate the environment of a greenhouse. However, most of these studies were done in western countries and the models validated and calibrated in the more of temperate climate and may not be applicable directly in the tropical and subtropical conditions available in Kenya. Also when these models are imported they come as executable programs without the source code and thus modification becomes even harder.

The method used in the analysis and simulation of greenhouse systems has generally been the method of energy balances which typically equates heat gains to losses (Walker *et al.*, 1983) and recently, Computational Fluid Dynamics (Lee *et al.*, 2002). Most investigators have studied the greenhouse as a system (Whittle and Lawrence, 1960; Walker, 1965; Takakura *et al.*, 1971; Kindelan, 1980; Avissar and Mahrer, 1982; Chalabi, 1989), while other investigator have been specific to the study of single factors and how they influence a greenhouse environment (Seginer and Kantz, 1989; AL-Kayssi *et al.*, 1990; Papadakis *et al.*, 1994; Baptista *et al.*, 1999; Seginer, 2002).

The models developed can be either steady state or dynamic. Steady state type of analyses has been found appropriate for solution of heating and ventilation requirements of commercial greenhouses (Walker *et al.*, 1983; Baptista et al., 2001). Dynamic non steady state analysis can evaluate transitional changes in interior and exterior temperatures and influence of the thermal storage of the structural components, plants or earth mass (Takura *et al.*, 1971; Wang and Boulard, 2000; Rodriguez *et al.*, 2002). The dynamic analyses are valuable as research tools for evaluation of the effect of changes in design parameters.

A general equation of the energy balance of greenhouse system is given by (Walker, 1965; Walker *et al.* 1983). It has the form

$$Q_{sr}+Q_r+Q_{eq}=\pm(Q_{cc}+Q_{so})+Q_G+Q_L+Q_{lk}+Q_{tr}+Q_{ph}+Q_{ma} \qquad (2.1)$$

where

Q_{sr} solar heat gain, J

Q_r gain due to plant respiration, J

Q_{ma} is gain due to heating or cooling, J

Q_{eq} is gain due to equipment, J

Q_{cc} is heat exchange due to conduction and convection, J

Q_{so} heat exchange with soil, J

Q_G loss of sensible heat due to ventilation, J

Q_L latent heat loss, J

Q_{lk} is leakage loss, J

Q_{tr} is heat loss by thermal radiation, J

Q_{ph} is heat loss due to photosynthesis, J

Each of these terms is defined by an equation and can be determined experimentally, except the convection changes (Baptista *et al.*, 2001).

Walker (1965) developed an analytical procedure for prediction of temperatures within both heated and naturally ventilated greenhouses. A mathematical energy balance of the form given in equation 2.1 involving solar heat gain, atmospheric thermal radiation, ventilation and conduction heat loss, evapotranspiration, and furnace heat was applied to an experimental model greenhouse and found to predict temperatures with a mean difference of 1.4 °C for four individual test days. The analysis procedure was also reported to predict temperature and heat requirements in a production greenhouse consistent with observed performance.

Takakura *et al.* (1971) considered both steady state and transient methods of analysis of the thermal environment of greenhouses using 25 separate differential equations for the energy balance simulation. The emphasis was on inside air and leaf temperatures, moisture balance, and heat storage of the floor. A specific FORTRAN simulation program was constructed for solution of the differential equations and testing of the model.

Experimental data collected in an unheated section of a glass greenhouse during the study were expressed by Fourier series to use in the simulation model. Predicted curves for soil surface temperature, inside air and leaf surface temperature were shown to be in reasonable agreement with observed data. Predicted air temperatures were closer to the measured values than soil and leaf surface temperatures. The variance in soil surface temperature was attributed to difficulty of testing average surface temperature, largely due to sunlight and shaded conditions continuously changing. Variation in the maximum rate of energy flow was also attributed to time lags, which arise in energy paths associated with large thermal capacity masses such as the soil layer.

Kindelan (1980) when simulating the greenhouse environment, represented soil with a one-dimensional heat diffusion equation in which the soil temperature at the deepest soil layer was set constant during simulation. The assumption here was that the soil was homogenous in its components and its thermal properties. However this is not true due to the high evaporation in the greenhouse, which makes the vertical soil moisture vary with depth.

Duncan *et al.* (1981) built a simulation model describing transient greenhouse energy flows. The calibration, validation, and sensitivity of the model were presented in addition to an analysis of certain winter heating season data showing overall energy conservation effects. The simulated heating requirements for a 7-month winter heating season were 8.9 percent less than calculated by conventional degree-day data when the base temperature was the same as the minimum greenhouse temperature.

Avissar and Mahrer (1982) designed a numerical model that simulated the diurnal changes of the greenhouse environment. The model consisted of a soil layer, a vegetative layer an air layer and cover. In order to obtain flexibility, sophisticated models were adopted to simulate each of the greenhouse sub layers. In this simulation model the vertical variation in the thermal properties of the soil was taken into consideration.

Chalabi and Bailey (1989) presented a model for the simulation of the dynamics of energy and moisture balance of the greenhouse microclimate. The model was a non-steady state one; it was described by a set of non-linear first order differential equations of the form:

$$\frac{dX}{dt} = f(X, Y(t), \Omega, t) \tag{2.2}$$

where

X is the output state vector (internal air temperature, internal water vapour content...)

Y is the input state vector (external air temperature, external water vapour content, heating pipe temperature ...)

Ω is the vector of constant parameter (stomata resistance, leaf area index, ...)

The differential equations derived were solved using the Advanced Continuous Simulation Language (ASCL). The model was shown to be adequate in simulating the environment in the structure. It is superior to other models, which assume that there are no spatial gradients in either the driving potentials of sensible or latent heat fluxes, i.e., temperature and water vapour. Rodriguez *et al.* (2002) have used a similar approach to model a greenhouse.

Specific studies of the elements of the greenhouse have also been done. Pieters *et al.* (1994) used a static one dimensional model describing heat transfer by conduction, convection, radiation, and phase change to, through and from greenhouse covers to determine the influence of convection and evaporation on static heat losses from a greenhouse. The influence was assessed qualitatively by means of numerical (iterative) version and quantitatively by application of symbolic calculation on a liberalized version of the model. The results that were presented for glasshouses and polyethylene-covered greenhouses demonstrated that the two materials reacted differently to the condensation phenomenon. Whereas during condensation heat losses to glass covers always increase due to latent heat of condensation brought from the inside air to the cover surface, heat losses from polyethylene covered greenhouses may increase or decrease depending on the inside air relative humidity and the far red irradiative properties of the covering material.

Papadakis *et al.* (1994) carried out Experimental investigation and modelling of heat and mass transfer between a tomato crop and the greenhouse environment. The transfer of sensible and latent heat between the canopy and the ambient air was assumed to take place via an exchange area equal to the total leaf area across two resistances, the internal and the external, which were properly defined. The external resistance was determined as a function of the Nusselt number. A method was proposed to parameterise the internal resistance as a function of the canopy temperature, the canopy full spectrum net radiation and the crop-air vapour pressure deficit. A model was proposed for the calculation of the crop temperature and crop transpiration rate as a function of time and the environmental variables. The calculated canopy temperature compared well with the measured one, which was found to be lower than that of the greenhouse air. Calculated canopy transpiration rates were presented as a function of time and the environmental variables. The canopy transpiration flux was found to be higher than that of the full spectrum crop net radiation on a 24 hours basis.

The effect of increasing soil moisture content on soil temperature, soil reflectance and soil heat storage of a greenhouse system has been studied by Al-Kayssi *et al.* (1990). The results of this study showed that an increase in moisture content decreased the soil temperature differences between day time and night time, which provides protection to the plant root system against sharp and sudden changes of soil temperature. It was also found that the solar energy absorption increased as the moisture content increased, which resulted into a higher heat storage capacity at higher moisture content. It was also concluded that plant growth rate and yield increased due to the modification of plant climate at higher moisture content.

Rosa *et al.* (1989) developed a model by which the solar irradiation can be computed inside a single span hemi cylindrical tunnel greenhouse. The model was mathematically exact and was found on the assumption that the cladding surface was fully diffusive and that the radiation diffused through the atmosphere and by the ground was fully isotropic.

It was concluded that the solar irradiation inside the greenhouse depends upon its orientation. A greenhouse with its longitudinal axis aligned along the north-south direction collected more radiation in summer and less in winter as compared with a greenhouse with its axis aligned along the east-west direction. On the other hand the east-west oriented greenhouse was more efficient in collecting solar radiation in winter than in summer. Finally, it was shown that the collected radiation depended upon the optical properties of the cladding surface being mainly determined by its transmittance.

Baptista *et al.* (1999) measured leakage and ventilation rates using tracer gas technique. The influences of wind speed, wind direction and temperature difference between inside and outside were analysed for each ventilator position. It was found that wind speed had a strong influence on leakage and ventilation rates. Temperature difference affected ventilation rates under low wind speeds. For each ventilator position, the air exchange rate was linearly related to wind speed. The results for 10 and 20% ventilator openings obtained by using the decay method were compared with those obtained by applying the theory of convection, using pressure differences generated by wind forces and temperature differences. It was established that the combined effect of wind and temperature difference gave satisfactory predictions of ventilation rates. Also, the values obtained by measurement and prediction based on pressure difference was in close agreement with a global wind effect coefficient.

Improvement in greenhouse ventilation design has been suggested by Seginer (2002) who have included the Penman-Monteith evapotranspiration equation as an element in the greenhouse ventilation design. With this approach, the design adjusts automatically not only to different radiation load and temperatures, but also to different humidity conditions.

3. THEORETICAL FRAMEWORK

3.1 Pertinent Factors Influencing the Greenhouse Climate

Factors that influence the air, crop and soil temperatures and relative humidity of a greenhouse system are: Solar heat gain; furnace heat; heat from equipment; plant respiration; photosynthesis; evapotranspiration; thermal radiation exchange between the greenhouse and its surroundings; conduction through the greenhouse floor; conduction through the greenhouse structural cover; ventilation; infiltration and ex-filtration through cracks; and condensation (Walker 1965, Chandra *et al.*, 1981; Kindelan, 1980; Avissar and Mahrer, 1982; Jones *et al.*, 1984; Seginer, 2002). All these factors should be taken into consideration when modelling the environment of a greenhouse, especially when doing energy balance.

3.1.1 Conduction.

Heat conduction occurs for example, between the two sides of the greenhouse cover and is proportional to the difference between the inner (T_{ci}) and outer (T_{co}) surface temperatures of the cover and inversely proportional to the thickness, b, of the cover. Heat conduction also takes place in the soil and structural components. Mathematically the conductive heat flux can be expressed as follows (Chapman, 1989)

$$q_{cond} = k(T_{ci} - T_{co})/b \qquad (3.1)$$

The thermal conductivity k is a characteristic of the cover material.

3.1.2 Convection

Convection takes place between the solids in the greenhouse system and the inside air and between the outer side of the cover and the outside air on the other hand. The convective heat flux is proportional to the difference between the surface temperatures of the solids T_s and the bulk fluid temperature T_f. The mathematical expression for the convective heat flux density thus becomes (Chapman, 1989)

$$q_{conv} = h_{conv}(T_s - T_f) \qquad (3.2)$$

The convection heat transfer coefficient h_{conv} depends on type of flow and is calculated according to laminar boundary layer theory (Pieters *et al.*, 1994). Nusselt number, Nu, is used to expresses the ratio of the conductive heat flux through the real or equivalent laminar boundary layer to the conductive heat flux that would take place if the same temperature difference $T_s - T_f$ was established over a layer of still fluid with a thickness equal to some well known characteristic length, d, of the solid, mostly measured in the direction of the fluid stream (Pieters *et al.*, 1994). Formally, this can be written as

$$Nu = dq_{conv} / k(T_s - T_f) \tag{3.3}$$

The relation between the convection coefficient and the Nusselt number then becomes (Chapman, 1989)

$$h_{conv} = kNu / d \tag{3.4}$$

3.1.3 Phase change

Phase change occurs if condensation or evaporation of water from one of the surfaces of the greenhouse cover takes place. Condensation can also take place on the plant leaves and soil surface of the greenhouse. The latent heat flux is expressed by (Garzoli and Blackwell, 1981; Pieters *et al.*, 1994)

$$H_{lt,cond} = h_{cond}\rho_a L(w_{ai} - w_s) \tag{3.5}$$

where

$H_{lt,cond}$ is latent heat flux, W m^{-2}

L is latent heat of condensation of fluid, J

W_{ai} is the humidity ratio of air

w_s is the humidity ratio of the saturated air at solid's temperature

h_{cond} is the coefficient of heat transfer given by the Lewis relationship, W m^{-2} $°C^{-1}$

ρ_a is the density of air, kg m^{-3}

The latent heat flux is positive for condensation and negative for evaporation from a wet surface.

3.1.4 Radiation

3.1.4.1 Solar radiation

Calculations to determine heat gain of a greenhouse from solar radiation are based on laws of physics and optics (Baptista *et al.*, 2001). The radiation intensity inside a greenhouse is due to the reflection, absorption, and transmittance of the covering. Transmittance is affected by slope of the covering corresponding to the angle of incidence of the solar beam. Small increase in transmittance is shown for angle of incidence from 0 to 0.79 radians, but decrease is seen for angles than 1.05 radians (Duncan *et al.* 1981).

Walker *et al.* (1983) expresses heat gain by solar radiation, Q_{sr}, into greenhouse, neglecting horizontal fluxes, at any time as

$$Q_{sr} = \tau_{c,sr} I_{sr} A_{gi} \tag{3.6}$$

where

$\tau_{c,sr}$ is the transmittance of the greenhouse cover to solar radiation

I_{sr} is the net solar radiation on a horizontal surface, W m^{-2}

A_{gi} is the inside ground surface area of the greenhouse, m^2

3.1.4.2 Thermal radiation

Long wave radiation is emitted, absorbed reflected, and transmitted by the solid surfaces of the greenhouse system, that is, the vegetation, soil, and the greenhouse cover (Pieters *et al.*, 1994). The fluxes expressed per unit surface area for a given solid surface is expressed by (Chapman, 1989):

$$H_{tr} = \varepsilon_s \sigma T_s^{\ 4} \tag{3.7}$$

where

H_{tr} is the thermal radiation heat flux, W m^{-2}

ε_s is the emmittance of solid surface

σ is the Stefan-Boltzmann constant, W m^{-2} K^{-4}

T_s is the absolute temperature of solid surface, K

3.1.5 Greenhouse ventilation

Ventilation is one of the most important tools for controlling greenhouse climate. The air exchange between the inside and outside of a greenhouse influences the environmental conditions, such as temperature, humidity and carbon dioxide concentration that affect the development and production of the crop. The measurement of ventilation and leakage rates is necessary to provide a good understanding of climate control in greenhouses. It is necessary to know the ventilation characteristics of a greenhouse in order to provide good control of the inside environmental conditions (Baptista *et al.*, 1999).

Ventilation and leakage rates are influenced by environmental factors such as wind speed, wind direction, temperature difference between inside and outside the greenhouse and ventilator aperture. One factor that indirectly influences the ventilation rate is the solar radiation, since it is an important component of the energy balance. When the intensity of the solar radiation is high, the temperature inside the greenhouse increases and the ventilation rate rises as a result of the stronger thermal buoyancy effect. Thus, in areas where the wind is not so strong, the difference in temperature is more important in the natural ventilation of greenhouses (Baptista *et al.*, 1999).

Various techniques have been used to measure and predict ventilation and leakage rates such as tracer gas techniques, energy balances and measurements of pressure deference between inside and outside. Investigators that have used the energy balance method to predict ventilation include: Kozai *et al.* (1980); Chalabi and Bailey (1989); and Fernandez and Bailey (1993). This method is based on the fact that the ventilation removes energy from the greenhouse as a way of preventing excessively high temperatures (Baptista *et al.*, 1999).

Baptista *et al.* (1999) measured leakage and ventilation rates using the decay and continuous injection tracer gas methods. The influence of wind speed, wind direction, ventilator aperture and temperature difference between inside and outside were analysed. Ventilation rates were predicted using various models based on the theory of natural convection (Bruce, 1978) and the effect of wind forces (Albright, 1990; Boulard and Baille, 1995) assuming that total ventilation is due to the combined effect of both natural forces.

Airflow through an opening is due to pressure difference between inside and outside of greenhouse structure. Papadakis *et al.* (1996) and Kittas *et al.* (1996) measured pressure differences between inside and outside temperatures in different greenhouses to identify wind pressure coefficients and their variation relating to wind characteristics. Kittas *et al.*, (1996) have shown that the wind-induced ventilation rate can be expressed as a function of a wind pressure coefficient, C_w.

3.1.5.1 Ventilation due to wind forces

Wind around a building creates a pressure field at the openings and hence produces airflow through them. These pressures may be positive, when air flows into the building or negative (suction), when the air flows out. The wind effect is usually split into two components (Boulard and Baille, 1995; Baptista *et al.*, 1999):

(i) A steady effect: induced by a static pressure distribution related to the mean wind speed and which can be described by Bernoulli's equation; and

(ii) A turbulent effect: induced by the fluctuating pressure distribution, linked with the turbulent characteristics of the wind interacting with the greenhouse or with the surroundings. It is assumed that the wind pressure coefficient C_w is the result of both of these effects (Kittas *et al.*, 1996; Boulard and Baille, 1995).

If it is assumed that the wind speed is constant around the opening, the pressure difference, ΔP, is given by Bernoulli's equation

$$\Delta P = \frac{1}{2}\xi\rho_a U_{op}^{\ 2} \tag{3.8}$$

where

ξ is the pressure drop coefficient, dimensionless

U_{op} is the average air velocity across the opening, m s^{-1}

ρ_a is density of air

From Equation (3.8), and defining the discharge coefficient of the opening as $C_d = \xi^{-0.5}$, the air velocity is given by

$$U_{op} = C_d \sqrt{\frac{2}{\rho_a} \Delta P} \tag{3.9}$$

In the case of a single opening, half of the area is the inlet and half is the outlet (Baptista *et al.*, 1999). The air exchange rate G ($m^3 s^{-1}$) through the opening is thus

$$G = \frac{A_{op}}{2} C_d \sqrt{\frac{2}{\rho_a} \Delta P} \tag{3.10}$$

where

A_{op} is area of the opening, m^2

Applying the same principal to air flow due to the wind pressure field, U_w being the wind speed measured at the reference height above the ground, the wind pressure difference, ΔP_w, is expressed as

$$\Delta P_w = \frac{1}{2} \rho_a C_w U_w^{\,2} \tag{3.11}$$

where

c_w is wind effect coefficient, dimensionless

Boulard and Baille (1995), and Kittas *et al.* (1996) combined Equations (3.10) and (3.11) to come up with air exchange due to the wind given by

$$G = \frac{A_{op}}{2} C_d \sqrt{C_w} U_w \tag{3.12}$$

Equation 3.12 can be used to estimate the global wind effect coefficient, $C_d C_w^{\,0.5}$.

3.1.5.2 Ventilation due to buoyancy effect

In absence of wind, thermal buoyancy guarantees the minimum air exchange. At daytime the greenhouse air may gain heat directly from heating systems and indirectly from solar radiation via plants, soil, structure of the greenhouse and items within the greenhouse such as benches. If two openings exist at different heights, hot air from the inside exits through a high opening while the same volume of cooler air enters through the lower openings. Air pressure varies and is different inside and outside the greenhouse. The air movement by natural convection is caused by this pressure difference. The size and location of the openings and the temperature difference between the inside and outside determines the efficiency of natural convection (Baptista *et al.*, 2001).

The pressure difference, $\Delta P_{T,}$ due to the stack effect results from the difference in vertical pressure, caused by the gradient of the air density between the inside and outside and can be expressed in the following equation as used by Kittas *et al.* (1996)

$$\Delta P_T = \rho_a g Z \frac{\Delta T}{T_o} \qquad (3.13)$$

where

Z represents the height of opening above the ground, m

g is the acceleration due to gravity, m s^{-2}

ΔT is the difference between the inside and outside temperature, K

T_o is the absolute outside air temperature, K

Bruce (1973) presented a simple equation to determine the air velocity through the outlet, U_{ol}, regarding the building as a vertical column, with two openings separated by a height, Z. The expression was

$$U_{ol} = C_d \left(\frac{2gZ\Delta T}{T_o} \right)^{\frac{1}{2}} \qquad (3.14)$$

Bruce (1978) presented a generalized equation for ventilation by natural convection in any confined volume with openings, defining the neutral plane where density of air inside and outside is equal and so no movement of air occurs at this level. The position of the neutral plane ($\bar{Z}$) is given by the equation:

$$\sum_{j=1}^{n}\int_{Aj}\frac{|\bar{Z}-Z|^{\frac{3}{2}}}{\bar{Z}-Z}dA_{op}=0 \qquad (3.15)$$

where

Z is height, m

j is j^{th} element

A_{op} is area of opening, m

n is number of openings

The expression assumes that air is an ideal gas; that there are negligible losses; that no vertical density exists and that the inside air density is approximately equal to outside air density.

3.1.6 Greenhouse crop transpiration

Research has been done in relation to transpiration of the greenhouse crops especially in relation to energy balance. Special attention has been given to heat and mass transfer between the greenhouse crop and the environment (Yang *et al.*, 1989; Yang *et al.* 1990).

Greenhouse plants exchange energy with the environment by evaporating water (transpiration), by radiation and by convection with the air. The heat exchanger of the plants is their leaves. Transpiration takes place almost exclusively through the stomata since very small amounts of water evaporate through cuticle. Convection (sensible) heat transfer between the plants and the air takes place in the boundary layer at both sides of leaves. The leaves are exclusively responsible for the solar radiation absorption and thermal radiation emission (Papadakis *et al.*, 1994).

3.1.6.1 Effect of greenhouse microclimate on crop transpiration

Transpiration is the only type of transfer process in the greenhouse that has both a physical and biological basis. It is almost exclusively responsible for the humid subtropical climate in greenhouses (Papadakis *et al.*, 1994).

Vapour that transpire from the leaf to free air have to overcome the resistance of the substomatal cavity and the resistance of the stomata it self. Crop transpiration rate (expressed in energy terms), $H_{lt,v}$, per unit leaf area, may be described mathematically as follows (Monteith, 1973)

$$H_{lt,v} = \rho_a C_a \frac{(e_{vs} - e_a)}{\gamma(r_i - r_e)} \tag{3.16}$$

where

$H_{lt,v}$ is the transpiration rate, W m^{-2}

r_i is crop internal resistance, s m^{-1}

r_e is the crop average external resistance, s m^{-1}

C_a specific heat capacity of air at constant pressure, J $kg^{-1}K^{-1}$

γ is the psychometric constant, 66.7 Pa K^{-1}

e_{vs} is the air vapour pressure at saturation, at leaf temperature, Pa

e_a is the actual air vapour pressure, Pa.

The difference (e_{cs} - e_a) is usually called leaf-air vapour pressure deficit, because it is assumed that the water vapour pressure inside stomata pores is saturated at any leaf temperature.

The combination of the energy balance and transfer equations may be used to derive the following equations for the calculation of the crop transpiration and the temperature difference between plants and air respectively (Monteith, 1973)

$$H_{lt,v} = \frac{\delta(H_{rad,nv} - S_v) + \rho_a C_a (e_{as} - e_a)/r_e}{\delta + \gamma(1 + r_i/r_e)} \tag{3.17}$$

$$T_v - T_{ai} = \frac{(r_i + r_e) + (H_{rad,nv} - S_v)/\rho_a C_a - (e_{as} - e_a)/\gamma}{\delta + \frac{\delta}{\gamma} + \frac{r_i}{r_e}} \tag{3.18}$$

where

T_v is vegetation temperature, °C

T_{ai} is air temperature, °C

δ is slope of the saturated vapour pressure curve, Pa K^{-1}

e_{as} is air vapour pressure at saturation at air temperature, Pa.

$H_{rad,nv}$ full spectrum crop net radiation per unit leaf area, W m^{-2}

S_v is rate of storage of heat by the crop per unit leaf area, W m^{-2}

Equation (3.17) has an advantage over equation (3.16) for the calculation of crop transpiration because the crop temperature does not need to be known (when S_v equals zero). On the other hand, equation (3.18) can easily be applied to calculate the crop temperature (Papadakis *et al.*, 1994).

3.1.6.2 Factors affecting crop internal resistance

The leaf internal resistance is influenced macroscopically mainly by the net solar radiation, the leaf-air vapour deficit, the leaf temperature, the CO_2 concentration and the leaf water potential, the most important factor among this group being the net solar radiation (Papadakis *et al.*, 1994).

Papadakis *et al.* (1994) expresses mathematically the relationship between this factors and the internal resistance by the following equation

$$r_i = \frac{(C_2 + T_v)^{C_3}(e_{vs} - e_a)^{C_4}}{(C_1 + H_{rad,nv})} \qquad (3.19)$$

where

C_1 to C_4 are experimentally determined coefficients for a particular crop

3.1.7 Greenhouse soil

Information about soil temperature is essential in evaluation of various biological and physical process-taking places in the soil-plant ecosystem. Most of heat transfer in the soils involves conductivity and volumetric heat capacity varying with space, mainly due to variation in soil moisture content (Papadakis *et al.*, 1989).

In studying greenhouse environment, calculation of heat flux in the soil is essential for predicting instantaneous thermal response of the greenhouse system using mathematical models (Kindelan, 1980; Avissar and Mahrer, 1982; Papadakis *et al.*, 1989; Arinze *et al.*, 1984; Wang and Boulard, 2000; Rodriguez *et al.*, 2002).

The soil surface temperatures result from the energy balance of the net radiation, sensible heat, latent heat and ground conductance. The thermal diffusion equation of the soil layer can be presented as (Avissar and Mahrer, 1982)

$$\frac{\partial T_{so}}{\partial t} = D_{Tz}\frac{\partial^2 T_{so}}{\partial^2 z} \tag{3.20}$$

where

T_{so} is soil temperature, °C

t is time, s

z is depth in meters, m

D_{Tz} is the thermal diffusivity at soil-depth z

Moisture is transported through the soil in both liquid and vapour phases. Hayhoe (1981) expresses one-dimensional equation for this process as

$$\frac{\partial \theta}{\partial t} = D_\theta \frac{\partial^2 T}{\partial^2 z} + D_T \frac{\partial^2 T_s}{\partial^2 z} - \frac{\partial k_h}{\partial z} - V_\theta(z,t) \tag{3.21}$$

where

t is time, min

θ is soil volumetric moisture content, cm^3 of water per cm^3 of soil

D_θ is the soil moisture diffusivity

D_T is the soil thermal diffusivity

k_h is hydraulic conductivity, cm min^{-1}

V_θ (z,t) is the root extraction term cm^3 min^{-1}

3.2 Model and Model Building

A model may be defined, as an abstraction of reality while model building is the process by which concepts of the reality are defined and developed further. Models may be mental, physical, or mathematical (Loewer *et al.*, 1994).

3.2.1 Mathematical models

These are quantitative expressions of one's mental and physical models; i.e. a mathematical model is a logical extension of how one supposes a system to operate (Loewer *et al.*, 1994). Within defined boundaries, a mathematical model should represent the state of the art with respect to the functioning of the system under study (Loewer *et al.*, 1994).

Mathematical modelling of a system involves the formulation of mathematical equations that adequately describe its physical set up into which known inputs (independent variables) are cast and by use of computational techniques, outputs (dependent parameters) are achieved upon which decisions on system design and control are based (Nyaanga, 2000).

According to Smith (1977), an ideal mathematical model should:

- Have a sound mathematical and physical basis
- Not have limitations with regard to the geometry, shape and physical composition of the domain.
- Be easy to input parameters which describe the required conditions (environment); have ability to handle transient and buoyant conditions
- Have sufficient accuracy; flexible enough to allow the choosing of a desired degree of approximation without reformulating the entire problem
- Involve a systematic procedure that can be automated for use on digital computers.

Models are useful in that, if well developed, they can be used to simulate the behaviour of the respective systems they represents. Once the mathematical equations representing the physical model are formulated and their algorithms of solutions incorporated into a computer program, the program can be used to test the effect of different levels of the exogenous variables on the system (Loewer *et al.* 1994).

3.2.2 Methods of solutions

Once a mathematical model is developed there becomes the need to solve it. The methods used to solve linear and nonlinear boundary value problems range from completely analytical to completely numerical. Some of these methods as given by Huebner (1975) include:

1. Direct integration (Exact solutions)
    - Separation of variables
    - Similarity solutions
    - Fourier and Laplace transformations.
2. Approximate solutions
    - Perturbations
    - Power series
    - Probability Schemes
    - Method of weighted residuals
    - Finite deference techniques
    - Ritz method
    - Finite element Method.

Exact solutions can be achieved by direct integration of the differential equations. This can be accomplished by separation of variables or by applying transformations, which make variables separable and leads to similarity solutions (Huebner, 1975). Occasionally Fourier or Laplace transformation of the deferential equation leads to exact solution. It should be noted, however that, the number of problems with exact solutions is severely limited.

Regular and singular perturbations methods are applicable primarily when nonlinear terms in the equations are small in relation to the linear terms, making their usefulness limited. The power series method is powerful and has been employed with the same success but since the method requires the generation of coefficients for each term in the series it is relatively tedious (Huebner, 1975). Also, it is difficult to demonstrate that the series converges.

The probability schemes, usually classified under the heading of Monte Carlo methods are used for obtaining a statistical estimate of a desired quantity by random sampling. These methods work best when the desired quantity is a statistical parameter and sampling is done from a selected population.

Due to availability of high speed digital computers, the method used mostly in obtaining approximate solutions of high accuracy are the weighted residual, finite difference and finite element methods.
The finite difference model of a problem gives a point wise approximation of the governing equations. This model, formed by writing difference equation for an array of grid points is improved as more points are used. With this method one can treat a fairly difficult problem.

Unlike the finite difference method, which envisions the solutions region as an array of grid points, the finite element method envisions the solutions region as built up of many small, interconnected sub regions or elements.

A finite element model of a problem gives a piecewise approximation to the governing equations. The basic premise of the finite element method is that solution region can be analytically modeled or approximated by replacing it with an assemblage of discrete elements. Since these elements can be put together in a variety of ways, they can be used to represent exceedingly complex shapes (Huebner, 1975).

3.2.3 Solution of differential equations

Solving differential equations is one of the major problems of numerical analysis. This is because such a wide variety of applications lead to differential equations, and so few can be solved analytically (Scheid, 1988). The classical initial value problem is to find a function y(x) which satisfies the first-order differential equation $y'=f(x,y)$ and take initial value $y(x_o) = y_o$ (Scheid, 1988).

A broad variety of methods have been devised for the approximation solution of differential equations. Some of these methods as given by Scheid (1988) are:

3.2.3.1 Method of isoclines

This is based upon geometrical interpretation of y'(x) as the slope of the solution curve; it gives a quantitative view of the entire solution family. The function f(x,y) defines the prescribed slope at each point. This direct field determines the character of the field.

3.2.3.2 Euler Method

Involves computation of a discrete set of y_k values, for arguments x_k using the differential equation

$$y_{k+1} = y_k + hf(x_k + y_k) \tag{3.22}$$

where

$$h = x_{k+1} - x_k$$

Euler method is not an accurate approximation of $y' = f(x,y)$

3.2.3.3 Taylor series

If y(x,y) is an analytical function then successive derivatives of y(x) maybe obtained as a series for y(x) written in standard Taylor format. Sometimes a single series will serve for all the arguments of interest. In other problems a single series may converge too slowly to produce the required accuracy for all arguments interest and several Taylor series with different points of expansion maybe used. The eventual truncation of any such series means that the solution is being approximated by a Taylor polynomial.

3.2.3.4 Runge-Kutta methods

These were developed to avoid the computation of high–order derivatives which the Taylor method may involve. In place of this derivatives extra values of the given function f(x,y) are used, in a way which duplicates the accuracy of the Taylor polynomial. The most common formulas are

$$k_1 = hf(x,y) \tag{3.23}$$

$$k_2 = hf(x + \frac{1}{2}h, y + \frac{1}{2}k_1) \tag{3.24}$$

$$k_3 = hf(x + \frac{1}{2}h, y + \frac{1}{2}k_2) \quad (3.25)$$

$$k_4 = hf(x + h, y + k_3) \quad (3.26)$$

$$y(x + h) \approx y(x) + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (3.27)$$

3.2.3.5 Predictor- corrector methods

This involves use of one formula to make a prediction of the next value of y_k, followed by the application of a more accurate corrector formula which then provides successive improvements. A simple predictor- corrector pair is

$$y_{k+1} \approx y_k + hy'_k \quad (3.28)$$

$$y_{k+1} \approx y_k + \frac{1}{2}h(y'_k + y'_{k+1}) \quad (3.29)$$

The predictor being the Euler's formula and the corrector being known as the modified Euler's formula. Because $y'_k = f(x_k, y_k)$ and $y'_{k+1} = f(x_{k+1}, y'_{k+1})$ the predictor estimates y_{k+1}. This estimate then leads to a y'_{k+1} value and then to a corrected y_{k+1}. Further corrections of y'_{k+1} and y_{k+1} can be made successively until a satisfactory result is obtained.

3.2.3.6 Milne method

This uses the predictor corrector pair given below in which the Simpson rule is recognizable. It requires four previous values (y_k, y_{k-1}, y_{k-2}, y_{k-3}) to prime it which must be obtained by a different method, often Taylor series.

$$y_{k+1} \approx y_k - 3 + \frac{4h}{3}(2y'_{k-2} - y'_{k-1} + 2y'k) \quad (3.30)$$

$$y_{k+1} = y_{k-1} + \frac{h}{3}(y'_{k+1} + 4y'_k + y'_{k-1}) \quad (3.31)$$

3.2.3.7 Adams method

This method uses the predictor pair given below and like the Milne method requires four previous values.

$$y_{k+1} \approx y_k + \frac{h}{24}(55y'_k - 59y'_k - 1 + 37y'_{k-2} - 9y'_{k-3}) \qquad (3.32)$$

$$y_{k+1} \approx yk - 1 + \frac{h}{24}(9y'_{k+1} + 19y'_k - 5y'_{k-1} + y'_{k-2} \qquad (3.33)$$

3.3 Computer Simulation

A computer simulation model consists of input data, computer programs and output information. These are termed as the computer software. Program design involves organising into logical order the necessary stages in the solution of the problem (Holmes, 1987). Flow charts and pseudo-code statements are used to enhance program design. Pseudo-statements should clearly state what each step does in the solution of the problem. Once the design have been tested and found feasible and reliable, the statements are coded in to a computer language being used, which can then be transferred into a computer.

The design may have to be corrected several times before it is error free (Holmes, 1987; Engel, 1985). The phases in the construction of a computer simulation model as suggested by Hillel (1977) are summarised in Figure 3.1.

Computer modelling reduces seemingly incomprehensible systems to manageable orderly proportions. A model is simplified and hence more readily definable and easily tractable version of reality.

As cited by Hillel (1977), Bacon in 1620 in his book *Novum organum* proposed the so-called scientific method of modelling which consists of four steps outlined below:

- Observation of the real system in operation
- Formulation of a hypothesis (a mathematical model) to explain how the system works
- Prediction of the system behaviour on the basis of the hypothesis (by combining sections to mathematical model) and

- Performance of experiments to test the validity of the model's prediction.

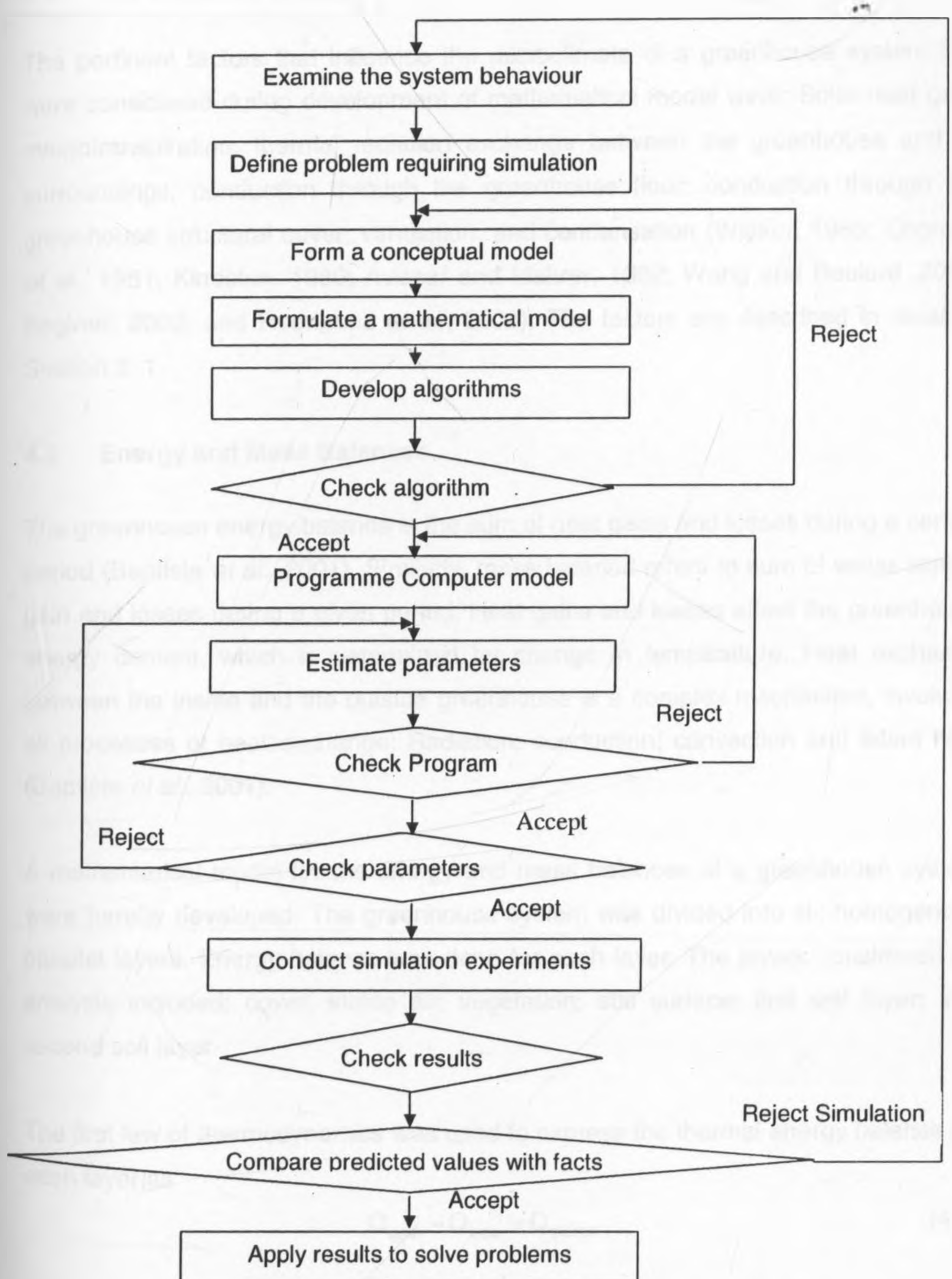


Figure 3.1: Phases in the construction of a simulation model (Hillel, 1977)

4. MODEL DEVELOPMENT

4.1 The Pertinent Factors

The pertinent factors that influence the microclimate of a greenhouse system that were considered during development of mathematical model were: Solar heat gain; evapotranspiration; thermal radiation exchange between the greenhouse and its surroundings; conduction through the greenhouse floor; conduction through the greenhouse structural cover; ventilation, and condensation (Walker, 1965; Chandra *et al.*, 1981; Kindelan, 1980; Avissar and Mahrer, 1982; Wang and Boulard ,2000; Seginer, 2002; and Rodriguez *et al.*, 2002). The factors are described in detail in Section 3. 1.

4.2 Energy and Mass Balances

The greenhouse energy balance is the sum of heat gains and losses during a certain period (Baptista *et al.*, 2001). Similarly, mass balance refers to sum of water vapour gain and losses during a given period. Heat gains and losses affect the greenhouse energy content, which is determined by change in temperature. Heat exchange between the inside and the outside greenhouse is a complex mechanism, involving all processes of heat exchange: Radiation; conduction; convection and latent heat (Baptista *et al.*, 2001).

A mathematical model for the energy and mass balances of a greenhouse system were hereby developed. The greenhouse system was divided into six homogenous parallel layers. Energy balance was done for each layer. The layers considered for analysis included: cover; inside air; vegetation; soil surface; first soil layer; and second soil layer

The first law of thermodynamics was used to express the thermal energy balance for each layer as

$$Q_{gain} - Q_{loss} = Q_{stored} \tag{4.1}$$

where

Q_{gain} is energy gain, J

Q_{loss} is energy loss, J

Q_{stored} energy stored, J

The heat fluxes have several components such as latent heat, short wave radiation long wave radiation, and conductive heat fluxes (Figure 4.1). These components are affected by thermal property of the layer, mass of the layer and its moisture content.

The rate of heat storage by a given layer can be expressed as

$$Q_{stored} = MC\frac{dT}{dt} \tag{4.2}$$

where

M is mass of a given layer, kg

C is thermal capacity of a layer j, J $kg^{-1}°C^{-1}$

$\frac{dT}{dt}$ is rate of change of temperature of a given layer, °C s^{-1}

Combining Equations 4.2 and 4.1 gives

$$MC\frac{dT}{dt} = Q_{gain} - Q_{loss} \tag{4.3}$$

For a given homogenous layer, for example, cover of greenhouse, the aim was to solve for T by substituting into Equation (4.3) the necessary equations expressing energy flows into and out of the layer.

The rate of change of moisture content of the air layer and the soil layer take the same form as given in Equation (4.3). In this study mass balance of moisture in the greenhouse air was done. The mass balance equation was represented by

$$\frac{dM_{W,ai}}{dt} = M_{Wg,ai} - M_{Wl,ai} \tag{4.4}$$

where

$M_{wg,ai}$ is mass water gained by the greenhouse air, kg s^{-1}

$M_{wl,ai}$ is mass of water lost by the greenhouse air, Kg s^{-1}

$\frac{dM_{W,ai}}{dt}$ is rate of change of water content of greenhouse air with temperature kg m^{-3} s^{-1}

Figure 4.1 shows the schematic illustration of the radiation, heat and mass fluxes as were considered in the study. Each arrow represents an individual flux, for which an equation was developed.

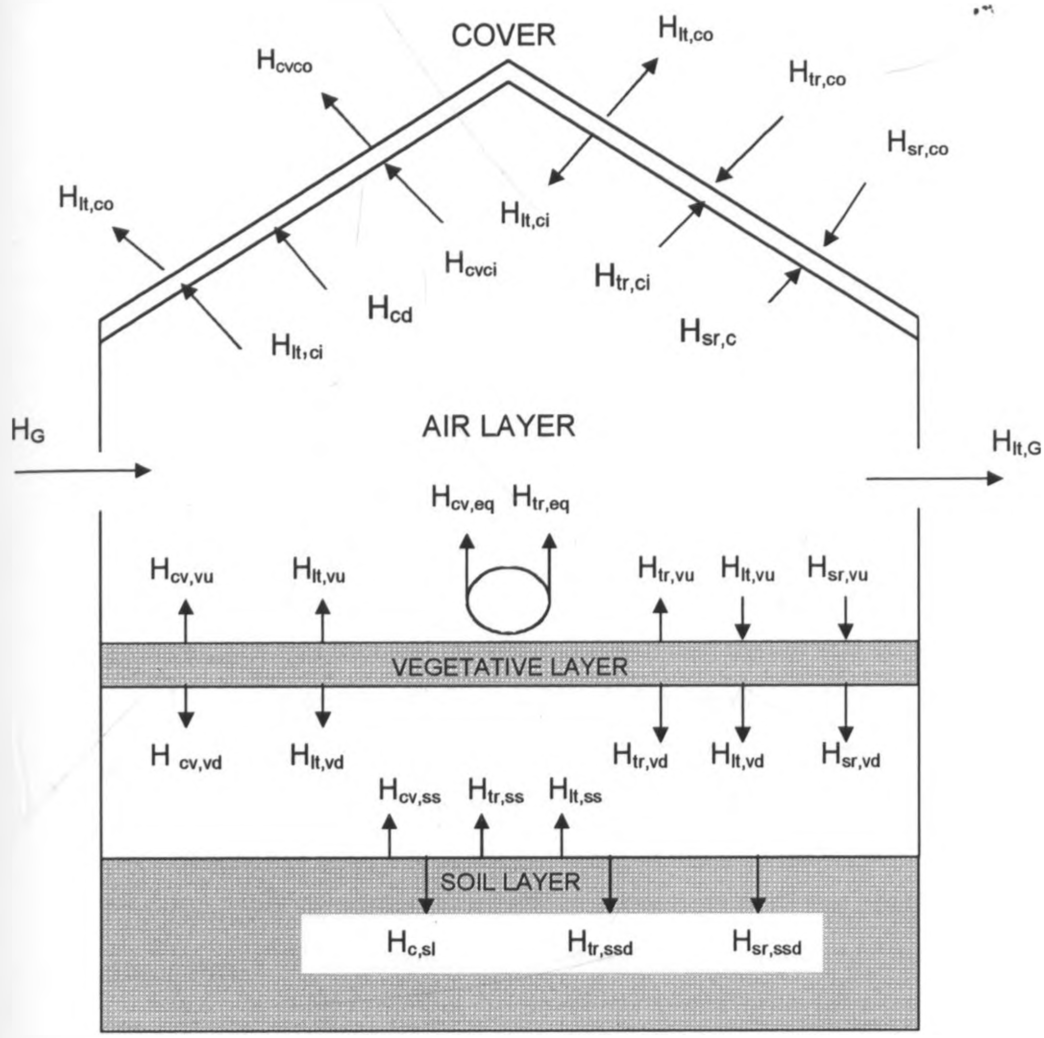


Figure 4.1: A schematic illustration of the radiation, heat and mass fluxes existing in a greenhouse system

where

H_{cd} heat conducted by the cover

$H_{c,sl}$ is heat conducted to the soil

$H_{lt,ss}$ is the latent heat flux from the soil surface

$H_{lt,co}$ is latent heat flux from topside of the cover

$H_{lt,vu}$ is the latent heat flux from upper side of vegetation

$H_{lt,vp}$ is the latent heat flux from lower side of vegetation

$H_{lt,G}$ latent heat flux from ventilation

$H_{lt,ci}$ is the latent heat flux to the bottom side of the cover

$H_{cv,ss}$ is the sensible heat flux from the soil surface

$H_{cv,ci}$ is the sensible heat flux from cover bottom

$H_{cv,co}$ is sensible heat flux from topside of the cover

$H_{cv,vd}$ is the sensible heat flux from lower side of vegetation

$H_{cv,vu}$ is the sensible heat flux from upper side of vegetation

H_G is the sensible heat flux from the ventilation

$H_{cv,ci}$ is the sensible heat flux to the bottom side of the cover

$H_{cv,co}$ is the sensible heat flux to the top side of the cover

$H_{tr,ss}$ is the thermal radiation emitted from the soil surface

$H_{tr,vu}$ is thermal radiation flux emitted by the top side of vegetation

$H_{tr,vd}$ is thermal radiation flux emitted by bottom side of vegetation

$H_{lt,vu}$ is latent heat flux from upper side of vegetation

$H_{lt,vd}$ is latent heat flux from lower side of vegetation

$H_{tr,ssd}$ is the thermal radiation flux received at the soil surface

$H_{tr,ssu}$ is the thermal radiation flux emitted by the soil surface

$H_{tr,ci}$ is thermal radiation received at the bottom of the cover

$H_{tr,co}$ is thermal radiation received at the topside of the cover

$H_{tr,v}$ is thermal radiation received at the vegetation

$H_{sr,g}$ is the solar radiation received at the ground level

$H_{sr,ci}$ is solar radiation received at the bottom of the cover

$H_{sr,co}$ is solar radiation flux received at the topside of cover

$H_{sr,vu}$ is solar radiation flux received at the top side of vegetation

$H_{sr,vd}$ is solar radiation flux received at the lower side of vegetation

$H_{cv,eq}$ is sensible heat flux from equipment

$H_{tr,eq}$ is thermal heat flux from equipment

4.3 Dynamic Model of Greenhouse Environment

The greenhouse environment can be described by a dynamic model represented by a system of differential equations which can be represented by (Chalabi and Bailey, 1989; Rodriguez *et al.*, 2002)

$$\frac{dY(t)}{dt} = f(Y(t), U(t), P(t), V(t), C, t) \tag{4.5}$$

where

Y(t) is a m-dimensional vector of state variables

U(t) is a n-dimensional vector of input variables

P(t) is a o– dimensional vector of disturbances

V(t) is a p-dimension of system variables

C is a q-dimensional vector of system constants

t is the time

f is a non-linear function based on mass and heat transfer balances

The number of equations describing the system and their characteristics depend on the greenhouse elements, the installed control actualators and the cultivation method (Rodriguez *et al.*, 2002). The model presented in this study corresponds to a naturally ventilated greenhouse located in Kenya and has been developed assuming some general hypothesis:

- The greenhouse is divided in to six elements; cover, internal air, vegetation, soil surface and two soil layers.
- The state variable of the model are the internal air temperature and humidity, cover temperature, vegetation temperature, soil surface temperature, first soil layer temperature and second soil layer temperature.
- The disturbance inputs of the system are the outside air temperature and humidity, wind speed, sky temperature, deep soil temperature, outside solar radiation and the evaporation rate inside the water pools on the soil surface
- The control input of the system is natural ventilation
- The heat fluxes are one dimensional. The model only considers the vertical dimension.

The physical processes included in the balances are: solar and thermal radiation absorption, heat convection and conduction, crop transpiration, condensation and evaporation.

4.3.1 Cover layer

The energy transfer processes by which the cover gains or loses heat are:

- Absorption of incoming solar radiation
- Convection with the outside and the inside air
- Thermal radiation with the interior and the exterior of the greenhouse and

- Latent heat of condensation on the inside surface of the greenhouse if present.

Given that the cover is made of single plastic film with a thickness in mierometers, the conduction heat flux is quantitatively not significant compared with other fluxes on the cover (Garzoli and Blackwell, 1981; Rodriguez *et al.*, 2002). The temperatures on the two sides are assumed to be the same. Only one cover temperature is thus modelled using the following heat transfer balances

$$M_c C_c \frac{dT_c}{dt} = H_{sr-c} - H_{cv,c-ao} - H_{cv,c-ai} - H_{lt,cond} + H_{tr-c} \quad (4.6)$$

where

T_c is cover temperature, °C

H_{sr-c} is solar radiation absorbed by the cover, W m^{-2}

$H_{cv,c-ao}$ is the convective flux with the outside air, W m^{-2}

$H_{cv,c-ai}$ is the convective flux with the internal air, W m^{-2}

$H_{lt,cond}$ is latent heat produced by condensation on the inside of cover, W m^{-2}

H_{tr-c} is net thermal radiation on the cover, W m^{-2}

M_c is mass of the greenhouse cover, kg m^{-2}

C_c is the specific heat of the cover material, J kg^{-1} °C^{-1}.

4.3.1.1 Convective heat transfers of the cover

The convective heat transfer with the outside air is given by (Chapman, 1989)

$$H_{cv,c-ao} = h_{co}(T_{ao} - T_c) \quad (4.7)$$

where

h_{co} is convective film transfer coefficient between the cover and outside air temperature, W m^{-2} °C^{-1}

T_{ao} is outside air temperature, °C

The convective flux with the internal air is given as (Chapman, 1989)

$$H_{cv,c-ai} = h_{ci}(T_c - T_{ai}) \quad (4.8)$$

where

h_{ci} is the convective film transfer coefficient between the inside air and the cover, W m^{-2}°C^{-1}

T_{ai} is the internal air temperature of the greenhouse, °C

The transfer coefficients h_{ci} and h_{co} were estimated by the empirical equation as given by Garzoli and Blackwell (1981). This equation is expressed as

$$h = 7.2 + 3.8V_f \tag{4.9}$$

where

h is transfer coefficient h_{ci} or h_{co}, W m^{-2} °C^{-1}

V_f is estimated velocity fluid past the solid surface, m s^{-1}

V_f was taken as the mean velocity of air inside the greenhouse when calculating for h_{ci} and as the wind speed on the outside of the greenhouse when calculating for h_{co}

4.3.1.2 Condensation on cover

Condensation forms on the inside surface of the cover if its temperature is below the dew point temperature of the air. If it is assumed that the cover is vapour leakage proof, inside the greenhouse there is a closed system at atmospheric pressure with a free water surface (Mavrogianopoulos, 1991). When condensation takes place, during the night, the quantity of heat given to the cover as latent heat ($H_{lt,cond}$) is given by the following expression

$$H_{lt,cond} = h_{cond}\rho_a L(w_{ai} - w_c) \tag{4.10}$$

where

h_{cond} is the coefficient of heat transfer given by the Lewis relationship, W m^{-2} °C^{-1}

w_{ai} is the humidity ratio of the air, kg of moisture per kg of dry air

w_c is humidity ratio of the saturated air at the temperature of the cover

L is the latent heat of condensation of water, 2454 x 10^3 J kg^{-1}

Transfer of heat takes place by the process of eddy diffusion (Garzoli and Blackwell, 1981). The Lewis-relationship is used to relate h_{cond} and h_{ci} as follows

$$h_{cond} = \frac{h_{ci}}{\rho_a c_a} \qquad (4.11)$$

where

C_a is the specific heat capacity of the air, J kg^{-1}°C^{-1}

Combining Equations 4.10 and 4.11 gives the following expression

$$H_{lt,cond} = \frac{Lh_{ci}}{c_a}(w_{ai} - w_c) \qquad (4.12)$$

By using the ideal gas law for air and water vapour, a relation between the relative humidity and the humidity ratio at a given temperature (T) is given by (Rogers and Mayhew, 1992)

$$w(T) = 0.622RH(T)\frac{e_{as}(T)}{P_a} \qquad (4.13)$$

where

RH(T) is relative humidity at air temperature of the greenhouse, %

$e_{as}(T)$ is the saturation vapour pressure at temperature, T, of the air of the greenhouse, k Pa

P_a is the atmospheric pressure, k Pa

The saturation vapour pressure at a temperature, T, is estimated by an empirical equation as given by Murray (1967), it is

$$e_{as}(T) = e_{as}(T^*)\exp\{B(T - T^*)/(T - T')\} \qquad (4.14)$$

where

B is constant valued at 17.27

T* is a standard temperature taken to be 273 K (0 °C)

$e_{as}(T^*)$ is saturation vapour pressure at T* (0.611 k Pa)

T' is a constant valued at 36 K

Equation 4.13 and 4.14 are used to calculate the values of w_{ai} and w_c. If the resulting value of the temperature of the cover provide the value of w_c that is greater than w_{ai} then condensation does not take place on the cover. Else if w_c is less than w_{ai} then condensation occurs.

4.3.1.3 Radiation on the cover

The cover receives thermal and shortwave radiation. The short wave radiation is sourced from the sun and is present during the day while the thermal radiation component is present all the times.

4.3.1.3.1 Short wave radiation

The intensity of short wave radiation incident on the cover is dependent on the metrological conditions of a given day. Part of this radiation is absorbed by the cover while the rest is transmitted through or reflected away from the cover. The quantitative values of the absorbed reflected and transmitted solar radiation is dependent on the thermal properties of the cladding material.

The solar radiation absorbed is expressed as

$$H_{sr-c} = a_c I_{sr} \tag{4.15}$$

where

a_c is the absorptivity of solar radiation by the cover

I_{sr} is the net solar radiation flux, W m^{-2}.

4.3.1.3.2 Thermal radiation

The cover exchanges thermal radiation with the greenhouse soil surface (footpaths), vegetation, the sky and the outside ground. The way that the cover reacts to thermal radiation is affected by the absence or the presence of condensation on it. In this study it is assumed that the radiation is emitted from the soil surface (footpaths) and uniform horizontal canopy surface (vegetative layer) to the cover itself. An apparent greenhouse ground (vegetative surface and soil surface) temperature, T_{gi}, is used to estimate the thermal radiation exchange between cover and greenhouse ground.

The thermal radiation, from the greenhouse ground, received by cover, outside ground and the sky is contributed to by the vegetative surface and open soil surface i.e. only a given percentage of the ground is covered by crop. Considering the areas, the apparent ground temperature, T_{gi}, can be expressed by

$$T_{gi} = \left(\frac{A_v}{A_{gi}} \varepsilon_v T_v{}^4 + \frac{A_{ss}}{A_{gi}} \varepsilon_{ss} T_{ss}{}^4 \right)^{\frac{1}{4}} \tag{4.16}$$

where

A_{gi} is the area of the inside greenhouse ground, m^2.

A_v is the greenhouse ground covered by vegetation, m^2

A_{ss} is open soil surface temperature, m^2

T_v is vegetation temperature, °C

T_{ss} is soil surface temperature, °C

ε_v is thermal emmittance of the vegetation surface

ε_{ss} is thermal emmittance of soil surface

When there is no condensation, most of the thermal radiation from the inside of the greenhouse passes directly through the cover to the sky without contributing heat (Garzoli and Blackwell, 1981). The magnitude of this radiation is given by

$$R_{gi-sky} = \sigma A_{gi} \tau_{c,tr} (T_{gi}^4 - T_{sky}^4) \tag{4.17}$$

where

R_{gi-sky} is the thermal radiation from the greenhouse house ground to the sky, W

$\tau_{c,tr}$ is the transmittance of the cover to thermal radiation

T_{gi} is the apparent greenhouse ground temperature, K

T_{sky} is the sky temperature, K

The radiation sky temperature is very dependent on the cloud cover. An empirical relationship as proposed by Swinbank (1963) and quoted by Wang and Boulard (2000) was used in this study. The expression is

$$T_{sky} = T_{ao}F_{cn} + 0.0552(1-F_{cn})T_{ao}^{1.5} \quad (4.18)$$

where

F_{cn} is the cloud cover factor (1, overcast and 0 clear)

There is also an exchange of thermal radiation between the inside surface of the cover and the floor of the greenhouse this can be expressed as (Garzoli and Blackwell, 1981)

$$R_{gi-c(0\%)} = \sigma A_{gi}\varepsilon_1\tau_{c,tr}(T_{gi}^4 - T_c^4) \quad (4.19)$$

$$\varepsilon_1 = \frac{1}{1+\frac{A_{gi}}{A_c}\left[\frac{1}{\varepsilon_c}-1\right]} \quad (4.20)$$

where

A_c is cover area, m^2

ε_c is the cover emittance

The amount of thermal radiation outward of the cover is dependent on the presence of condensate. Without condensate this radiation has two components that are the one pass directly through the cover to the sky and that emitted outwards from the cover itself to the sky and the surrounding ground. The radiation passing directly to the sky is equal to the one given in equation (4.17).

The outward radiation in absence of condensate, $R_{co(0\%)}$, was thus expressed as (Garzoli and Blackwell, 1981)

$$R_{co(0\%)} = \sigma A_{gi}\tau_{c,tr}(T_{gi}^4 - T_{sky}^4) + \sigma A_c\varepsilon_c F_{c-sky}(T_c^4 - T_{sky}^4) + \sigma A_c\varepsilon_c F_{c-go}(T_c^4 - T_{go}^4)$$

(4.21)

where

F_{c-sky} is the shape factor for radiation exchange between cover and sky

F_{c-go} is the shape factor for radiation exchange between cover and outside ground

T_{go} is the temperature of the surrounding outside ground, K

The net thermal radiation on the cover, $H_{tr-c,}$ in the absence of condensation is thus given by the difference between the thermal radiation incident on the inside of the cover and the radiation emitted outward from the cover and is expressed as

$$H_{tr-c} = \frac{1}{A_{gi}}\left(R_{gi-ci(0\%)} - R_{co(0\%)}\right)$$
$$= \frac{1}{A_{gi}}\left(\begin{array}{l}\sigma A_{gi}\varepsilon_1\tau_{c,tr}(T_{gi}^4 - T_c^4) - \sigma A_c\varepsilon_c F_{c-s}(T_c^4 - T_{sky}^4) \\ -\sigma A_c\varepsilon_c F_{c-go}(T_c^4 - T_{go}^4)\end{array}\right)$$

(4.22)

With condensation present, the internal thermal radiation is unable to pass directly through the cover, because water is opaque to thermal radiation (Garzoli and Blackwell, 1981; Pieters *et al.* 1994).

If it is assumed that the condensate completely covers the inside surface of the cladding material then all the internal thermal radiation will be incepted by the cover. In such an event, the thermal radiation to the cover, $R_{gi-cond}$ is expressed as

$$R_{gi-cond} = \sigma\varepsilon_2 A_{gi}(T_{gi}^4 - T_c^4) \quad (4.23)$$

where

$$\varepsilon_2 = \frac{1}{1 + \frac{A_{gi}}{A_c}\left[\frac{1}{\varepsilon_{cond}} - 1\right]} \quad (4.24)$$

where

ε_{cond} is the emittance of the condensate

The outward thermal radiation, $R_{co(100\%)}$, from the cover, assuming the same total coverage of the cover by the condensate, consists of that emitted from the condensate film and passing outward through the cover, together with that emitted from the cover itself, to the sky and the to the surrounding ground. This was expressed as

$$R_{co(100\%)} = \sigma A_c \varepsilon_c F_{c-sky}(T_c^4 - T_{sky}^4) + \sigma A_c \varepsilon_{cond} F_{c-sky} \tau_{c,tr}(T_c^4 - T_{sky}^4) + \sigma A_c \varepsilon_{cond} F_{c-go} \tau_{c,tr}(T_c^4 - T_{go}^4) + \sigma A_c \varepsilon_c F_{c-go}(T_c^4 - T_{go}^4) \qquad (4.25)$$

Thermal radiation absorbed by the cover assuming 100% coverage by condensation is given by

$$\begin{aligned} H_{tr-c} &= \frac{1}{A_{gi}}\left(R_{gi-ci(100\%)} - R_{co(100\%)}\right) \\ &= \frac{1}{A_{gi}}\left(\begin{aligned} &\sigma \varepsilon_1 A_{gi}(T_{gi}^4 - T_c^4) - \sigma A_c \varepsilon_c F_{c-sky}(T_c^4 - T_{sky}^4) - \sigma A_c \varepsilon_c F_{c-go}(T_c^4 - T_{go}^4) \\ &- \sigma A_c \varepsilon_{cond} F_{c-sky} \tau_{c,tr}(T_c^4 - T_{sky}^4) - \sigma A_c \varepsilon_{cond} F_{c-go} \tau_{c,tr}(T_c^4 - T_{go}^4) \end{aligned}\right) \end{aligned} \qquad (4.26)$$

In reality, however condensation forms as discrete droplets, the maximum coverage being about 67% (Walker and Walton, 1971). In such a case the relationship that applies for the total radiation, $R_{gi-ci(67\%)}$ on the inside of the cover is given by the following expression

$$R_{gi-ci(67\%)} = 0.33\sigma A_{gi} \tau_{c,tr}(T_c^4 - T_{sky}^4) + 0.33\sigma A_{gi} \varepsilon_1 (T_{gi}^4 - T_c^4) + 0.67\sigma A_{gi} \varepsilon_2 (T_{gi}^4 - T_c^4) \qquad (4.27)$$

The outward thermal radiation, $R_{co(67\%)}$, from outside of the cover is expressed as

$$R_{co(67\%)} = 0.33\sigma A_{gi} \tau_{c,tr}(T_{gi}^4 - T_{sky}^4) + \sigma A_c \varepsilon_c F_{c-sky}(T_c^4 - T_{sky}^4) + \sigma A_c \varepsilon_c F_{c-go}(T_c^4 - T_{go}^4) + 0.67\sigma A_c \varepsilon_{cond} F_{c-sky} \tau_{c,tr}(T_c^4 - T_{sky}^4) + 0.67\sigma A_c \varepsilon_{cond} F_{c-go}(T_c^4 - T_{go}^4) \qquad (4.28)$$

Thus with 67% coverage the absorbed radiation on the cover is given by the expression

$$H_{tr-c} = \frac{1}{A_{gi}}\left(R_{gi-ci(67\%)} - R_{co(67\%)}\right)$$

$$= \frac{1}{A_{gi}}\begin{pmatrix} 0.33\sigma A_{gi}\tau_{c,tr}(T_{gi}^{4} - T_{sky}^{4}) + 0.33\sigma A_{gi}\varepsilon_1(T_{gi}^{4} - T_c^{4}) \\ +0.67\sigma A_{gi}\varepsilon_2(T_{gi}^{4} - T_c^{4}) - 0.33\sigma A_{gi}\tau_{c,tr}(T_{gi}^{4} - T_{sky}^{4}) \\ -\sigma A_c\varepsilon_c F_{c-sky}(T_c^{4} - T_{sky}^{4}) - \sigma A_c\varepsilon_c F_{c-go}(T_c^{4} - T_{go}^{4}) \\ -0.67\sigma A_c\varepsilon_{cond}F_{c-sky}\tau_{c,tr}(T_c^{4} - T_{sky}^{4}) + 0.67\sigma A_c\varepsilon_{cond}F_{c-go}(T_c^{4} - T_{go}^{4}) \end{pmatrix}$$

(4.29)

Following the findings of Walker and Walton (1971), the condensate was taken to occupy 67% of the cover. This was appropriate because if condensate was present on the inside of the cover of the greenhouse, it was in droplets. Equation (4.29) was thus implemented in the simulation program.

4.3.2 Air Layer

The greenhouse air temperature was modelled as given below

$$M_a C_a \frac{dT_{ai}}{dt} = H_{cv,c-ai} + H_{cv,ss-ai} + H_{cv,v-ai} - H_{ven} \qquad (4.30)$$

where

$H_{cv,c-ai}$ is the convective flux with the cover, W m^{-2} °C^{-1}

$H_{cv,ss-ai}$ is the convective heat flux with soil surface, W m^{-2} °C

$H_{cv,v-ai}$ is the convective heat flux with vegetation, W m^{-2} °C

H_{ven} is the heat lost by natural ventilation, W m^{-2} °C

M_a is the mass of air in the greenhouse per unit ground area, kg m^{-2}

C_a is the specific heat capacity of air, J kg^{-1} °C^{-1}

4.3.2.1 Convective heat flux of the air

The convective heat flux with the cover is given as (Chapman, 1989)

$$H_{cv,c-ai} = h_{ci}(T_c - T_{ai}) \qquad (4.31)$$

where

h_{ci} is the convective film transfer coefficient between the inside air and the cover, W m^{-2} °C^{-1}

The convective flux with the soil surface ($H_{cv,ss-ai}$) is expressed as

$$H_{cv,ss-ai} = h_{ss}(T_{ss} - T_{ai}) \qquad (4.32)$$

where

h_{ss} is convective heat transfer coefficient between the soil surface and the air, W m^{-2} °C

4.3.2.2 Ventilation heat flux

Seginer and Kantz (1989) express the heat flux due to ventilation, H_{ven}, by

$$H_{ven} = \frac{1}{A_{gi}}\left[C_a \rho_a G_v (T_{ai} - T_{ao})\right] \qquad (4.33)$$

where

C_a is specific heat of air, J kg^{-1}°C^{-1}

ρ_a is the density of air, kg m^{-3}

G_v is the ventilation flux, m^3 s^{-1}

Given that driving forces for natural ventilation are the buoyancy and wind (Wang and Boulard, 2000; Baptista *et al.*, 1999), a relationship which account for both effect was taken into account. The ventilation flux was thus estimated by the equation (Albright, 1990; Zhang *et al.*, 1989):

$$G_v = \sqrt{G_w^2 + G_T^2} \qquad (4.34)$$

where

G_w is the ventilation flux due to the wind, m^{-3} s^{-1}

G_T is the ventilation flux due to temperature difference, m^{-3} s^{-1}

Albright (1990) suggests the below empirical equation to determine the ventilation rate due to wind

$$G_w = \frac{A_{op}}{2} E U_{op} \tag{4.35}$$

where

A_{op} total area of ventilation opening, m^2

U_{op} is average wind speed through opening, m s^{-1}

E is the effectiveness of opening

The total area of openings, A_{op}, is divided by two because half area is taken as the inlet and half the outlet. E is the effectiveness of the opening depending on the wind direction. It has the value of 0.5-0.6 at right angles to the opening winds and 0.25-0.35 for diagonal winds (Baptista *et al.*, 1999). For agricultural buildings, the value recommended is 0.35, which is the global coefficient of Equation (3.12) taking into account the effectiveness of the opening and the pressure due to wind action.

Bruce (1978) presents an equation to predict the flow through an opening due to temperature difference ΔT by the following equation

$$G_T = C_d \frac{A_{op}}{3} \sqrt{gZ \frac{\Delta T}{T_{oa}}} \tag{4.36}$$

where

g is the acceleration due to gravity, m s^{-2}

Z is the height of the opening, m

4.3.2.3 Moisture balance of air in the greenhouse

The humidity of the air was based on a water balance equation. The main sources of water vapour in the greenhouse air are the crop transpiration, the evaporation from the soil surfaces and pools and the water influx from fogging or cooling (Rodriguez *et al.*, 2002). Vapour outflow from the greenhouse takes place through condensation on the internal side of the cover, the ventilation and vapour lost through infiltration losses.

Transpiration from vegetation can be estimated by Equation (3.17). However, where there is no enough transpiration data available on a particular crop, e.g. for internal and external resistance, the modified version of Equation 3.17 can be used (Allen *et al.*, 1999), with some fixed parameters as recommended by Walter *et al.* (2000). The modified expression is as follows

$$ET_{ref} = \frac{0.408\delta(H_{rad,so} - H_{so}) + \gamma \frac{C_n}{T_{ai} + 273} U_{ca}(e_{as} - e_a)}{\delta + \gamma(1 + C_d U_c)} \quad (4.37)$$

where

ET_{ref} is the reference crop evapotranspiration in mm of water per hr

$H_{rad,so}$ and H_{so} are the net radiation and soil heat flux density in MJ m^{-2} h^{-1} for hourly data

δ is slope of the saturated vapour pressure curve, kPa K^{-1}

$H_{rad,so}$ and H_{so} are the net radiation and soil heat flux density in MJ m^{-2} h^{-1} for hourly data

C_d and C_n are crop coefficients, dimensionless

γ is the psychometric constant, 0.67 kPa K^{-1}

e_{as}-e_a is vapour pressure deficit, kPa

U_{ca} is the mean air speed at the canopy in m s^{-1}

The coefficients in the numerator (C_n) and the denominator (C_d) are given specific values depending on the calculation time step and the reference crop (Snyder, 2000).

The output units from Equation (4.37) are in mm per day for the daily or monthly calculations and in mm h^{-1} for the hourly time step. For the daily data, $H_{rad,so}$ is input in MJ $m^{-2}d^{-1}$ and H_{so} is assumed to be zero. For the hourly calculations, H_{so} is assumed equal to 10% of $H_{rad,so}$ when $H_{rad,so}$>= 0 and is assumed equal to 50% of R_n for R_n<0. In addition, the surface (canopy) resistance is set equal to 50 s m^{-1} during daytime and 200 s m^{-1} at night. This change accounts for night time stomatal closure and improves the daytime estimates (Snyder *et al.* 2002). For citrus seedlings C_n is 0.37 and C_d is 0.24 at day time and 0.94 at night (Snyder *et al.* 2002).

The E_{ref} is mathematically equivalent to the kilograms of water lost by evapotranspiration per unit area, m^2.

The slope of the water vapour saturation curve at temperature, T is given by the relation (Murray, 1967)

$$\delta = \frac{2504}{(T_{ai} - 35.86)^2} e^{17.27(T_{ai} - 273.16)/(T_{ai} - 35.86)} \tag{4.38}$$

The mean air velocity at the canopy, U_{ca}, can be described by the relations (Kindelan, 1980)

$$U_{ca} = U_m \left(\frac{aA_{gi}}{V_g} \right)^{2/3} \tag{4.39}$$

where

a is the mean height of canopy

U_m is the mean air velocity in the greenhouse

U_m is given by the expression (Wang and Bourlard, 2000)

$$U_m = \frac{G_v}{A_f} \tag{4.40}$$

where

A_f is the frontal area of the greenhouse.

The humidity ratio of the greenhouse air was thus modelled by the following water mass balance equation

$$\frac{dw_{ai}}{dt} = \frac{A_{gi}}{\rho_a V_g} \left(M_{W,evtr} - M_{W,cond} - M_{W,vent} - M_{W,losses} \right) \tag{4.41}$$

where

$M_{W,\ evtr}$ is the evapotranspiration flux from vegetation and soil, kg s^{-1} m^{-2}

$M_{W,\ cond}$ is the condensation flux from the cover, kg s^{-1} m^{-2}

$M_{W,\ ven}$ is the outflow by natural ventilation, kg s^{-1} m^{-2}

$M_{W,\ losses}$ is the vapour lost by infiltration losses, kg s^{-1} m^{-2}

The water lost by infiltration was not considered in this study. The remaining fluxes were approximated as follows

$$M_{W,ven} = \frac{\rho_a G v}{A_{gi}}(w_{ai} - w_{ao}) \tag{4.42}$$

$$M_{W,cond} = \frac{A_c}{A_{gi}} h_{cond} \rho_a (w_{ai} - w_c) \tag{4.43}$$

$$M_{W,evtr} = E_{ref} \tag{4.44}$$

4.3.3 Vegetation layer

The distribution of the greenhouse crop on the ground is not homogeneous for most greenhouse crops due to the presence of access paths (Papadakis *et al.*, 1994). The crop is also not homogeneous in the vertical direction. However, for irrigation purposes or for greenhouse climate control and management purposes, one may consider that there is a "momentary average crop temperature" and a "momentary average crop transpiration rate" (Papadakis *et al.*, 1994). In other words the knowledge of the precise temperature and transpiration distribution of a greenhouse crop in the vertical and horizontal direction is not necessary for the above purposes (Papadakis *et al.*, 1994).

Measurement of temperature in the vertical direction has shown that the temperature difference along that profile is not much. Yang *et al.* (1989), measured vertical temperature profiles of a well-developed greenhouse cucumber crop and found maximum difference 2.5 °C.

The greenhouse crop can thus be treated as a homogeneous porous volume through which the greenhouse air may easily circulate. The crop can be considered partially transparent to solar and thermal radiation, having instantaneous but uniform temperature and characterized by an instantaneous but uniform transpiration rate per unit leaf area (Papadakis *et al.*, 1994).

On the basis of these assumptions and supposing that the crop temperature is identical to that of the foliage, Papadakis *et al.* (1994) expressed the energy balance of a greenhouse crop per unit leaf area by the following equation

$$0.5M_vC_v\frac{dT_v}{dt}=H_{rad,nv}-H_{lt,v}+H_{cv,v-ai} \qquad (4.45)$$

where

T_v is vegetation temperature

M_v is the leaf mass per unit leaf area, kg m^{-2}

C_v is the crop specific heat, J kg^{-1} °C^{-1}

$H_{rad,nv}$ is the full spectrum crop net radiation per unit leaf area, W m^{-2}

$H_{lt,v}$ is the crop transpiration rate per unit leaf area, W m^{-2}

$H_{cv,v-ai}$ is the sensible heat transfer between the greenhouse air and the crop per unit leaf area, W m^{-2}.

In Equation (4.45) fluxes due to chemical reactions (for example, photosynthesis) are not taken into account, since these fluxes were considered as negligible in comparison with other fluxes appearing in the equation.

4.3.3.1 Convective heat transfer

The convective heat transfer, $H_{cv,v-a}$, between leaves and air, per unit leaf area, is given by the following equation (Papadakis *et al.*, 1994)

$$H_{cv,v-ai}=\rho_aC_a\frac{(T_{ai}-T_v)}{r_e} \qquad (4.46)$$

where

T_v, is the average leaf temperature, °C

r_e is the average external resistance to sensible heat transfer between crop and air, s m^{-1}

C_a is the specific heat capacity of the air, J kg^{-1} °C^{-1}

The group ρ_aC_a/r_e has the same dimension as the convective heat transfer coefficient. The heat transfer coefficient, h_v, of plants was thus estimated by an empirical expression as given by (Seginer and Livne, 1971) and quoted by Kindelan (1980). The expression is

$$h_v = 1.9\left(\frac{|T_v - T_{ai}|}{\ell}\right)^{\frac{1}{4}} + 5.2\left(\frac{U_{ca}}{\ell}\right)^{\frac{1}{2}} \tag{4.47}$$

where

ℓ is the characteristic dimension of the leaf, m

U_{ca} is air velocity in the canopy (Equation 4.39)

4.3.3.2 Net radiation

Full spectrum crop net radiation per unit leaf area, $H_{rad,nv}$ is composed of the solar radiation and thermal radiation and can be expressed as

$$H_{rad,nv} = H_{sr,v} + H_{tr,v} \tag{4.48}$$

where

$H_{sr,v}$ is solar radiation absorbed by vegetation, W m^{-2}

$H_{tr,v}$ is thermal radiation absorbed by vegetation, W m^{-2}

4.3.3.2.1 Short wave radiation

The solar radiation absorbed by the vegetation is that which is received by the vegetation after transmission by the cover. It can be expressed as

$$H_{sr,v} = a_v \tau_{c,sr} I_{sr} \tag{4.49}$$

where

a_v is absorptivity of the vegetation

$\tau_{c,sr}$ is the transmittance of the cover to solar radiation

4.3.3.2.2 Thermal radiation

If one assumes that vegetation has unity emittance and zero reflectance to thermal radiation and that the crop canopy completely covers the ground. The procedure used by Silva and Rosa (1987) can be used to determine the net thermal radiation on the vegetative surface. With the cladding material treated as a grey body and considering multiple reflections. If one considers an infinite long single span greenhouse. The radiation flux emitted by the cover arriving at the vegetation directly of after several reflections can be given by (Silva and Rosa, 1987)

$$\begin{aligned} A_v H_{tr,c-v} &= A_c \varepsilon_c \sigma T_c^4 F_{c-v}(1+\rho F_{c-c}+\rho^2 F_{c-c}^2 ....) \\ &= \varepsilon_c \sigma T_c^4 A_c F_{c-v}/(1-\rho F_{c-c}) \end{aligned} \tag{4.50}$$

where

A_v is horizontal area of vegetation, m^2

$H_{tr,c-v}$ is thermal radiation flux from cover to vegetation, W m^{-2}

F_{c-v} is shape factor for exchange of diffuse radiation between cover and vegetation

F_{c-c} is shape factor for exchange of diffuse radiation between cover and to cover

Given that $A_1F_{12} = A_2F_{21}$ we have $A_cF_{c-v} = A_vF_{c-v}$ so that

$$H_{tr,c-v} = F_{v-c}\varepsilon_c \sigma T_c^4/(1-\rho F_{c-c}) \tag{4.51}$$

Similarly, the flux arriving at vegetation that has been emitted by vegetation it self, $H_{tr,v-v}$ is expressed by,

$$H_{tr,v-v} = F_{v-c}F_{c-v}\rho\sigma T_v^4/(1-\rho F_{c-c}) \tag{4.52}$$

For the flux density arriving at the vegetation due to external atmospheric and terrestrial radiation we have

$$H_{tr,sky-v} = \frac{F_{v-c}F_{c-sky}\tau_{c,tr}\varepsilon_{sky}\sigma T_{sky}^4}{(1-\rho F_{cc})} \tag{4.53}$$

$$H_{tr,go-v} = \frac{F_{v-c}F_{c-go}\tau_{c,tr}\sigma T_{go}^4}{(1-\rho F_{cc})} \tag{4.54}$$

The net thermal radiation emitted vegetation ($H_{rad,v}$) is thus expressed by

$$H_{rad,v} = H_{tr,c-v} + H_{tr,v-v} + H_{tr,sky-v} + H_{tr,go-s} - \sigma T_v^4 \qquad (4.55)$$

or

$$H_{rad,nv} = \frac{\varepsilon_c \sigma T_c^4 + F_{c-v} \rho \sigma T_v^4 + \tau_c (F_{c-sky} \varepsilon_{sky} \sigma T_{sky}^4 + F_{c-go} \sigma T_{go}^4)}{(1-\rho F_{cc})} - \sigma T_v^4 \qquad (4.56)$$

4.3.4 Soil surface

The soil (greenhouse thermal mass play) plays an important role on the greenhouse climate control (Rodriguez *et al.*, 2002). At daytime soil absorbs the solar radiation on its surface. This absorbed heat is transferred to the deep layers of soil. At night the soil transfers this heat to the greenhouse environment from these layers. The conductive fluxes are very significant as this is the mode by which heat is transferred between the soil layers.

Following a similar procedure used by Wang and Boulard (2000) and Rodriguez *et al.* (2002), the soil was divided into layers: Surface; first layer, second layer and deep layer. The deep layer was assumed to have a constant temperature (Rodriguez *et al.*, 2002). The soil surface temperature, $T_{SS,}$ was determined by energy balancing of net radiation, latent heat, sensible heat and ground conductive heat fluxes at the soil surface. The energy balance for the soil surface was expressed as

$$M_{ss} C_{ss} \frac{dT_{ss}}{dt} = H_{sr,ss} - H_{cv,ss-ai} - H_{cd,ss-s1} - H_{lt,ss} - H_{rad,ss} \qquad (4.57)$$

where

$H_{sr,ss}$ is the solar radiation absorbed by the soil surface, W m^{-2}

$H_{cv,ss-ai}$ is the convective flux with the greenhouse air, W m^{-2}

$H_{cd,ss-s1}$ is the conductive heat flux between the soil surface and the first layer of soil located at a depth DZ_i, W m^{-2}

$H_{lt,ss}$ is the latent heat produced by evaporation on soil surface, W m^{-2}

$H_{rad,ss}$ is the thermal radiation emitted by the soil surface, W m^{-2}

T_{ss} is the soil surface temperature, °C

C_{ss} is the specific heat of the soil surface layer, J Kg^{-1}°C^{-1}

M_{ss} is the mass of the soil surface layer, Kg m^{-2}

4.3.4.1 Convective flux of the soil surface

The convective flux with the greenhouse air is given by

$$H_{cv,ss-ai} = h_{ss}(T_{ss} - T_a) \tag{4.58}$$

where

h_{ss} is convective heat transfer coefficient between the soil and the interior air, W m^{-2}

The transfer coefficient, h_{ss} can be expressed as (Kindelan, 1980)

$$h_{ss} = 1.52|T_{ai} - T_{ss}|^{1/3} + 5.2\left(\frac{U_m}{l_{ss}}\right)^{1/2} \tag{4.59}$$

where

l_{ss} is the characteristic length of the soil surface

4.3.4.2 Radiation exchanges

4.3.4.2.1 Short wave radiation

The solar radiation absorbed by the soil is that which is received by the ground after transmission by the cover and absorption by the plants.

$$H_{sol,ss} = a_{ss}\tau_{v,sr}\tau_{c,sr}I_{sr} \tag{4.60}$$

where

a_{ss} is absorbance of solar radiation by the ground

$\tau_{v,sr}$ is the net transmittance of vegetation to solar radiation

4.3.4.2.2 Thermal radiation

Assuming that the inside soil surface has unity emittance and zero reflectance to thermal radiation (Silva and Rosa, 1987). Treating the cladding material as a grey body and considering multiple reflections and only bare soil surface (without vegetation), following the same approach as used for vegetation and the net thermal radiation on the soil surface ($H_{rad,ss}$) per unit area of bare soil surface was estimated by the expression

$$H_{rad,ss} = \frac{\varepsilon_c \sigma T_c^4 + F_{c-ss}\rho\sigma T_{ss}^4 + \tau_{c,tr}(F_{c-sky}\varepsilon_a \sigma T_{sky}^4 + F_{c-go}\sigma T_{go}^4)}{(1-\rho F_{c-c})} - \sigma T_{ss}^4 \quad (4.61)$$

4.3.5 Deep soil layers

Heat flow in soil is complicated because heat flow is associated with water flow. However in most cases it is sufficient to estimate heat flow using apparent thermal conductivity, which includes the effect of water flow (Rodriguez *et al.*, 2002; Wang and Boulard, 2000). The heat flow is then that in a solid body.

Suppose that the greenhouse soil is divided into three even layers in depth and the temperature at the middle of each layer are the assumed average temperatures of the layers, T_{s1}, T_{s2} and T_d (Figure 4.2). The boundary conditions are surface soil temperature, T_{ss} and deep layer temperature T_d.

Referring to the Figure 4.2, the electric passive network can be used to represent the heat flow in a given soil layer.

Figure 4.2: Heat flow and temperature regime in the soil layer (a). Left: Heat flow (b). Electrical network analogy

The conductive heat flux ($H_{cd,ss-s1}$) between the soil surface and the first layer is given by

$$H_{cd,ss-s1} = k_{s1}(T_{ss} - T_{s1})/DZ_{T_{s1}} \quad (4.62)$$

where

M_{s1} is the mass of the first soil layer, kg m^{-2}

C_{s1} is the specific heat capacity of the soil making the first layer, J kg^{-1} $°C^{-1}$

K_{s1} is thermal conductivity of the first soil layer, W m^{-1} $°C^{-1}$

T_{s1} is the midpoint temperature of the first soil layer, °C

DZ_{Ts1} is the distance between points of measurements of T_{ss} and T_{s1}, m.

First soil layer temperature was modelled by the equation

$$M_{s1}C_{s1}\frac{dT_{s1}}{dt} = k_{s1}(T_{ss} - T_{s1})/DZ_{T_{s1}} - k_{s1}(T_{s1} - T_{s2})/DZ_{T_{s2}} \quad (4.63)$$

where

M_{s1} is the mass per unit area of the first soil layer, kg m^{-2}

C_{s1} is the specific heat capacity of the soil making the first layer, J kg^{-1} $°C^{-1}$

K_{s1} is thermal conductivity of the first soil layer, W $m^{-1}$$°C^{-1}$

T_{s1} is the temperature at the midpoint of the first soil layer, °C

T_{s2} is the temperature at the midpoint of the second soil layer, °C

DZ_{Ts2} is the vertical distance between points of measurement of T_{s1} and T_{s2}, m

The second soil layer temperature was modelled by the expression:

$$M_{s2}C_{s2}\frac{dT_{s2}}{dt} = k_{s2}(T_{s1} - T_{s2})/DZ_{Ts_2} - k_{s2}(T_{s2} - T_d)/DZ_{T_d} \quad (4.64)$$

where

M_{s2} is the mass of the second soil layer, kg m^{-2}

C_{s2} is the specific heat capacity of the soil making the first layer, J kg^{-1} °C^{-1}

k_{s2} is the conductivity of the first soil layer in W m^{-1} °C^{-1}

T_d is the deep soil layer temperature assumed constant during the simulation period, °C

DZ_{Td} is the vertical distance between points of measurement of T_{s2} and T_d, m

5. MATERIALS AND METHODS

5.1 Method of Solution

The state variable approach was used in the analysis of the greenhouse system. The method requires that the variables used to formulate the system equations be chosen in such a way that they can be written as a single matrix equation of the form (Huelsman, 1986)

$$\mathbf{y}'(t) = \mathbf{A}\mathbf{y}(t) + \mathbf{u}(t) \tag{5.1}$$

where

$\mathbf{y}(t)$ is the column vector of state variables $y^k(t)$

t is the independent variable, time in this case

A is the square matrix, which maybe a function of t or of the state variable y

U (t) is a column matrix with elements $u^k(t)$ representing inputs into the system

For the greenhouse system, the state variable of the mathematical model as developed in Chapter 4 are the internal air temperature and humidity, cover temperature, vegetation temperature, soil surface temperature, first soil layer temperature, and second soil layer temperature.

Equation (5.1) thus included differential equations expressing dynamic energy balance for; cover temperature (Equation 4.6), air temperature (Equation 4.30), vegetation temperature (Equation 4.45), soil surface temperature (Equation 4.57), first soil layer temperature (Equation 4.63), and second soil layer temperature (Equation 4.64). The equation used to express the humidity of the greenhouse air (Equation, 4.41) was solved independently.

5.1.1 Numerical technique

The general form of first order ordinary differential equations used to represent the temperature (T) of an element of the greenhouse system was

$$T'(t) = g(t, y) \tag{5.2}$$

where

g is an arbitrary function representing temperature of a greenhouse element

t is time, s or hr

Given the function g(t,y) defined in Equation (5.2) and a known value T_i of the dependent variable T(t), at some value t_i of the independent variable t, we define four functions as required by the fourth order Runge-Kutta method as follows (Huelman, 1986; Scheid, 1988).

$$g_1 = g(t_i, T_i) \tag{5.3}$$

$$g_2 = g(t_i + \frac{\Delta t}{2}, T_i + \frac{\Delta t g_1}{2}) \tag{5.4}$$

$$g_3 = g(t_i + \frac{\Delta t}{2}, T_i + \frac{\Delta t g_2}{2}) \tag{5.5}$$

$$g_4 = g(t_i + \Delta t, T_i + \Delta t g_3) \tag{5.6}$$

where

$\Delta t = t_{i+1} - t_i$, i.e. time step of solution

Having evaluated the functions above the next value of T(t) is found by the relation (Huelman, 1986; Scheid, 1988)

$$T_{i+1} = T_i + \frac{1}{6}(g_1 + 2g_2 + 2g_3 + g_4)\Delta t \tag{5.7}$$

The error for this method is proportional to $(\Delta t)^5$ (Huelman, 1986).

Solving the set of simultaneous first order differential equations representing the greenhouse system i.e. the matrix first order differential equation require that the relations in Equations (5.3) to (5.7) be given as matrix operations resulting into the following Equations (Huelman, 1986):

$$\mathbf{g}_1 = \mathbf{g}(t_i, \mathbf{T}_i) \quad (5.8)$$

$$\mathbf{g}_2 = \mathbf{g}(t_i + \frac{\Delta t}{2}, \mathbf{T}_i + \frac{\Delta t \mathbf{g}_1}{2}) \quad (5.9)$$

$$\mathbf{g}_3 = \mathbf{g}(t_i + \frac{\Delta t}{2}, \mathbf{T}_i + \frac{\Delta t \mathbf{g}_2}{2}) \quad (5.10)$$

$$\mathbf{g}_4 = \mathbf{g}(t_i + \Delta t, \mathbf{T}_i + \Delta t \mathbf{g}_3) \quad (5.11)$$

$$\mathbf{T}_{i+1} = \mathbf{T}_i + \frac{1}{6}(\mathbf{g}_1 + 2\mathbf{g}_2 + 2\mathbf{g}_3 + \mathbf{g}_4)\Delta t \quad (5.12)$$

where

$\mathbf{T}_i$ is an n-element defining the value of the dependent variables $T^{(k)}(t)$ ($k = 1, 2, 3\ldots n$) at some value t_i of the independent variable t

$\mathbf{g}_1$ is a column matrix with n elements $g^{(k)}(t)$ determined by evaluating the matrix function **g** of the expression above at values of its arguments $(t_i, \mathbf{T}_i)$

$\mathbf{g}_2$ is a column matrix with elements $g_2^{(k)}$ determined by evaluation of **g** at the values of its arguments $(t_i + \Delta t/2,\ \mathbf{T}_i + \Delta t\mathbf{g}_1/2)$

$\mathbf{g}_3$ is a column matrix with elements $g_3^{(k)}$ determined by evaluation of **g** at the values of its arguments $(t_i + \Delta t/2,\ \mathbf{T}_i + \Delta t\mathbf{g}_2/2)$

$\mathbf{g}_4$ is a column matrix with elements $g_4^{(k)}$ determined by evaluation of **g** at the values of its arguments $(t_i + \Delta t,\ \mathbf{T}_i + \Delta t\mathbf{g}_3)$

$\mathbf{T}_{i+1}$ is a column matrix defining the new value of the n dependent variable $T^{(k)}(t)$ at t_{i+1}, as found by the application of the numerical technique.

The new values of temperatures of greenhouse elements as specified by the column matrix $\mathbf{T}_{i+1}$ was used as the stating point for new determination of additional values of the element of **T**(t), and the process was continued iteratively to the desired final value of t.

5.2 Computer Simulation Program

The algorithm as given in Section 5.1.1 was implemented in Delphi version 5. Delphi is a combination of object oriented Pascal programming and visual programming for windows (Cantu, 2000). Delphi is basically Object Pascal language brought to a high level; it has a fast compiler, great database support, close integration with Windows programming and powerful component technology (Cantu, 2000).

5.2.1 Program subroutines

The main program is combinations of procedures and functions (Subroutines).These include one that solve the differential equations using the fourth order Runge-Kutta algorithm and those that are used to input, at every time step, the moving boundary conditions such as solar radiation, wind speed, outside humidity and outside temperature. Figure 5.1 shows the simulation program structure.

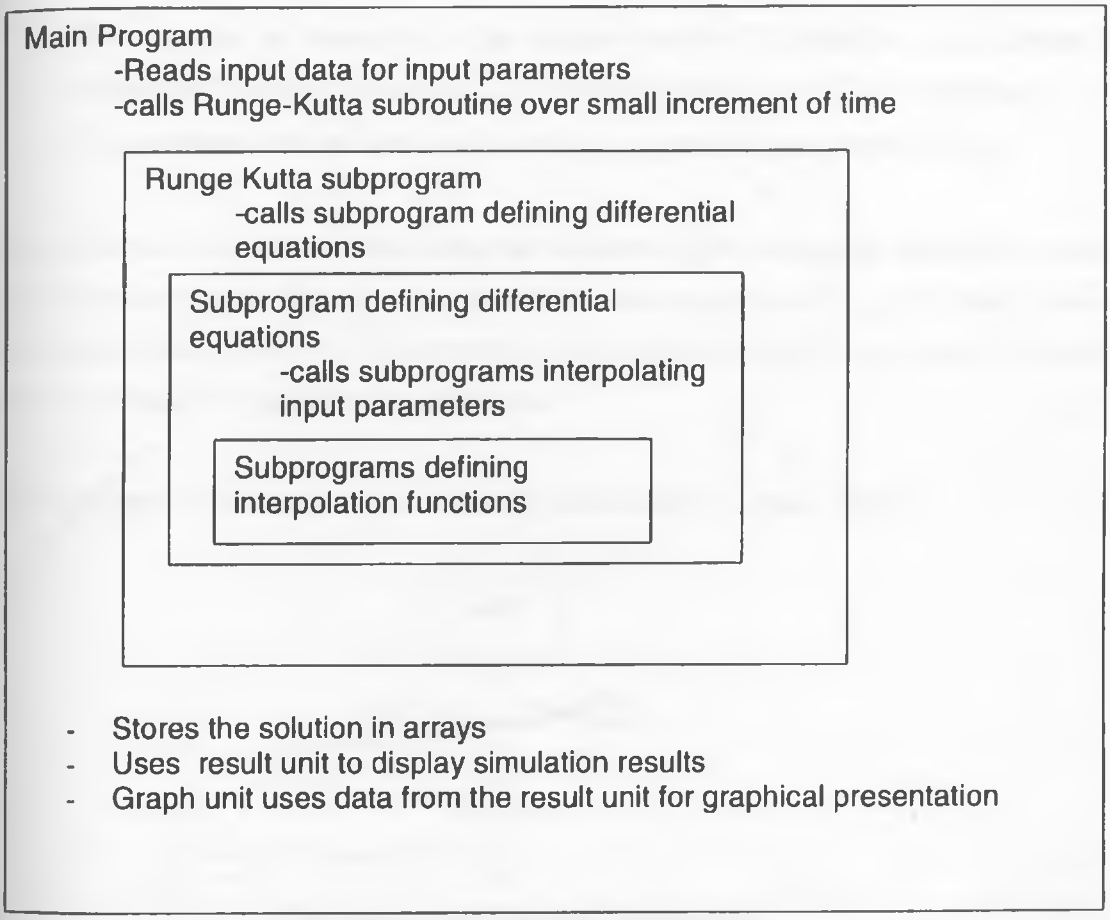


Figure 5.1: Computer simulation program structure

5.2.1.1 Procedure: Solve System Matrix

The purpose of this subroutine is to solve the first-order matrix differential equation $\mathbf{T} = \mathbf{g}(t, \mathbf{y})$ and thus to find the elements of the column matrix T (t) at the value of time (t) specified by time of stop (t_{stop}), starting from initial time, t_i, a known value of time, and $\mathbf{y}_i$, initial values of the system variables, where $\mathbf{T}_i = \mathbf{T}(t_i)$. 'Solve system matrix' calls the procedure ('System Differential equations') which defines the nonlinear differential equations **g**(t, **T**). The arguments T and g in the subroutine are both one dimensional arrays.

The input argument of the 'Solve System Matrix' subprogram includes the following:

- The initial value t_i of independent variable time (t)
- The one dimensional array of variables $T_{Initial}[i]$ in which are stored the initial values of the variables in the differential equations, that is the column matrix $\mathbf{T}_i$ where , $\mathbf{T}_i = \mathbf{T}(t_i)$
- The number of elements in the column matrix T(t), that is , the number of variables The final value of t_{stop} of t for which the value of T(t) is desired
- The number of iterations used by the subroutine in going from t_i to t_{stop}

The output is a one dimensional array of variables T[i] in which are stored the values of the variable in the first order matrix differential equations at t_{stop} (the final value of the independent t), that is, the elements of the column matrix $\mathbf{T}(t_{stop})$ which represent the temperatures of greenhouse elements.

The flow chart for the procedure:' Solve System Matrix 'is given below

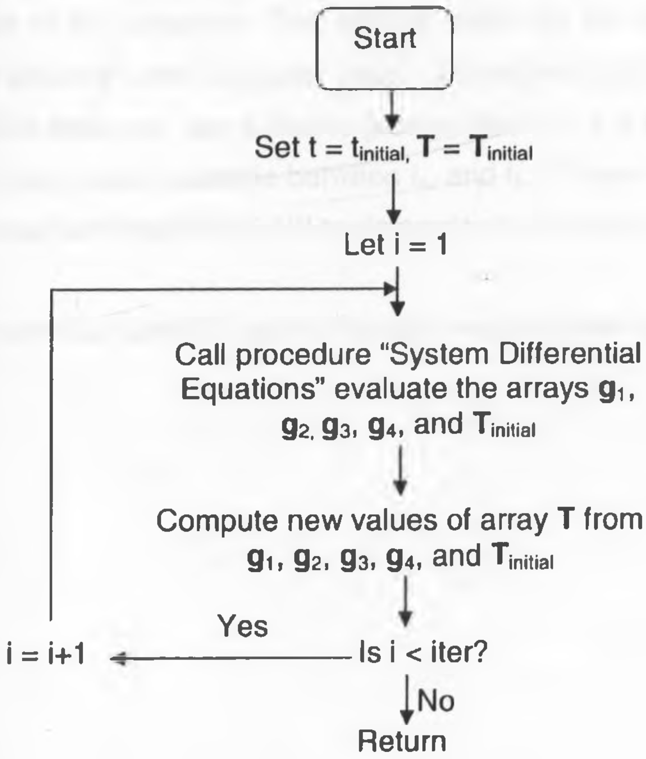


Figure 5.2: Flowchart for procedure 'Solve System Matrix'

5.2.2 Interpolation functions

The purposes of these functions are to give piecewise linear-approximation of global solar radiation, outside temperature, and outside relative humidity from a set of n points (t_i,u_i) measured experimentally. The approximated values as given by these subroutines at any time, t, are fed into the simulation program.

For a given set of n data points (t_i, u_i), defining a piecewise linear representation for a given function u (t), where $u_i = u(t_i)$, the value of u at any time, t, is given as (Huelman, 1986)

$$u = u_{i-1} + \frac{u_i - u_{i-1}}{t_i - t_{i-1}}(t - t_{i-1}) \tag{5.13}$$

The above equation computes the slope of the line segment between the points (t_{i-1}, u_{i-1}) and (t_i, u_i) and determines the value of the value of u by proportion.

The value of t_i are given in increasing order, thus the following inequality must be satisfied, $t_1 <= t <= t_n$. If t does not lie within this range, the function stops further execution of the program. The second action of the function is to determine the smallest value of t_i that is greater than t. it does this by comparing t with the values t_2, t_3,... until it finds one, say t_k that is greater than t. If t_k is the first value of the t_i that is greater than t, then t must lie between t_k, and t_{k-1}. These values and values of u_k and u_{k-1} are inserted Equation (5.13) to determine the value of u.

The general flow chart for such a function was as given in Figure 5.3.

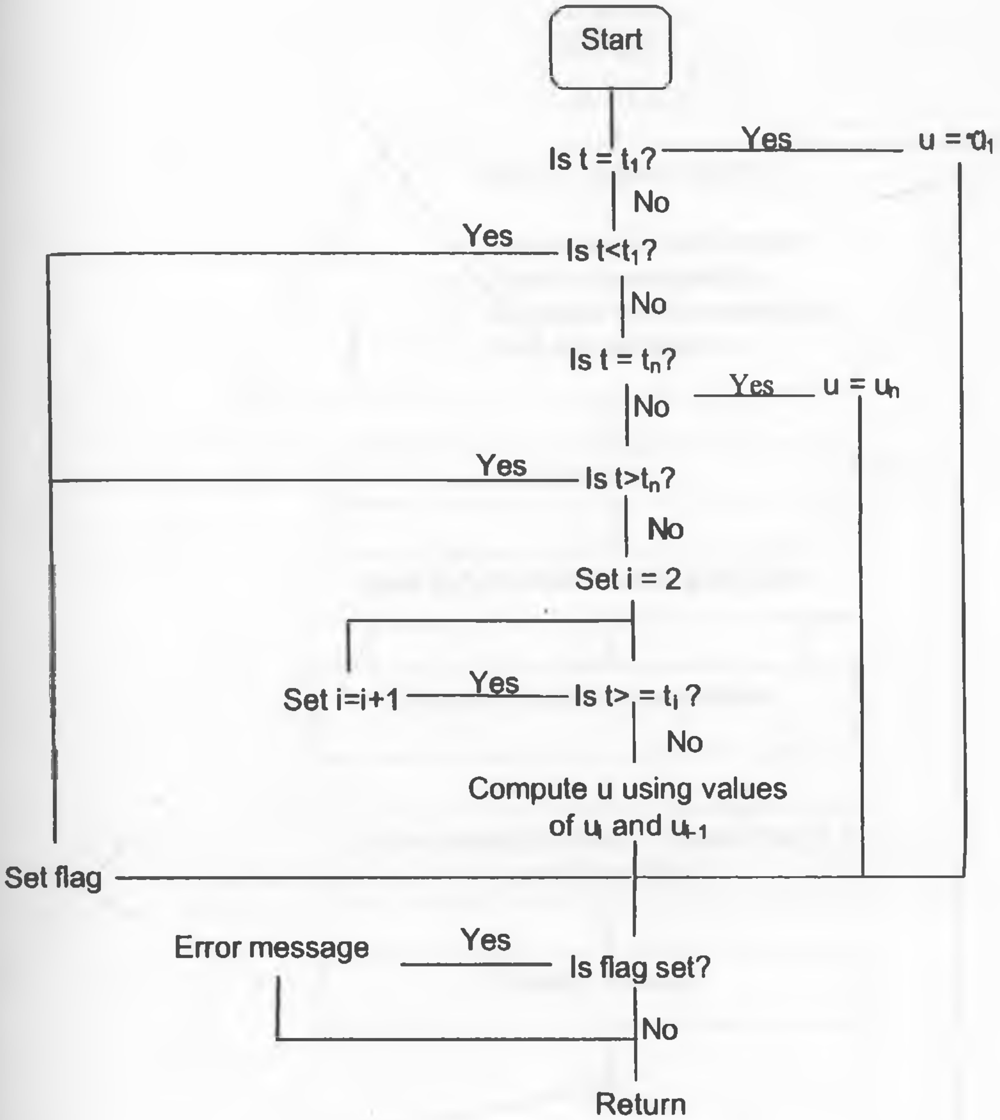


Figure 5.3: General flowchart for the interpolations functions, Solrad, OutTemp and OutRH

The overall schematic flow chart for the computer program was as given in the Figure 5.4.

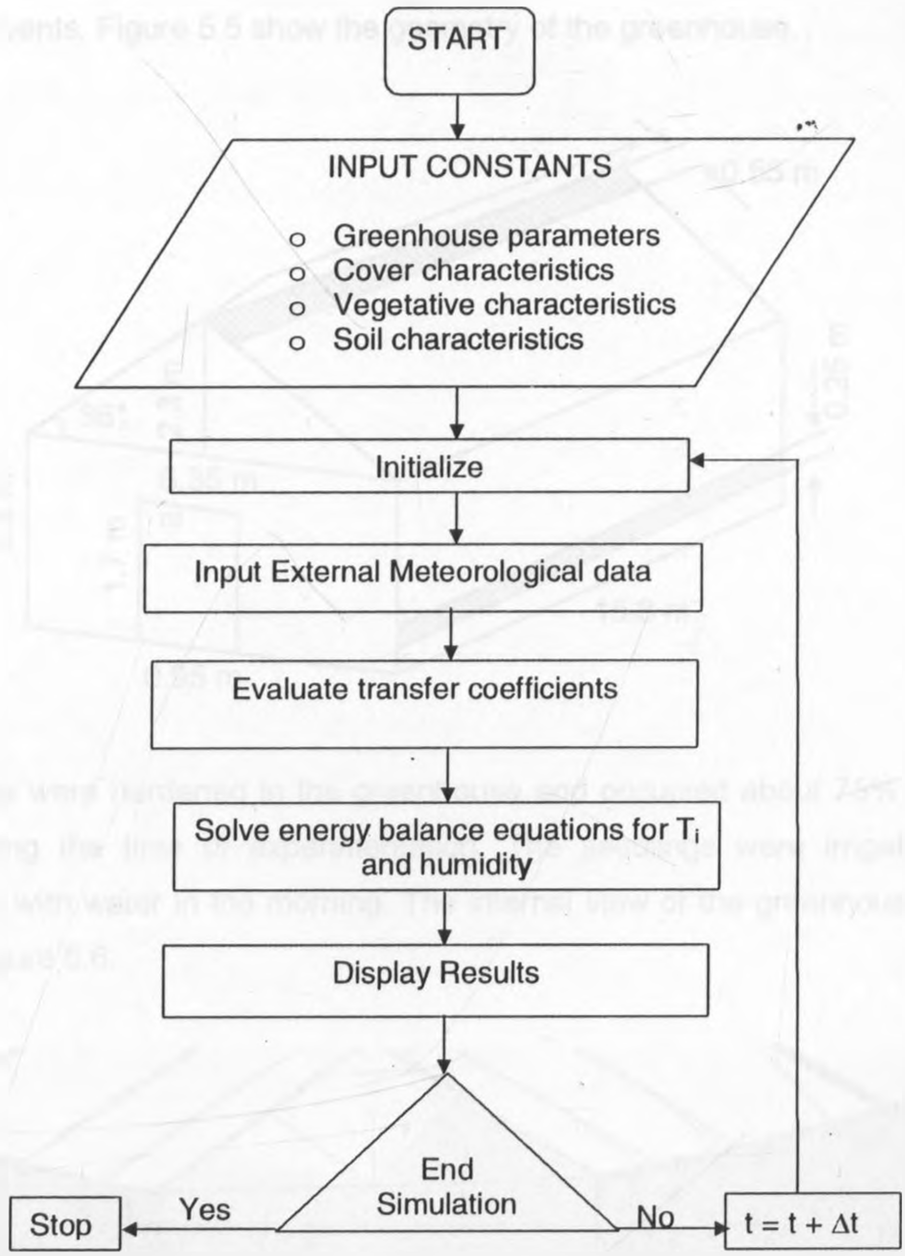
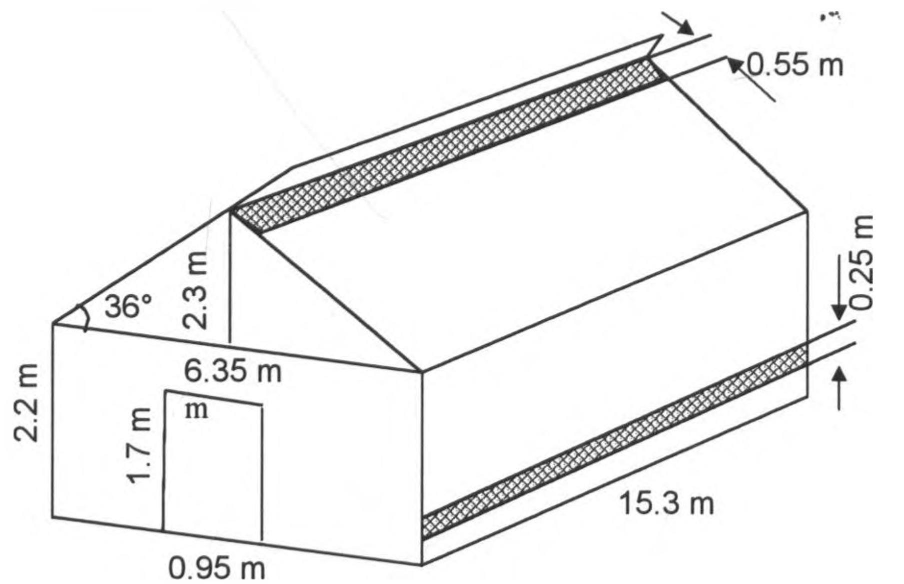


Figure 5.4: General flowchart of computer program for greenhouse simulation

5.3 Physical Model Experiments

5.3.1 Site and greenhouse

Experiments were carried out from mid June 2003 to early July 2003 in a single-span greenhouse located at the Field Station, Kabete Campus, University of Nairobi. The greenhouse was polyethylene covered and naturally ventilated. It had a roof vent and the side vents that were fixed in dimension and were covered by insect Screen with a porosity of 0.6. The door to the greenhouse was closed most of the time to prevent entry of insects. It was thus assumed that ventilation took place only through the continuous vents. Figure 5.5 show the geometry of the greenhouse.



Citrus seedlings were hardened in the greenhouse and occupied about 75% of the floor area during the time of experimentation. The seedlings were irrigated by sprinkling them with water in the morning. The internal view of the greenhouse was as shown in Figure 5.6.

Figure 5.5: A schematic diagram of the even span greenhouse used in the study

The estimated physical characteristics of the greenhouse cover, soil and vegetation are given in Table 5.1 (Mastalerz, 1977; Godbey *et al.*, 1979; Walter *et al.* 1983; Wang and Bourlard, 2000; Seginer, 2002).

Table 5.1: Characteristic of the cover, the vegetation and the soil

Element		Solar radiation		Thermal Radiation
Cover				
Material	Polyethylene			
Transmissivity, %		62		0.7
Reflectivity, %		13		11
Vegetation				
Transmissivity, %		17		-
Reflectivity, %		22		5
Absorptivity, %		61		95
Heat Capacity, kJ kg^{-1} K^{-1}	4.18			
Soil surface				
Reflectivity		40		15
Absorptivity		60		85
Subsoil temperature, °C	20			
Soil layers				
	First layer		Second layer	Third layer
Thickness, m	0.6		0.6	0.6
Conductivity, W m^{-1} K^{-1}	2.5		2.0	2.0
Mass density, Kg^{-1} m^{-3}	1090		1140	1140
Heat Capacity, J Kg^{-1} K^{-1}	1200		1250	1350

5.3.2 Climatic measurements

The temperatures of the greenhouse elements: cover, air and soil were measured using a Data logger (Delta-T Logger, model DL2, Cambridge, U.K.) with copper-constantan thermocouples (accuracy ±0.5 °C) as the temperature sensors. The logger sensed the temperature of an element every five minutes and recorded the average after every 30 minutes.

The Data logger used inbuilt calibration tables (resident linearization tables) that automatically transform the thermocouple output voltage into temperature measurements in °C (Delta-T Devices, 1992). The output voltage was proportional to the temperature difference between the thermocouple junction and the cold junction. The logger's terminal panel is designed to be isothermal (i.e. terminals held at the same temperature).

The logger had a thermistor mounted on it to measure its temperature. The thermistor could be optionally switched to channel 1 to provide cold junction for thermocouples measurements (Delta-T Devices, 1992). To obtain an absolute temperature reading the temperature of the cold junction was measured and added to the temperature difference derived from thermocouple voltage. The logger could automatically perform this calculation known as 'cold junction compensation 'or 'cold junction referencing' (Delta-T Devices, 1992).

Tests were necessary to ensure proper functionality of the data logger channels before temperature measurements were taken. To ensure that the logger accurately measured temperatures of the layers, the channels to be used we put in ice water and then boiling water and displayed temperatures noticed; a reading of 0° C in ice water and 96 °C in boiling water indicated that a given channel was properly functioning. After selecting the good channels to use, the data logger was taken to the field.

Measurements were taken at the centre of the greenhouse. The advantage with this is that air at the centre of the greenhouse is stiller as compared to other locations in the greenhouse (Boulard *et al.*, 1999). Due to presence of temperature gradient in the greenhouse air, a profile was constructed on which was mounted thermocouples at the midpoint of the greenhouse. The average of the measured temperatures along this profile showed that the average temperature of the greenhouse air occurred at a height of 1.5 m above the greenhouse floor. It was therefore assumed that the inside air temperature was at uniform temperature with the value measured at this point.

The outside temperature around the vicinity of the greenhouse was measured by a thermocouple mounted at a height of 1.5 m outside the greenhouse and shaded from the sunrays to reduce error of measurement. Thermo-hydrographs (model, T9420, Isuzu Seisakusho Company Limited, 1991) was used to record relative humidity of the inside and outside air relative humidity at the same height. Average daily wind speed was recorded at the nearby Kabete meteorological weather station, which is situated 50 meters from the greenhouse.

The soil surface temperature was taken at a depth of 0.02 by a thermocouple positioned at the midpoint of the greenhouse. Along the same vertical axis soil temperature was monitored by thermocouples at depth of 0.15 and 0.30 m. The temperature recording here was also half hourly.

The assumed average temperature of the cover was measured by two thermocouples. One was cello taped on the outside of the cover on the eastern side of the greenhouse at diagonal distance of 2 m from the eave, while the other was attached to the cover using the same method, on the inside and on the Western side of the roof.

Global solar radiation was measured outside the greenhouse using a solar integrator (Solar intergrator-CC12, Kipp and Zonel DelFT, 1985). The integrator had an accuracy of $\pm 0.2\%$. The global solar radiation was printed every 30 minutes.

5.4 Model Verification and Validation

Verification is the process by which the internal logic of a given model is determined, while validation is the process of establishing the adequacy of a given model and involves tests to determine whether the given model is adequate or not i.e. whether the model is in agreement with the system or not (Murthy *et al.*, 1990).

The computer model was verified to ascertain that the programming logic conformed to intentions presented in the flow chart. Verification was performed for each of the procedures and functions using the debugging tools of DELPHI 5 before they were merged to form the main program.

The logic of the main program was tested further using pre-test data from a greenhouse not used for validation data collection. The data was input into the program to see if it gave expected output and adjustments made as was necessary.

To validate the model, comparisons were made between simulated and observed cover, greenhouse air, and soil surface temperatures and relative humidity of air in the greenhouse. Data analysis was done as recommended by Yang *et al.* (1990), Loewer *et al.* (1994) and Nyaaga (2000)

5.5 Data Analysis

A group of statistical parameters as suggested by Yang *et al.* (1990), Loewer *et al.* (1994) and Nyaaga (2000) were used to test the agreement between the model predictions and experimental data. The ones considered done were paired two sample t- test and linear regression between measured and simulated data to determine the square of correlation coefficient value (R^2-value).

5.5.1 Paired two sample t-test

The pair in this case was the physical model greenhouse and the mathematical model of the physical greenhouse house as represented by physical laws. The assumption was that the two models are similar and thus for given inputs, e.g. solar radiation, at a given time, one expects the outputs of both to be the equal at that particular time.

Paired t-test enables judgement as to whether the difference between predicted and the measured values is purely by chance or not. The differences, $D_{i,}$ in the individual pairs are assumed to be distributed about a mean $U_{d,}$ which represent the average difference between the effects of the two treatments over the population of which these pairs are random samples (Snedecor and Cochran, 1980).

The deviation $Di\text{-}U_d$ maybe due to various causes in particular inherent difference between the models and any errors in measuring instruments. Another source of variation is the different effects the inputs may actually have on the models.

In the analysis the deviation $D_i\text{-}U_d$ is assumed to be normally and independently distributed with population mean zero. When these assumptions hold, the sample mean difference D_m is normally distributed about U_d with standard error, $\sigma_D/\sqrt{N}$, where σ_D is the standard deviation of the population differences and N is is number of data points.
The value of σ_D is seldom known, but the sample furnishes an estimate given by (Snedecor and Cochran, 1980)

$$SD = \sqrt{\frac{\sum (D_i - D_m)^2}{N-1}} \tag{5.14}$$

Hence $S_{D_m} = S_D / \sqrt{N}$ is an estimate of σ_{D_m}, based on (N-1) degree of freedom.

The important consequence of these results is that the quantity as expressed in Equation (5.14) follows the Student's t distribution with (N-1) degree of freedom, where N is the number of pairs (Snedecor and Cochran, 1980). The t distribution was thus used to test the null hypothesis that $U_d = 0$ and to calculate a confidence interval for U_d

$$t = \frac{D_m - U_d}{S_{D_m}} \tag{5.15}$$

5.5.2 Coefficient of Determination (R^2 value)

If a model is perfect than plot of the observed versus the predicted would yield a straight line sloped at 45° and passing through the origin. The R^2 value in this case is 1. Otherwise, the correlation coefficient is determined by the following expression (Snedecor and Cochran, 1980)

$$R^2 = \frac{(\sum x_i y_i)^2}{\sum x_i^2 \sum y_i^2} \tag{5.16}$$

where

x_i is an individual observed value for a given set of input conditions

y_i is an individual predicted value for a given set of input conditions

5.6 Sensitivity Analysis

This is the systematic variation of values of parameters or input variables, one at a time, while keeping all others constant over some range of interest and observing the effect upon the models response (Loewer *et al.*, 1994). Sensitivity analysis help determines the parameters or input variables to which the system is more sensitive.

If a model response is highly sensitive to the parameters of the model then the model is of limited use for prediction purposes, as small errors in parameters will result in larger errors in the model response (Murphy *et al.*, 1990).

In this study sensitivity analysis were done to test the effect of solar radiation, wind speed, effective vent area and initialisation on the output of the greenhouse air and soil temperatures.

6. RESULTS AND DISCUSSION

6.1 Pertinent Factors Affecting Greenhouse Environment

Pertinent factors that influence the air, crop and soil temperatures and relative humidity of a greenhouse system were identified from established works. These were: Solar heat gain; furnace heat; heat from equipment; plant respiration; photosynthesis; evapotranspiration; thermal radiation exchange between the greenhouse and its surroundings; conduction through the greenhouse floor; conduction through the greenhouse structural cover; ventilation; infiltration and ex-filtration through cracks; and condensation. These have been described in detail in Section 3.1.

Apart from furnace heat, heat from equipment, plant respiration, photosynthesis, and infiltration and ex-filtration through cracks, the above factors were considered in the development of a mathematical model to enable simulation of the greenhouse environment.

6.2 Mathematical Model

A one dimensional mathematical model was developed based on the energy balance principle. The greenhouse system was divided in six elements: cover, air, vegetation, soil surface, first soil layer, and second soil layer and deep soil layer. The dynamic energy balances of the elements were represented by non-linear differential equations. Details of development of the equations are given in Section 4.

The interactions between the six layers included heat transfer by conduction, convection, solar radiation, thermal radiation and latent heat exchanges. The equations were solved simultaneously for given boundary conditions using a fourth order Runge-Kutta relations as described in Section 5.1. The algorithms for the solution of these equations were coded into a computer language, Delphi.

6.3 Computer Simulation Program

A computer simulation program (GREENSIM) was written in DELPHI 5 to simulate the environment of a greenhouse. The program is stand alone and runs in windows operating system (See Appendix1 for program source code) Appendix 2 shows the input, output and graphical windows of the GREENSIM.

The differential equations describing the dynamic energy balance of the greenhouse system elements were solved simultaneously using the subroutine "Procedure Solve System Matrix" (see program source code, Appendix 1).

The input parameters into the simulation program were the deep soil layer temperature, wind speed, external air temperature, outside relative humidity, and global solar radiation. Since the external air temperature and relative humidity and global solar radiation are moving boundary conditions i.e. change with time, they were fed into the program using subroutines: SOLRAD, OUTTEMP and OUTRH (Appendix 1).

The energy and mass balance equations were solved for given boundary conditions at time steps of 1 min, to obtain the unknown temperatures of cover, air, vegetation, soil surface, first soil layer and second soil layer, and relative humidity of air in the greenhouse.

6.4 Model Validation

In order to test the validity of the computer model developed in this study, simulation experiments were carried out. The external climatic parameters used in the simulations were: Global solar radiation, ambient temperature and external relative humidity measured over the five days of June, 30^{th} to July, 4^{th} 2003. Average wind speed over the same period was used directly as a constant parameter in the model.

6.4.1 Observed ambient conditions

Weather data for June, 30^{th} to July, 4th, 2003 were chosen for model verification and validation (Appendix 4). These days were considered more stable than other days of experimentation. Figure 6.1 show the diurnal trend of global solar radiation during this period. The ambient temperature and humidity over the same period are given in Figures 6.2 and 6.3 respectively.

The wind speed used in the model was taken as the average over this period and was collected from the nearby Kabete meteorological station. The average wind speed over the period was 0.5 m s^{-1}. The assumption of average wind speed during this period might contribute to errors in outputs of the simulation program, since wind does contribute greatly to ventilation of a greenhouse (Baptista *et al.*, 2001).

However, in design of greenhouses average wind speed is generally used because designs are based on optimal conditions (Walter et al., 1983).

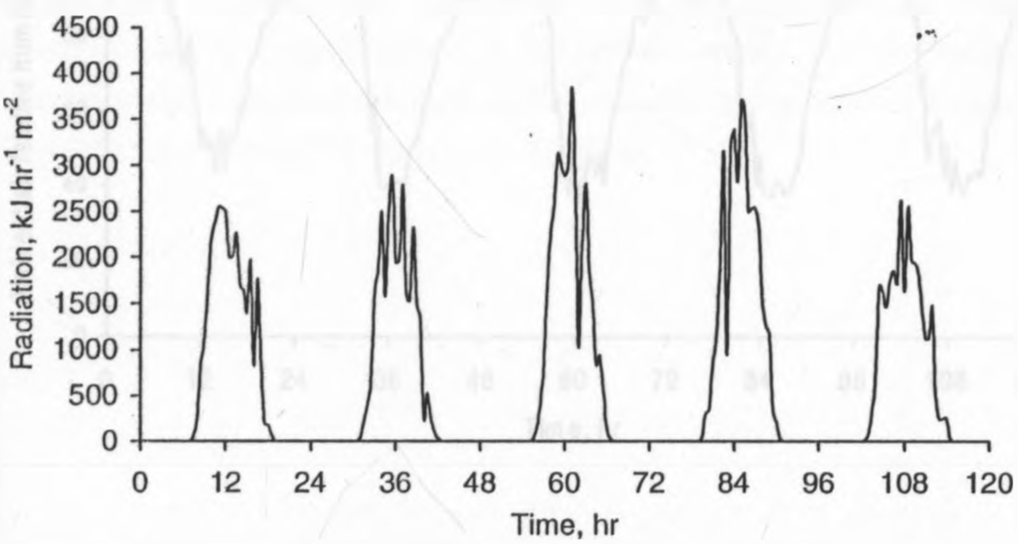


Figure 6.1: The diurnal cycles of the external global solar radiation for the period of 30th June – 4th July, 2003

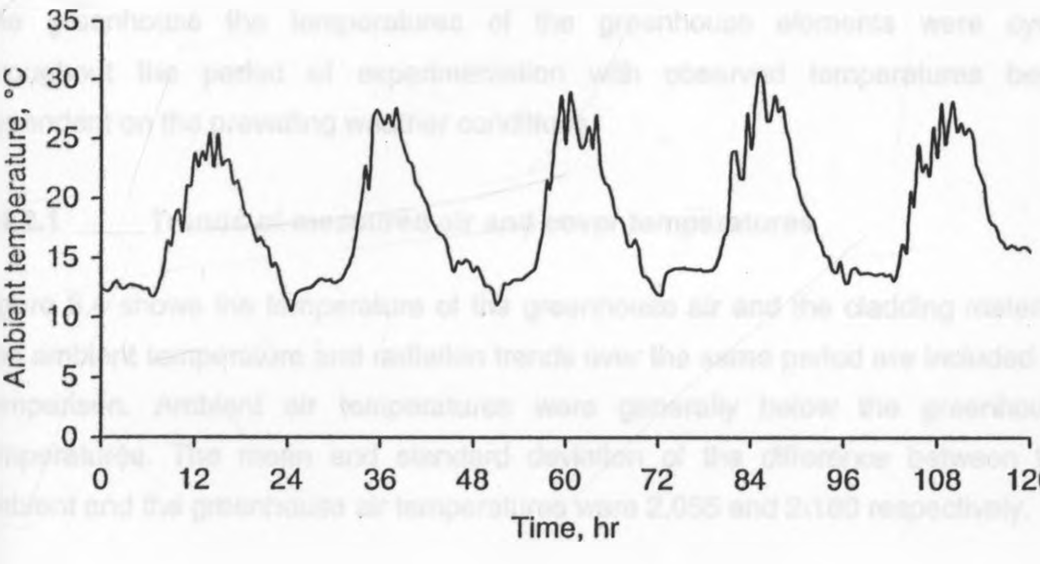


Figure 6.2: The diurnal cycles of the ambient temperature for the period of 30th June – 4th July, 2003

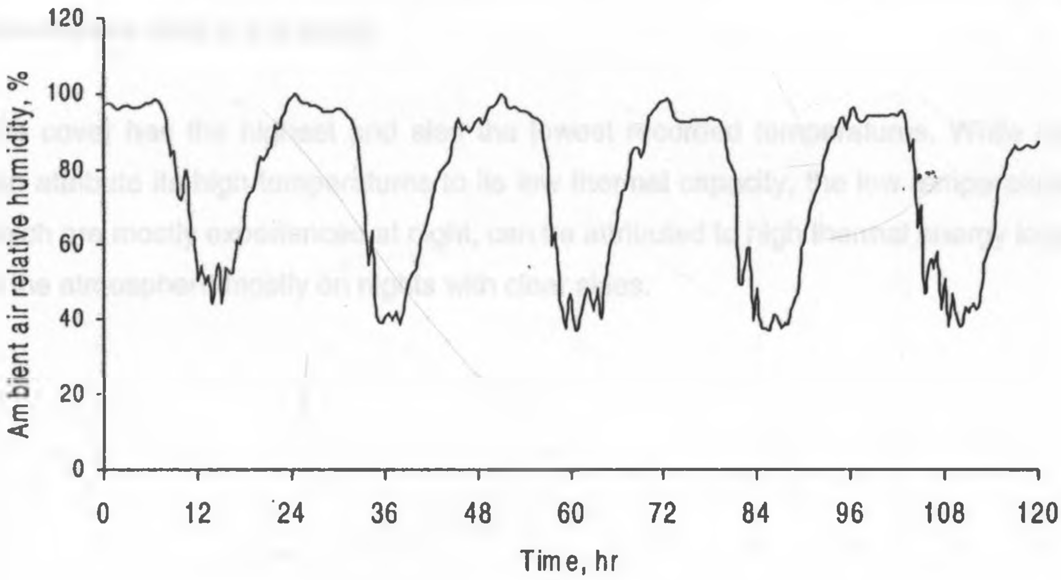


Figure 6.3: The diurnal cycles of the ambient relative humidity for the period of 30th June – 4th July, 2003

6.4.2 Observed greenhouse conditions

The greenhouse the temperatures of the greenhouse elements were cyclic throughout the period of experimentation with observed temperatures being dependent on the prevailing weather conditions.

6.4.2.1 Trends of measured air and cover temperatures

Figure 6.4 shows the temperature of the greenhouse air and the cladding material. The ambient temperature and radiation trends over the same period are included for comparison. Ambient air temperatures were generally below the greenhouse temperatures. The mean and standard deviation of the difference between the ambient and the greenhouse air temperatures were 2.055 and 2.180 respectively.

The inside air and the cladding material temperatures were very responsive to the solar radiation. High incident global solar radiation resulted into almost immediate (negligible lag) temperature rise. These rises can be attributed to the low thermal capacity of air and the covering material. Also, the high temperature achieved by the cladding material can be independently attributed to its low mass and appreciable level of solar radiation absorption (estimated at 0.25 for the polyethylene cover of the greenhouse used in the study).

The cover has the highest and also the lowest recorded temperatures. While one can attribute its high temperatures to its low thermal capacity, the low temperatures which are mostly experienced at night, can be attributed to high thermal energy loses to the atmosphere mostly on nights with clear skies.

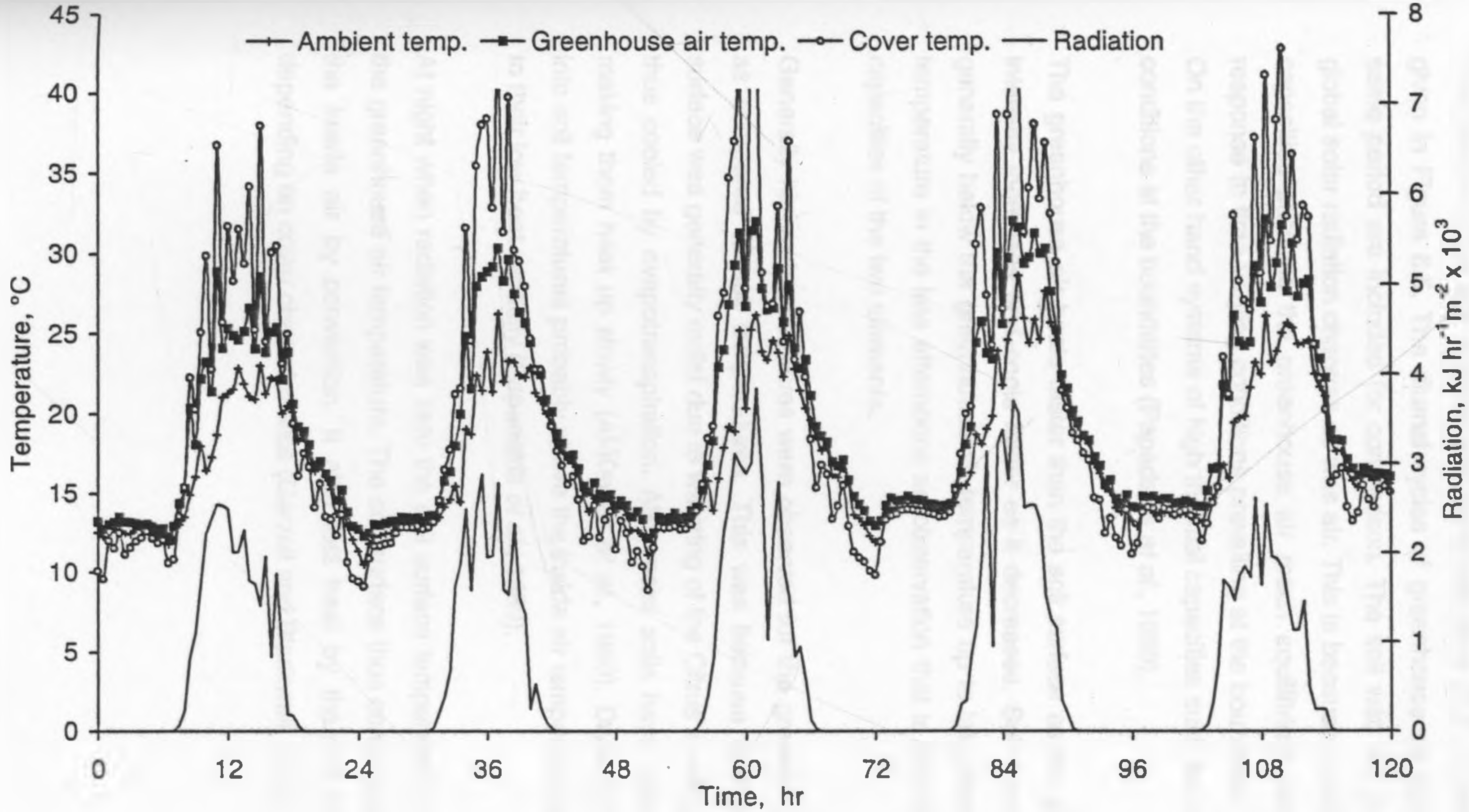


Figure 6.4: The diurnal cycles of the greenhouse air, ambient and cover temperatures and radiation (kJ hr^{-1} m^{-2}) for the period of 30th June – 4th July, 2003

6.4.2.2 Trends of measured soil temperatures

The trends of the soil surface and deep soil layer (0.3 m) temperatures were as given in Figure 6.5. The diurnal cycles of greenhouse air temperature during the same period are included for comparison. The soil was not as fast responsive to global solar radiation changes as was air. This is because, systems of small thermal capacities such as the greenhouse air reach equilibrium temperature quickly in response to time varying conditions prevailing at the boundaries e.g. solar radiation. On the other hand systems of high thermal capacities such as soil respond slowly to conditions at the boundaries (Papadakis *et al.*, 1989).

The greenhouse air heats faster than the soil surface as the global solar radiation intensity increases and cools faster as it decreases. Soil temperatures were thus generally below the greenhouse air temperature up to late mornings and above air temperature in the late afternoons an observation that is directly related to thermal capacities of the two elements.

Generally higher temperatures were observed for the greenhouse air temperatures as compared to soil temperatures. This was because during the study the soil surface was generally moist due to watering of the Citrus seedlings. Soil surface was thus cooled by evapotranspiration. Also moist soils have higher thermal capacity making them heat up slowly (Al-Kayssi *et al.*, 1990). Dryer greenhouse soil result into soil temperatures probably above the inside air temperatures during the day due to their low heat capacity (Papadakis *et al.*, 1989).

At night when radiation was zero the soil surface temperature was generally above the greenhouse air temperature. The soil surface thus continuously released heat to the inside air by convection. It also lost heat by thermal radiation to the sky, depending on cover characteristics (Garzoli and Blackwell, 1981).

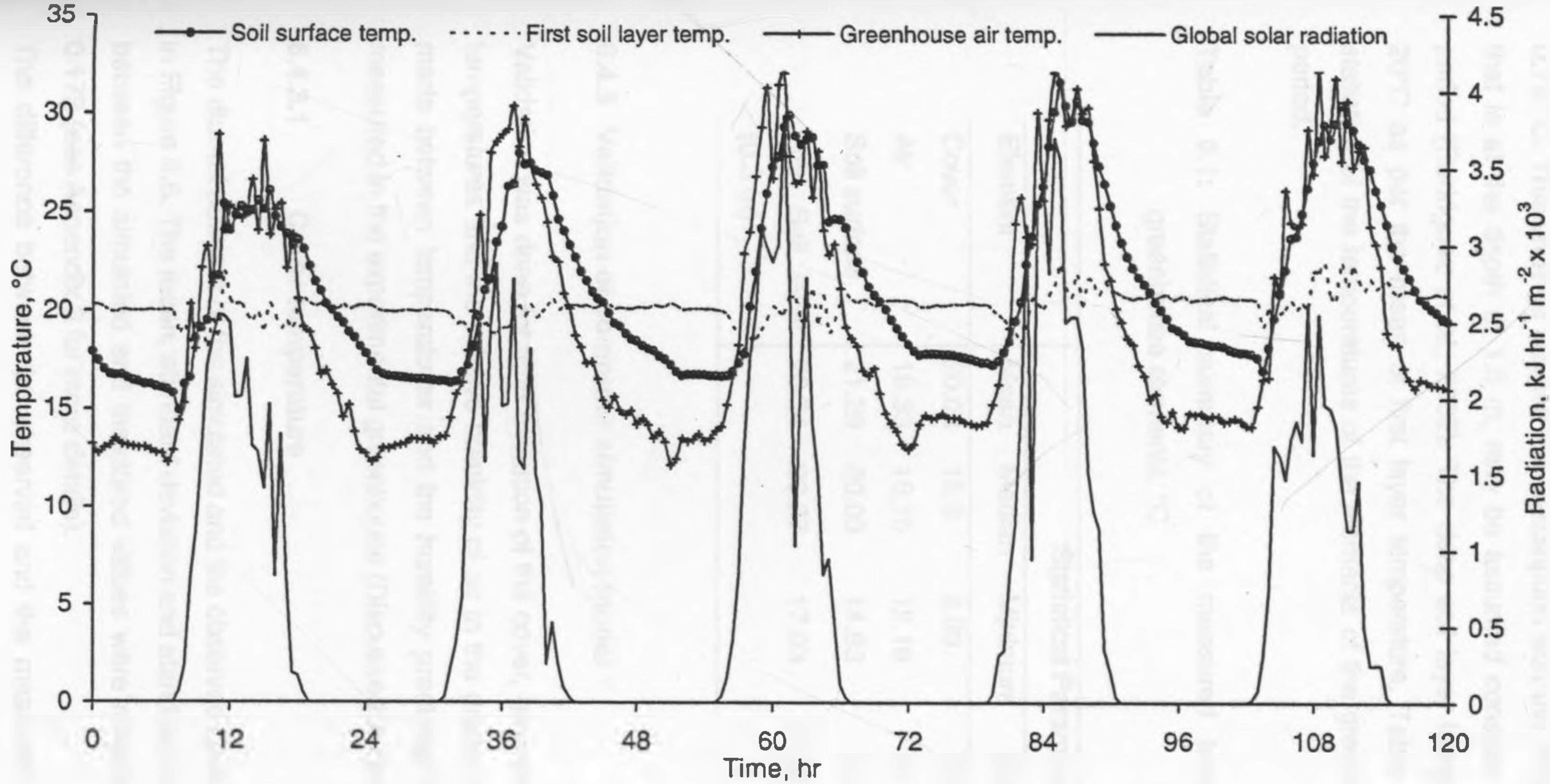


Figure 6.5: The diurnal cycles of the greenhouse air, soil surface and first soil layer temperatures and global solar radiation for the period of 30th June – 4th July, 2003

The first soil layer temperature also varied, but slightly. For the five days, the mean temperature of this layer (242 data points) was 20.24 °C with a standard deviation of 0.75 °C. This findings support the assumption that the deep soil layer temperature, that is at the depth of 1.5 m, may be assumed constant over a given simulation period (Rodriguez *et al.*, 2002). The deep soil layer temperature was taken to be 20°C as per the mean of first layer temperature. Table 6.1 gives the summary statistics of the temperatures of the elements of the greenhouse over the five days period.

Table 6.1: Statistical summary of the measured temperature trends of the greenhouse elements, °C

	Statistical Parameters				
Element	Mean	Median	Minimum	Maximum	S.D
Cover	20.03	15.5	8.89	42.8	9.17
Air	19.33	16.75	12.16	32.16	5.93
Soil surface	21.29	20.09	14.93	31.56	4.25
First Soil layer (0.3 m)	20.24	20.27	17.93	22.45	0.75

6.4.3 Validation of computer simulation model

Validation was done for time evolution of the cover, greenhouse air and soil surface temperatures and the relative humidity of air in the greenhouse. Comparisons were made between temperatures and the humidity predicted by the model and those measured in the experimental greenhouse (Discussed in Section 6.4.1).

6.4.3.1 Cover temperature

The diurnal patterns of the simulated and the observed cover temperatures are given in Figure 6.6. The mean, standard deviation and standard error of mean of difference between the simulated and measured values were respectively, 1.272, 2.665 and 0.172 (see Appendix 3 for more details).

The difference between the observed and the measured could be due to many factors such as the convective transfer coefficients which are very hard to determine to accurate levels due to their time varying behaviour. It should also be noted that in this study wind speed, which is very important when it comes to determination of heat transfer coefficient, was assumed constant. However, the trends are sufficient for gaining insight into the dynamic behaviour of the cover temperature.

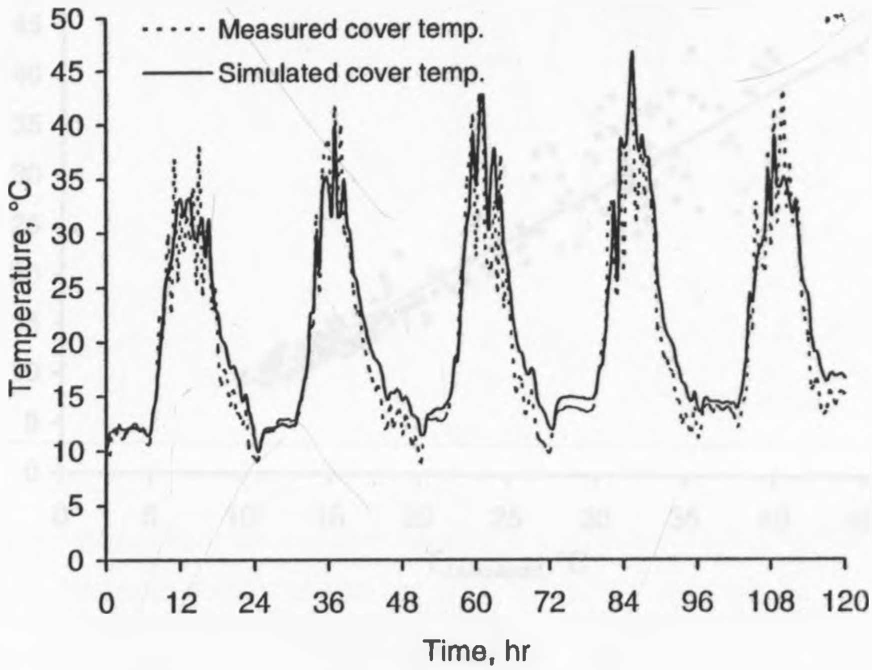


Figure 6.6: Simulated and observed diurnal cycles of the cover temperature for the period of 30th June – 4th July, 2003

The cover temperature determines whether condensation takes place on the cover (Pieters *et al.,* 1994; Kindelan, 1980). Presence of condensate on a polyethylene cover makes it opaque to thermal radiation, thus influencing the microclimate of the greenhouse.

To illustrate the relationship between the measured and the simulated values it is necessary to carry out linear regression between the measured and the simulated values (Loewer *et al.*, 1994). In an ideal situation one expects slope of 1, intercept of 0 and R^2 of 1.

Experimentally determined cover temperature were plotted against simulated temperature. The linear regression for 242 observations (Figure 6.7) illustrated satisfactory agreement between the measured and simulated values (R^2 of 0.916, slope of 1 and an intercept of -1.295).

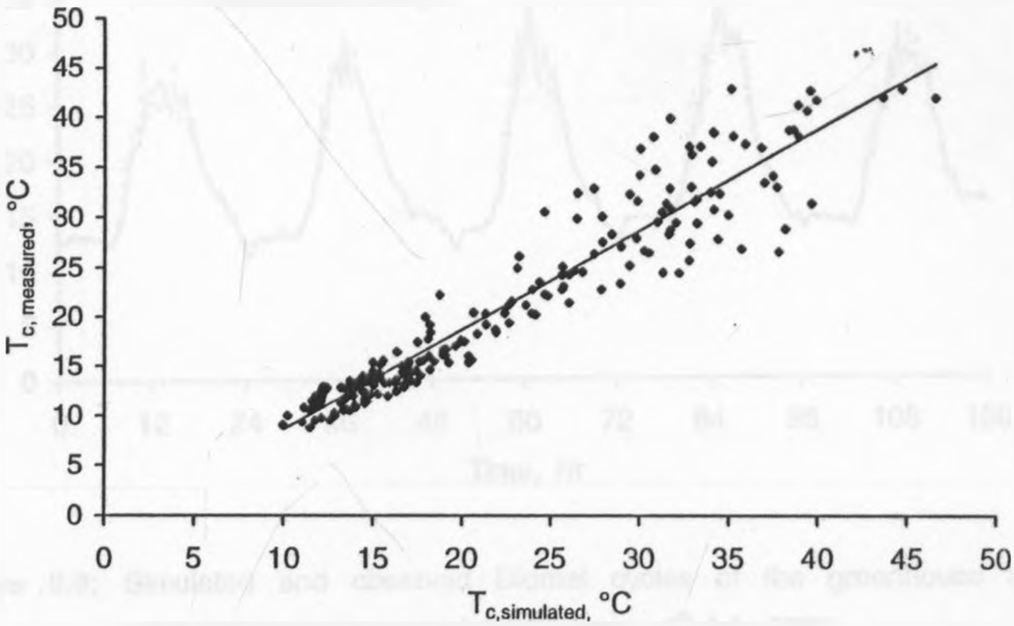


Figure 6.7: Simulated cover temperature, T_c plotted against the experimental data

$$T_{c,measured} = 1.001 T_{c,simulated} - 1.295, \qquad R^2 = 0.916$$

Cover temperature might look insignificant when it comes to growth of plants, however it should be remembered that cover temperature determines whether condensation takes place or not. Presence of condensate might result into water dripping on some flowers, thus affecting their quality (Musembi, 2002). Choice of covering material then becomes important and a simulation program like GREENSIM could help with decision making.

6.4.3.2 Air temperature

The simulated and measured diurnal cycles of greenhouse air temperature are plotted in Figure 6.8. The mean, standard deviation and standard error of mean of difference between the simulated and measured values were respectively, 0.111, 1.164 and 0.075.

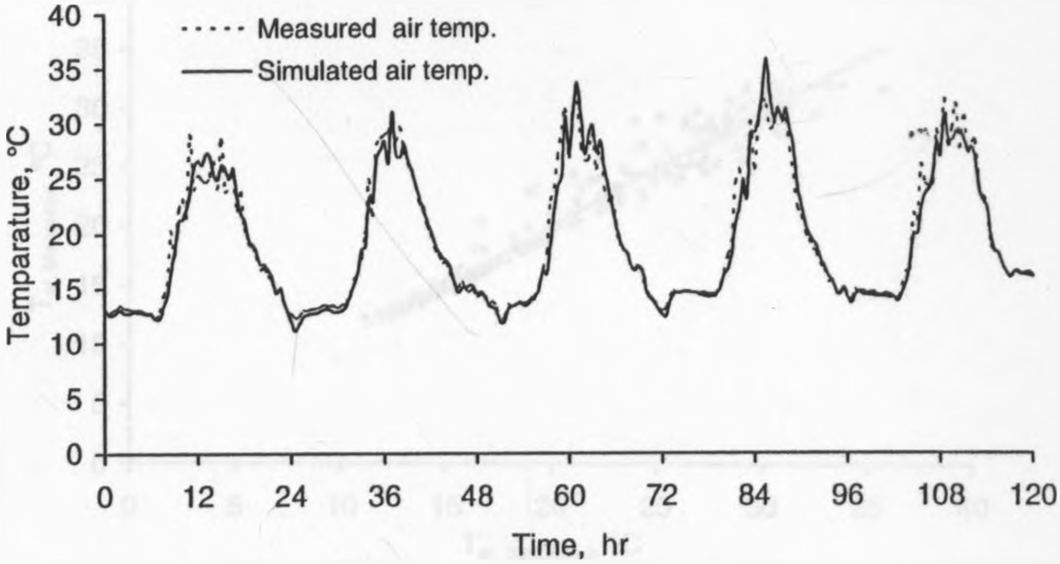


Figure 6.8: Simulated and observed Diurnal cycles of the greenhouse air temperature for the period of 30th June – 4th July, 2003

The major differences between the simulated and measured air temperatures were observed during at some pick hours of radiation. This could be attributed to some greenhouse and climate parameters being assumed constants while they are not, for example, assuming a constant wind speed lower than the actual one experienced at a certain time will result in under estimation of the ventilation rate. This results into the model returning a high temperature than the observed. The wind speed also affects heat transfer coefficients of which under estimation or over estimation could result into errors.

The linear regression line was plotted for simulated greenhouse air temperature versus measured air temperature (Figure 6.9). A good agreement was found between simulated and measured values of temperature (R^2 of 0.964, slope of 0.963 and intercept of 0.796), implying that the model was satisfactory for simulating greenhouse air temperature.

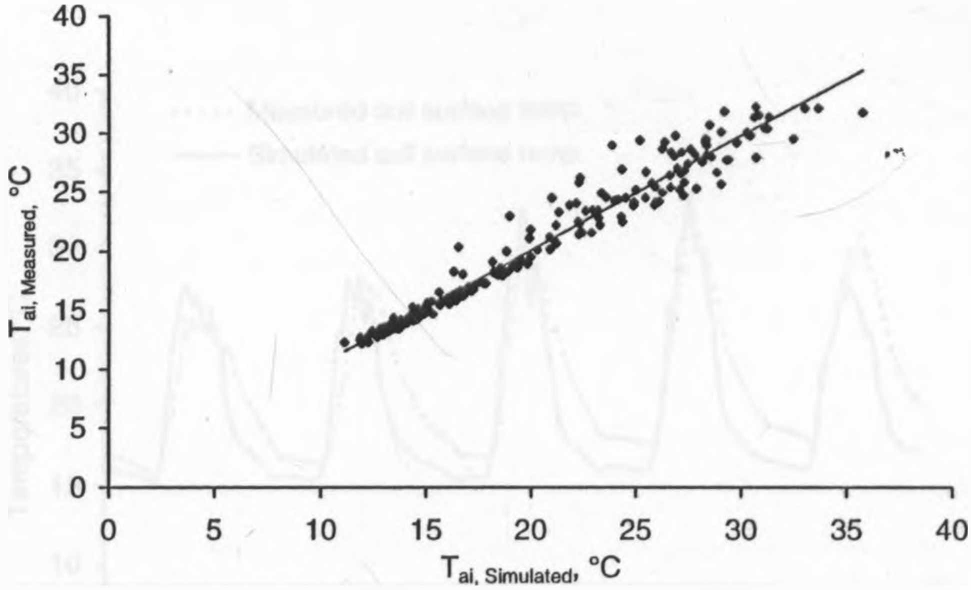


Figure 6.9: Simulated greenhouse air temperature plotted against the experimental data. $T_{ai,measured} = 0.964T_{ai,simulated} + 0.796$, $R^2 = 0.963$

6.4.3.3 Soil surface temperature

The diurnal cycles of simulated and measured soil surface temperatures are given in Figure 6.10. The mean, standard deviation and standard error of mean of the difference between the measured and simulated temperatures were 1.469 °C, 2.665 °C and 0.151 °C respectively (Appendix 3).

There was lag between the simulated and the measured soil surface temperatures. Simulated soil surface temperatures were generally lower than the measured soil temperatures during the nights and late afternoons implying that the model overestimated rate of heat exchange between the soil and the other elements of the greenhouse system as the intensity of the radiation reduced.

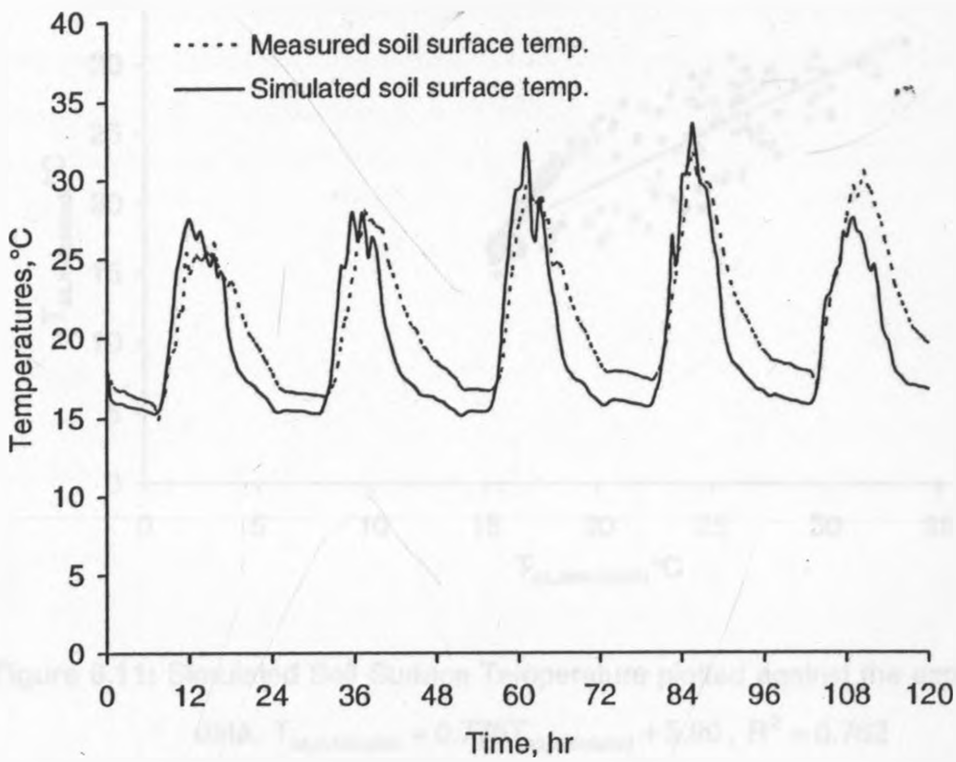


Figure 6.10: Simulated and observed diurnal cycles of the greenhouse soil surface temperature for the period of 30th June – 4th July, 2003

These could be due to the fact that the soil layer thickness (0.04 m) used in the model was too thick and assumption of average temperature of the layer, as the model assumes, could not accurately compare with the temperature measured at the midpoint of this layer.

Despite the differences, the current model could be useful for gaining insight in the dynamic behaviour of the greenhouse soil surface temperature. As illustrated by the linear regression results of simulated soil surface temperature versus measured soil surface temperature (Figure 6.11). There was acceptable agreement between simulated and measured values of temperatures (R^2 of 0.762, slope of 0.776 and intercept of 5.901).

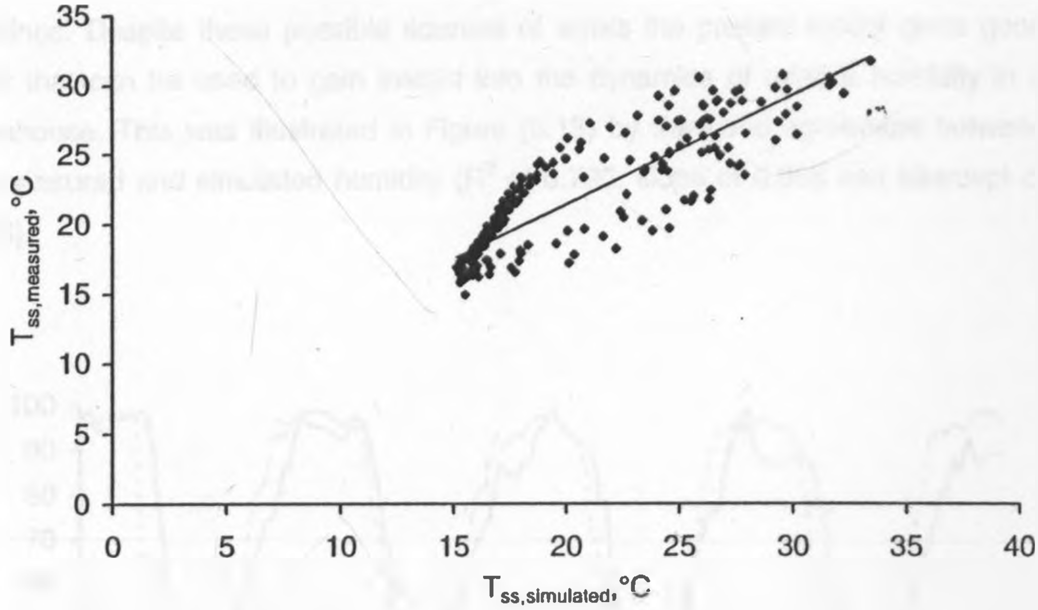


Figure 6.11: Simulated Soil Surface Temperature plotted against the experimental data. $T_{ss,measured} = 0.776T_{ss,simulated} + 5.90$, $R^2 = 0.762$

6.4.3.4 Relative humidity

The diurnal cycles of relative humidity of air in the greenhouse are shown in Figure 6.12. The mean, standard deviation and the standard error of mean of the difference between simulated and measured relative humidity were 0.716%, 10.66% and 0.687% respectively. Relative humidity of the greenhouse air is directly affected by ventilation of the greenhouse system. Ventilation rate determines movement of moisture in and out of the greenhouse and depends on the prevailing weather conditions which might be hard to capture accurately in a model for example presence or absence of cloud cover thus affecting the results of the predicted relative humidity of the inside air.

Estimation of evapotranspiration using modified Monteith equation (Equation 4.37) could have also contributed to the differences. However, modified Penman-Monteith equation was the most appropriate empirical relation to use in this study to estimate evapotranspiration of citrus seedlings as no explicit expression was available. More accurate result can be obtained if internal resistance and the external resistance are correlated to solar radiation intensity as has been done for Tomatoes (Wang and

Boulard, 2000). In the future, it may be of interest to fit such a model for citrus seedlings. Despite these possible sources of errors the present model gives good result that can be used to gain insight into the dynamics of relative humidity in a greenhouse. This was illustrated in Figure (6.13) by the good agreement between the measured and simulated humidity (R^2 of 0.795, slope of 0.965 and intercept of 3.156).

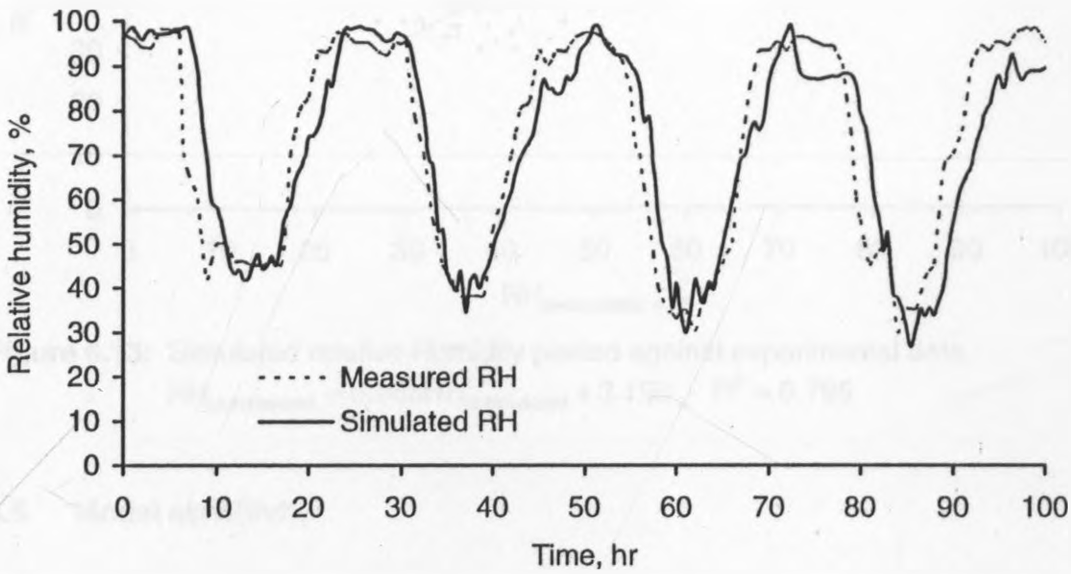


Figure 6.12: Simulated and observed diurnal cycles of the relative humidity (RH) of greenhouse air for the period of 30th June – 4th July, 2003

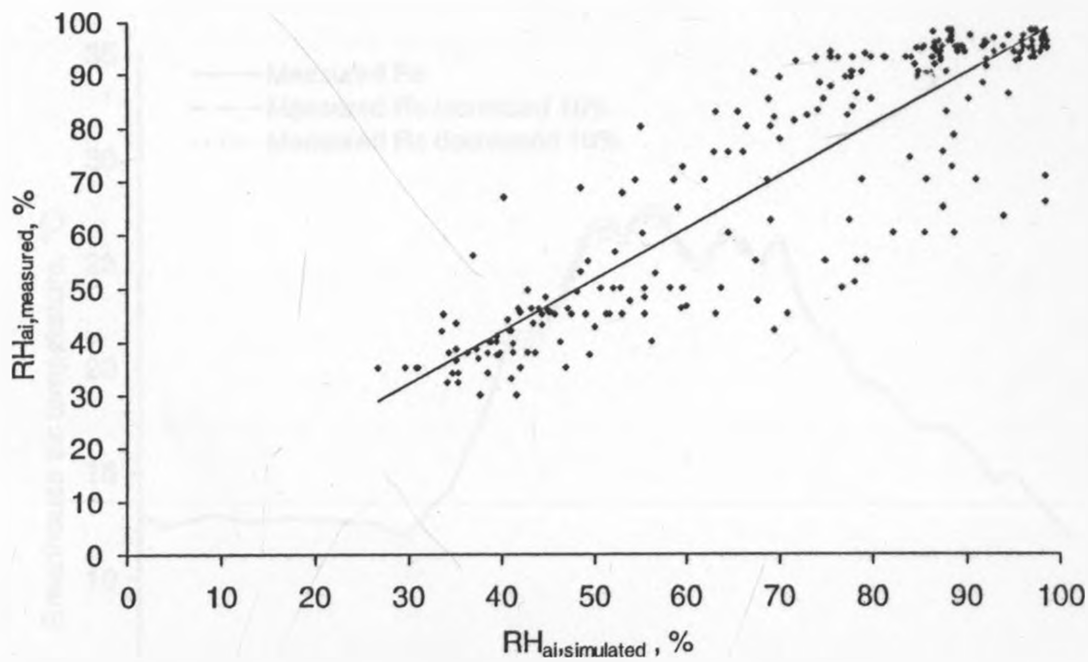


Figure 6.13: Simulated relative Humidity plotted against experimental data.
$RH_{ai,measured} = 0.965RH_{ai,simulated} + 3.156$, $R^2 = 0.795$

6.5 Model sensitivity

The sensitivity analysis was done for solar radiation, wind speed and effective vent opening area to see how they affect the soil surface and internal air temperature of the greenhouse.

6.5.1 Solar radiation

The measured solar radiation was increased by 10% and decreased 10% on the 30th June, 2003, so as to see the effect on the simulated greenhouse air and soil temperatures. It was noted that increasing or decreasing the solar radiation by 10% had negligible effect on the simulated greenhouse air temperature (Figure 6.14). The highest temperature differential was 0.7 °C. Thus an error in measurement of solar radiation up to 10% is not expected to affect simulation greenhouse air temperature much. The same effect on the soil surface temperature is shown by Figure 6.15. The effect on soil temperature is more evident during peak hours of solar radiation. The maximum difference in temperature resulting from the 10% increase in solar radiation was 1.42 °C.

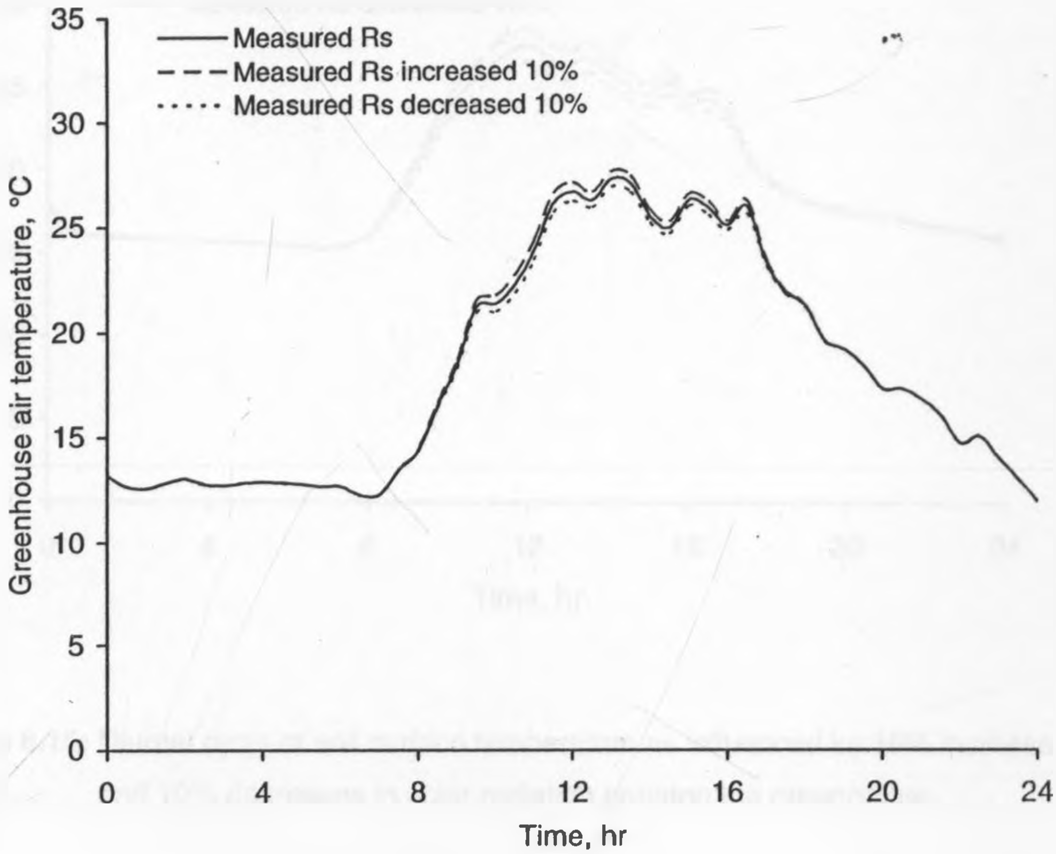


Figure 6.14: Diurnal cycle of greenhouse air temperature as influenced by 10% increase and 10% decreases in solar radiation (Rs) entering the greenhouse

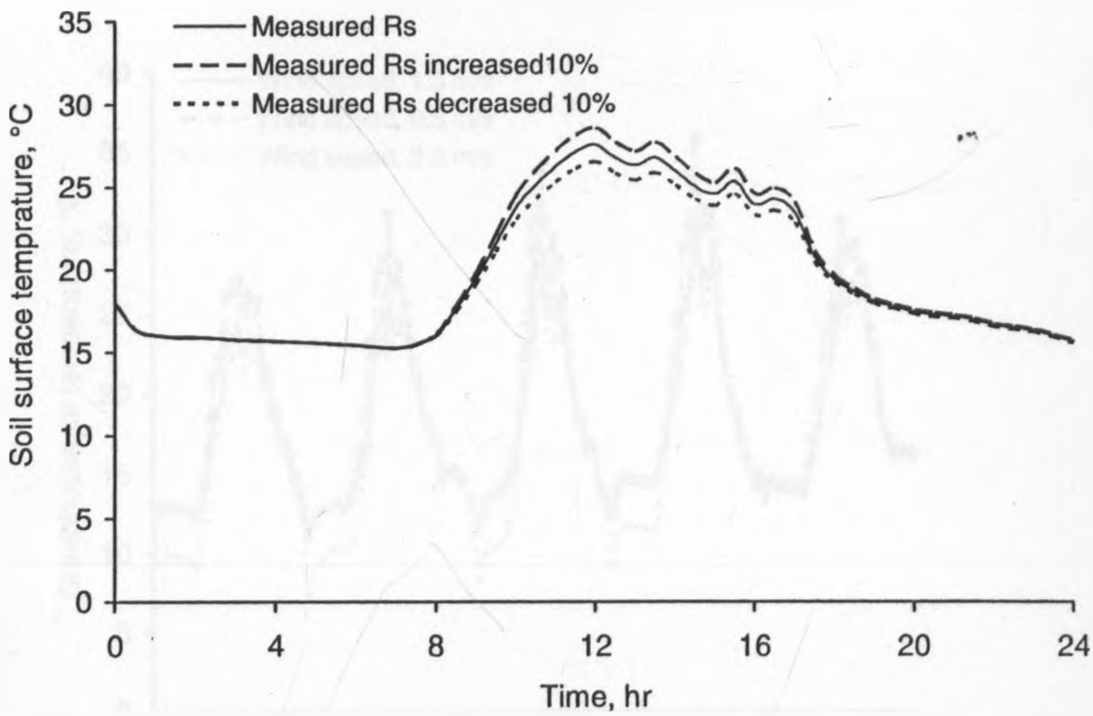


Figure 6.15: Diurnal cycle of soil surface temperature as influenced by 10% increase and 10% decreases in solar radiation entering the greenhouse

6.5.2 Wind speed

Wind speed was varied to see how it affects the simulated greenhouse air temperature and the soil surface temperature. Figure 6.16 shows the effect of wind speed on the greenhouse air temperatures while Figure 6.17 shows the same for soil surface temperature. Comparison was made for the average wind speed of 0.5 m s^{-1} used in this study and arbitrarily chosen wind speeds of 1.5 m s^{-1} and 3.5 m s^{-1}.

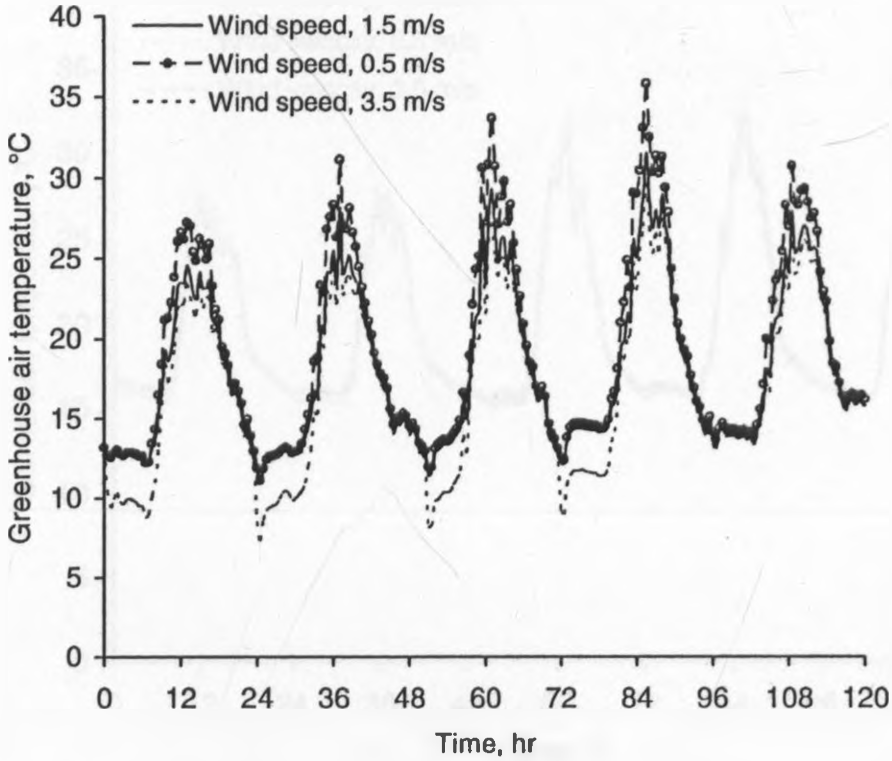


Figure 6.16: Diurnal cycles of greenhouse air temperature as influenced by wind speed

The reduction in greenhouse air temperature as the wind velocity increases was attributed to increased ventilation rate and higher heat transfer coefficients which both result into reduced built up of heat in the greenhouse. However wind velocity does not significantly affect the soil surface temperature. This is due to the facts that wind speed has little effect on the heat transfer coefficient between the soil surface and the air.

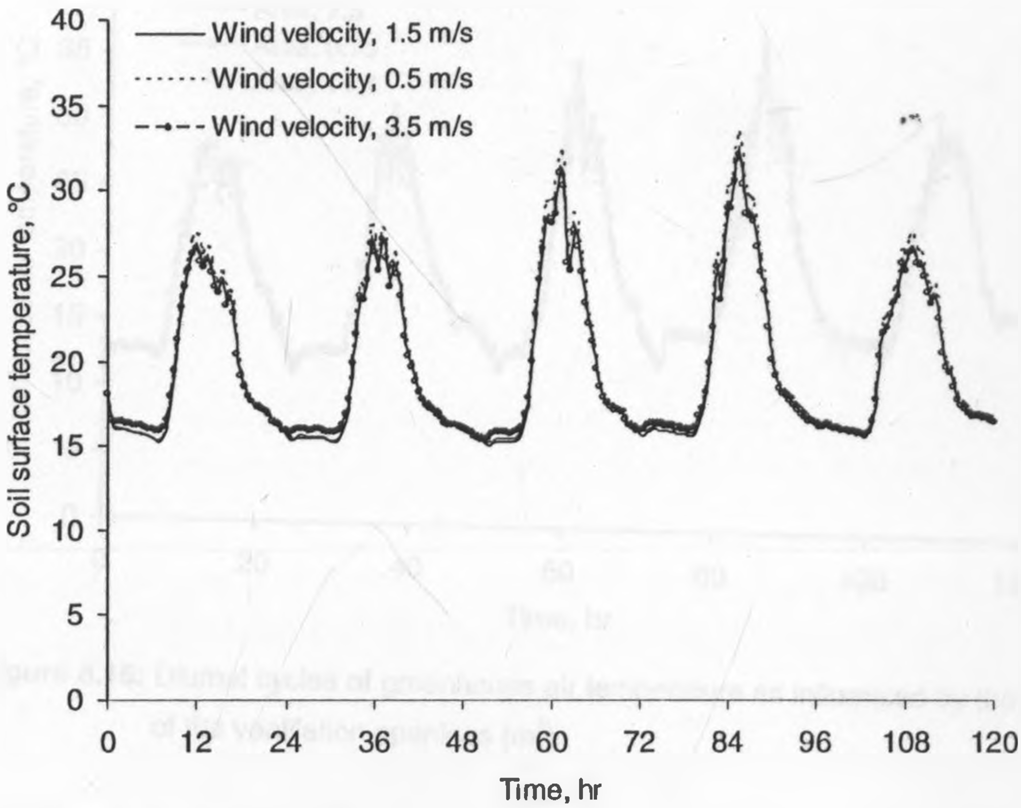


Figure 6.17: Diurnal cycles of greenhouse soil surface temperature as influenced by wind speed

6.5.3 Effective area of vents

Effect of the vent area on the greenhouse air temperature was tested. Figure 6.18 shows the diurnal trend in greenhouse air temperature as affected by the effective area of the vent openings of the physical model. The total area of vents directly affects the ventilation rate due to thermal buoyancy. Thus, noticeable effect on greenhouse air temperature is witnessed during pick solar radiation hours, where higher temperature differential due to effect of vent area is evident (Figure, 6.18). The model can therefore for be used effectively in determining the appropriate area of ventilation openings.

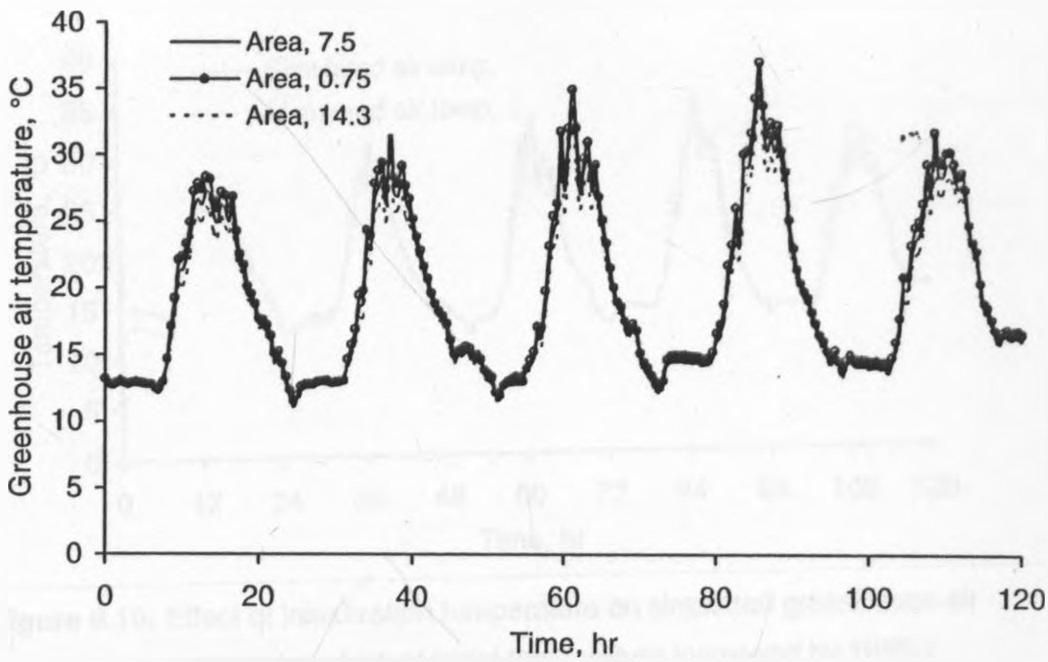


Figure 6.18: Diurnal cycles of greenhouse air temperature as influenced by the area of the ventilation openings (m^2)

6.5.4 Effect of Initialization

Sensitivity analysis were done to see how choice of initial temperatures of the of the greenhouse air and soil surface affect the simulated results. To achieve this objective, actual (experimental) initial values of temperature measurements were increased by 100 % and run made to see the model response. Figure 6.19 and 6.20 show the effect of doubling the initial value of the temperatures. This represents 100% error in choice of the initial boundary conditions.

It was noted that error up to 100% had little effect on the simulated greenhouse air temperature. This can be attributed to the low thermal capacity of air. However, where thermal capacity is high as for the soil surface, the effect is greater and initialization might be required beyond 36 hours (Figure 6.20).

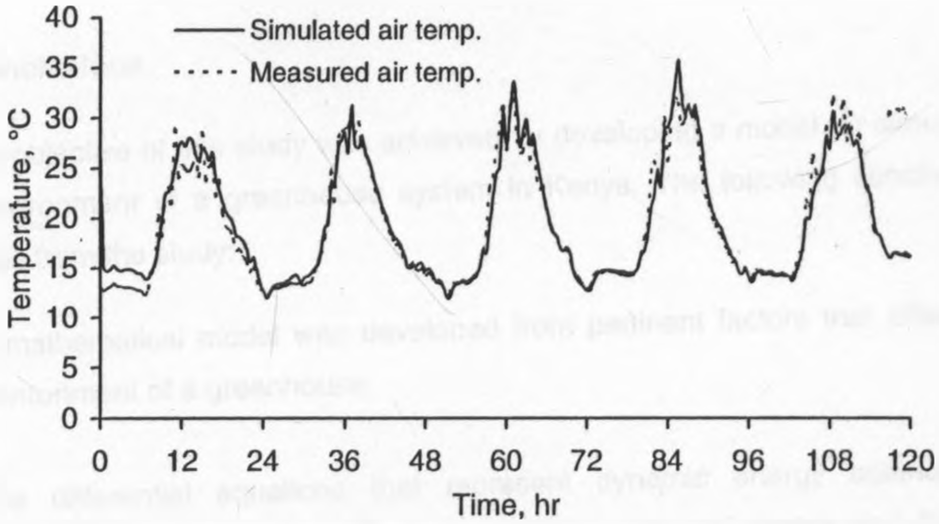


Figure 6.19: Effect of initialization temperature on simulated greenhouse air temperature (actual initial temperature increased by 100%)

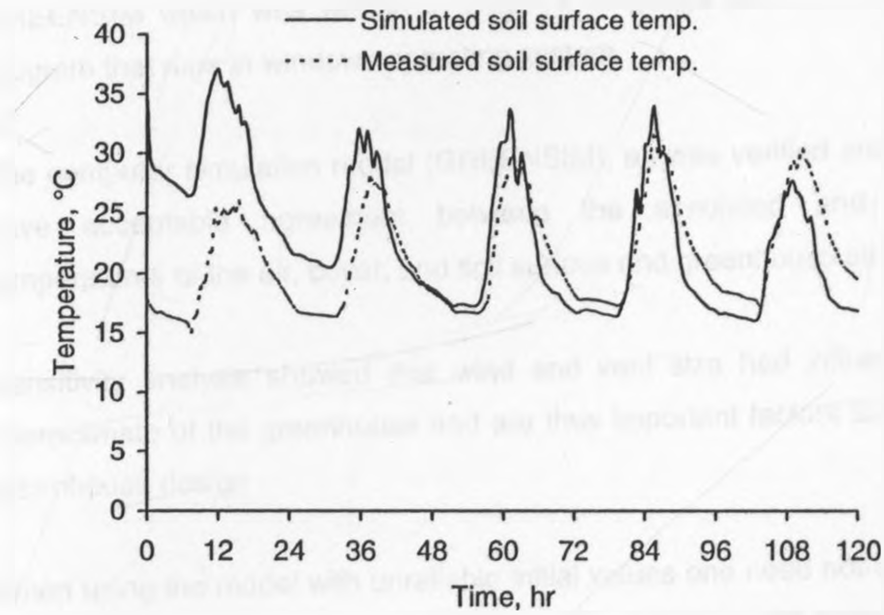


Figure 6.20: Effect of Initialization temperature on simulated greenhouse soil surface temperature (actual initial temperature increased by 100%)

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The main objective of this study was achieved by developing a model for simulation of the environment of a greenhouse system in Kenya. The following conclusions were made from the study:

1. A mathematical model was developed from pertinent factors that affect the environment of a greenhouse.

2. The differential equations that represent dynamic energy balances of greenhouse elements: cover, air, vegetation, and soil layers and that for moisture balance of the greenhouse air were solved numerically using a computer program, GREENSIM.

3. GREENSIM which was written in DELPHI language and is a stand alone program that runs in windows operating system

4. The computer simulation model (GREENSIM), as was verified and validated, gave acceptable agreement between the simulated and measured temperatures of the air, cover, and soil surface and greenhouse air humidity

5. Sensitivity analysis showed that wind and vent size had influence on the microclimate of the greenhouse and are thus important factors to consider in greenhouse design

6. When using the model with unreliable initial values one need not take beyond 36 hours of simulation to predict reliable results provided the error is not more than 100% of the correct initial values

7. The GREENSIM can be used to test the effect of covering materials, soil types, greenhouse vent area and meteorological conditions on the microclimate of a greenhouse instead of using expensive observations.

7.2 Recommendations

1. In future it will be necessary to include into the computer simulation model subroutines that feed the wind speed and sky clearness factor at every time step of the simulation

2. It will be an advance in the research when empirical relationship between the stomatal resistance and internal global solar radiation for citrus seedlings is developed

3. Though the one dimensional model developed here could be found useful for understanding of the dynamics of the greenhouse environment, greater insight could be achieved by using advanced techniques such as Computational Fluid Dynamics

4. The focus for the future is, therefore, the study of the distributed climate of the greenhouse. This requires the equations governing fluid flow and includes turbulent transfer. These equations can then be coded and solved using computer fluid dynamics softwares.

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APPENDIX 1: SOURCE CODE FOR GREENSIM

This appendix gives the source code for GREENSIM. The major subroutines, as discussed in Chapter 5, Materials and Methods, Section 5.2.1, include: Solve System Matrix; Solrad; OutTemp; and OutRH. These are bolded for clearity. Several support subroutines which have also been given.

Program GreenHoUsesim;

```
Uses
  Forms,
  GrSimulation in 'GrSimulation.pas' {GrSim},
  GraphUnit in 'GraphUnit.pas' {GraphF},
  Result in 'Result.pas' {ResultF},
  Table2 in 'Table2.pas' {TableF},
  FullResult in 'FullResult.pas' {FullResultF},
  Aboutfrm in 'Aboutfrm.pas' {AboutForm};
var
   Splash :TAboutForm;
begin
  Application.Initialize;
  Splash:=TAboutForm.Create(Nil);
  Splash.OkBtn.Visible := False ;
  Splash.Show;
  Application.CreateForm(TGrSim, GrSim);
  Application.CreateForm(TGraphF, GraphF);
  Application.CreateForm(TResultF, ResultF);
  Application.CreateForm(TForm2, Form2);
  Application.CreateForm(TTableF, TableF);
  Application.CreateForm(TFullResultF, FullResultF);
  Application.CreateForm(TAboutForm, AboutForm);
  Splash.Hide ;
  Splash.Free;
  Application.Run;
end.

Unit Aboutfrm;
interface
Uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, jpeg, ExtCtrls,MMsystem, ComCtrls;
type
   TAboutForm = class(TForm)
   Panel1: TPanel;
   Image1: TImage;
   OkBtn: TBitBtn;
   Label1: TLabel;
   Label2: TLabel;
   Timer2: TTimer;
   ProgressBar1: TProgressBar;
```

```
   Procedure Timer2Timer(Sender: TObject);
   Procedure FormActivate(Sender: TObject);
  end;
var
  AboutForm: TAboutForm;
implementation

Procedure TAboutForm.Timer2Timer(Sender: TObject);
begin
      Timer2.Tag := Timer2.Tag + Integer(Timer2.Interval) ;
end;
Procedure TAboutForm.FormActivate(Sender: TObject);
begin
  Timer2.Tag :=0;
  Timer2.Enabled := True;
  progressbar1.Brush.color:=clInfoBK;
  progressbar1.Position:=0;
  PlaySound ('C:\My Documents/GreenSound.wav', 0, snd_Async);
   while Timer2.Tag <= 7000 Do
     begin
      if ( Timer2.Tag mod 70) = 0 then
        ProgressBar1.Position:= Timer2.Tag div 70;
        Application.ProcessMessages ;
    end;
     Timer2.Enabled := False;
end;
end.

Unit GrSimulation;
interface
Uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Menus,GraphUnit,Result, Math,Table2,FullResult,LineFunc;
type
Array10 = array[1..10] of  Double;
TGrSim  = class(TForm)
   SimButton: TButton;
   Memo1: TMemo;
   Memo2: TMemo;
   Label1: TLabel;
   Label2: TLabel;
   Label3: TLabel;
   MainMenu1: TMainMenu;
   File1: TMenuItem;
   Open1: TMenuItem;
   Save1: TMenuItem;
   SaveAs1: TMenuItem;
   Edit1: TMenuItem;
   Cut1: TMenuItem;
   Copy1: TMenuItem;
   Paste1: TMenuItem;
   SelectAll1: TMenuItem;
   View1: TMenuItem;
   Simulate1: TMenuItem;
```

```
    Close1: TMenuItem;
    Help1: TMenuItem;
    AboutBox1: TMenuItem;
    Edit2: TEdit;
    Label8: TLabel;
    Label9: TLabel;
    Edit3: TEdit;
    Memo3: TMemo;
    Edit4: TEdit;
    Edit5: TEdit;
    Edit6: TEdit;
    Edit7: TEdit;
    Edit8: TEdit;
    Edit9: TEdit;
    Edit10: TEdit;
    Edit11: TEdit;
    Edit12: TEdit;
    Edit13: TEdit;
    Label4: TLabel;
    Label5: TLabel;
    Label6: TLabel;
    Label7: TLabel;
    Label10: TLabel;
    Label11: TLabel;
    Label12: TLabel;
    Label13: TLabel;
    Label14: TLabel;
    Label15: TLabel;
    Edit14: TEdit;
    Memo4: TMemo;
    Label16: TLabel;
    Label17: TLabel;
    Result1: TMenuItem;
    Tabulation1: TMenuItem;
    Label18: TLabel;
    Edit15: TEdit;
    Procedure SimButtonClick(Sender: TObject);
    Procedure AboutBox1Click(Sender: TObject);
    Procedure Simulate1Click(Sender: TObject);
  public
    Procedure System_Differential_Equations(t: Double;var  Tem,g:array10);
    Procedure Solve_System_Matrix(tinitial: Double;var yinitial:array10;
              nvars:integer;tstop: Double;iter:integer; var y:array10);
    Function  SolRad(t: Double): Double;
    Function  OutTemp(t: Double): Double;
    Function  OutRH(t: Double): Double;
    Procedure Delay(Seconds,Millisec:word);
  end;
var
 GrSim: TGrSim;
 ndata:integer;
 tdata,Tem_data,Rad_Data,OutRH_data:array of double;
Vg, Ma, Ca, Q, Hco, Hc, Mv, Mc, Cc, Ab, Tsr, Bol, Ag, Ac, Hci, ks, ds, cs,
```

```
Hs,Hv,Tg, Lo, Cd, Cw, gr, Ue, Ra, QrCnet, QrSnet, RHa, Vpsa, Vpsc,        Qcond,
Mwater, Wbance, Rate, Dsp, Re, Rf, Trw, Rwater, SpHao, g_6 ,t ,dt, Double;
Implementation

Procedure TGrSim.Delay(Seconds,Millisec:word);
var
  TimeOut:TdateTime;
begin
   TimeOut:=Now+EncodeTime(0,seconds div 60,Seconds mod 60, MilliSec);
   {wait until timeout time}
    while now<TimeOut do
    Application.ProcessMessages
end;
Function Pwr (X, Y : Double ) :  Double; (* raise x to the power y*)
begin
  Pwr := 0;
  if (Y = 0.0) then
  Pwr := 1.0
  else if (X = 0.0) and (Y > 0.0) then
    Pwr := 0.0
  else if X<0 then
    Pwr := - Exp(Y * Ln(Abs(X)))
  else  if X>0 then
    Pwr := Exp(Y * Ln(X))
  else if (X <= 0.0) and (Frac(Y) = 0.0) then
  if (Frac(Y / 2)) = 0.0 then
    Pwr := Exp(Y * Ln(Abs(X)))
end;
```

Function TGrSim.OutTemp(t: Double): Double;

```
var
   i,im:integer;
   outrange:boolean;
begin
  outrange := false;
  Result := 0;
   if t = tdata[ndata] then
     OutTemp := Tem_data[ndata]
   else if t>tdata[ndata] then
     outrange := true
   else if t = tdata[1] then
     OutTemp := Tem_data[1]
   else if t < tdata[1] then
      outrange := true
   else
     begin
       i:=2;
         begin
           while t >= tdata[i]do
             i:=i+1;
             im:=i-1;
             OutTemp:=Tem_data[im]+(Tem_data[i]-Tem_data[im])*(t-tdata[im])
               /(tdata[i]-tdata[im]);
         end;
```

```
    end;
if outrange =  true then
  begin
  OutTemp := 99999.0;
  messagedlg('The value of t is out of range',mtinformation,[mbok],0);
  halt(1);
  end
 end;
```

Function TGrSim.SolRad(t: Double): Double;

```
var
   i,im:integer;
   outrange:boolean;
begin
  Result:=0;
  outrange:=false;
  if t= tdata[ndata] then
    solrad:=Rad_data[ndata]
  else if t>tdata[ndata] then
    outrange:=true
  else if t=tdata[1] then
    solrad:=Rad_data[1]
  else if t< tdata[1] then
    outrange:= true
  else
    begin
      i:=2;
      begin
        while t>=tdata[i] do
          i:=i+1;
          im:=i-1;
          Solrad:=Rad_data[im]+(Rad_data[i]-Rad_data[im])*(t-tdata[im])
                  /(tdata[i]-tdata[im]);
    end;
    end;
if outrange= true then
    begin
    Solrad := 99999.0;
    messagedlg('The value of t is out of range',mtinformation,[mbok],0);
    halt(1);
    end
end;
```

Function TGrSim.OutRH(t: Double): Double;

```
var
    i, im:integer;
    outrange:boolean;
begin
    Result := 0;
    Outrange := false;
  if t = tdata[1] then
     OutRH := OutRH_data[1]
  else if t < tdata[1] then
    outrange := true
```

```
  else if t = tdata[ndata] then
    OutRH := OutRH_data[ndata]
  else if t >tdata[ndata] then
    outrange := true
  else
    begin
     I := 2;
      begin
        while t >= tdata[i] do
          i := i+1;
          im := i-1;
OutRH:= OutRH_data[im]+( OutRH_data[i]- OutRH_data[im])*(t-
tdata[im])/(tdata[i]-tdata[im]);
end;
end;
if outrange =  true then
   begin
   OutRH := 99999.0;
   messagedlg('The value of t is out of range',mtinformation,[mbok],0);
   halt(1);
   end
end;
```

```
Procedure TGrSim.System_Differential_Equations(t:Double;var Tem,g:array10);
var
   Tsky, Ra1, Ra2, Ra3, Ra, qrso, qrco, qrsky, EmCo, Pco, Tco, EmSo, Fcc,    Fcs,
   Fca, Fsky, E1, E2, Emcond, Tvp, Avp, SpHai, SHuc, Hcond, L, Enwai, Enwao, Af,
   Um, Us, MwMax, AbHai, Vpai, SHveg, Rn, Gf:Double;
   Solar,TemO, RHO, QrVnet, EmVeg, qrVeg, Tg, qrgi: Double;
begin
{absorptivity,transmivity and reflectivity  of cover,soil}
 Fsky := 0.5; {Cloud cover factor: 1,overcast; 0, clear}
 Fcc := 0.364;
 Fcs := 0.636;
 Fca := 0.818;
 EmCo := 0.23; {emmisivity of cover}
 Pco := 0.07;  {Reflectivity of cover}
 Tco := 0.7;   {Transmisity of cover}
 EmSo := 0.95; {emmissivity of soil}
 EmVeg := 0.95; {emmissivity of vegetation}
 Emcond := 0.95; {emmissivity of condensate}
 Avp := 17.27; {Vapour pressure constant}
 Tvp := 36 ;{vapour pressure constant,K}
 L : =2454; { Latent heat of condensation of water,kJ/kg}
 Af := 45;
{ Humidity ratio, Specific Humidity of inside air}
 MwMax := (0.622*
        100/100*
        0.611*exp(17.27*((Tem[2]+273)-273)
        /((Tem[2]+273)-36))/
        (101.325-
        100/100*
        0.611*exp(17.27*((Tem[2]+273)-273)
        /((Tem[2]+273)-36))))*Vg*1.2;
```

```
if Mwater < MwMax then
  begin
    AbHai:=(Mwater*1000)/Vg;{Absolute humidity of greenhouse air g/m^3}
    SpHai:=Mwater/(Vg*1.2); {Humidity ratio of greenhouse air, kg/kg dry air}
  end
else
  begin
   AbHai:=(MwMax*1000)/Vg; {Absolute humidity of internal air g/m^3}
   SpHai:=MwMax/(Vg*1.2);  {Humidity ratio of greenhouse air, kg/kg dry air}
  end;
  { Humidity ratio (Specific Humity) of outside air}
    SpHao:=(0.622*
          OutRH(t)/100*
          0.611*exp(17.27*((OutTemp(t) +273)-273)
          /((OutTemp(t)+273)-36))/
          (101.325-
          OutRH(t)/100*
          0.611*exp(17.27*((OutTemp(t)+273)-273)
          /((OutTemp(t)+273)-36))));
 {Enthalpy  greenhouse air  taking care of specific humidity,kJ/kg air}
  Enwai:= 1.005*Tem[2]+ SpHai*(2501.3+1.86*Tem[2]);
 {Enthalpy  outside air at taking care of specific humidity,kJ/kg air}
  Enwao:= 1.005*OutTemp(t)+ SpHao*(2501.3+1.86*OutTemp(t));
 {Saturation vapour pressure at a temprature T[i],Kpa}
   Vpsc:=0.611*exp(Avp*((Tem[1]+273)-273)/((Tem[1]+273)-Tvp));{cover}
   Vpsa:=0.611*exp(Avp*((Tem[2]+273)-273)/((Tem[2]+273)-Tvp));{air}
 {Vapour pressure of air at any given temperature T is given as}
   Vpai:=(AbHai*(Tem[2]+273.15))/2165;
 {Relative humity of air at a Temprature T}
   RHa:=Vpai/Vpsa;
 {when condensation takes place on the cover the humidity ratio cover should be
 that at saturation as refered by the covers Temperature}
   SHuc:=0.622*Vpsc/(101.325-Vpsc);
 {Heat transfer coefficient is given by the Lewis relationship}
   Hcond:=Hci/1.2*1.006;
 {Sky Temperature as given by Swinbank}
   Tsky := Fsky*OutTemp(t) + 0.0552*(1 - Fsky)*(Pwr(OutTemp(t),1.5));
 {Apparent greenhouse ground temperature}
   Tg:= pwr((0.75*0.95*pwr(Tem[6],4)+ 0.25*0.95*pwr(Tem[3],4)),0.25);
 {Far red radiation from the Elements}
   qrsky:=Bol*Pwr((Tsky+273.15),4); {Flux from Sky}
   qrco:=Bol*Pwr((Tem[1]+273.15),4); {Flux from cover}
   qrso:=Bol*Pwr((Tem[3]+273.15),4);{Flux from soil}
   qrVeg:=Bol*Pwr((Tem[6]+273.15),4);{Flux from vegation}
   qrgi:=Bol*Pwr((Tg+273.15),4);{Flux from greenhouse ground}
 {Radiation constants}
   E1:=1/(1+(Ag/Ac)*(1/EmCo-1));
   E2:=1/(1+(Ag/Ac)*(1/Emcond-1));
 {Thermal radiation balance for the soil layer is as follows}
   QrSnet:=((EmCo*qrco + Fcs*Pco*qrso + Tco*Fca*qrsky)/(1-Pco*Fcc))-
qrso*Emso;
 {Thermal balance for vegetative layer is as follows}
```

```
  QrVnet:=((EmCo*qrco + Fcs*Pco*qrso + Tco*Fca*qrsky)/(1-Pco*Fcc))-
qrVeg*EmVeg;
 {choosing between prencence of condensate or not on the greenhouse cover}
   if SHuc > SpHai then
     begin
    {1. without condensation}
     Wbance:=0;
     Qcond:=0;
     {The thermal radiation balance for the Cover is as follows}
     QrCnet:=(Fcs*Ac*EmCo*(qrco-qrSky)-E1*Ag*(qrgi-qrco));
     end
   else
     begin
       Wbance:=Ac*Hcond*(SpHai-SHuc);
       Qcond:=Ac*L*Hcond*(SpHai-SHuc);

       {The thermal radiation balance for the Cover is as follows}
       QrCnet:=(0.33*Ag*Tco*(qrgi-qrsky)+ Ac*Emco*Fcs*(qrco-qrsky)
            + 0.67*Ac*Emcond*Fcs*Tco*(qrco-qrgi) -0.33*Ag*Tco*(qrgi-qrsky)
            -0.33*Ag*E1*(qrgi-qrco)- 0.67*Ag*E2*(qrgi-qrco))
         end;
  {slope of water vapour saturation curve at a temprature T estimated by}
    Dsp:= 2504000/Power(((Tem[2]+273.16)-35.86),2)
         *exp(17.27*((Tem[2]+273.16)-273.15)/((Tem[2]+273.15)-35.86));

  {Determination of the ventilation rate}
  if Tem[2]+273.15 = OutTemp(t)+273.15 then
         Ra1:= 0
  else
   {ventilation equations}
   Ra1:=strtofloat(edit10.text)/2*Cd*Ue;
   Ra2:= gr*0.82*((Tem[2]+273.15)-(OutTemp(t)+273.15))/(OutTemp(t)+273.15);
   Ra3:=0.6*7.5/3*pwr(Ra2,0.5);
   Ra:=3600*Pwr((pwr(Ra1,2)+pwr(Ra3,2)),0.5)/StrToFloat(Edit9.Text);
   Rate:= 3600*Pwr((pwr(Ra1,2)+pwr(Ra3,2)),0.5)/Vg;
   Um:= Vg/Af*Rate/3600;             {mean velocity of air in the greenhouse}
   Us:=Um*pwr(0.1*Af/Vg,0.667);       {mean velocity of air at the canopy}
   {Transfer coeffient of the soil}
   Hs:=(1.52*pwr(Abs(Tem[2]-Tem[3]),0.333)+5.2*pwr(Us/6.5,0.5))*3.6;
   {Tranfer coefficient of the vegatation}
   Hv:=(1.9*pwr((abs(Tem[6]-Tem[2])/0.02),0.25)+ 5.2*pwr((Us/0.02),0.5))*3.6;
   {Transfer coeffient of the cover}
   Hci:= 3.6*(7.2 + 3.8*Um);
  {Removed water from the greenhouse volume}

 {Determination of transpiration rate}
    Rn:=0.6*Solrad(t)+ QrSnet;
     if Rn>= 0 then
        Gf:= 0.1*Rn
    else
       Gf:=0.5*Rn;
   { Transpiration in mm of water}
  if solrad(t) > 0 then
    Trw:= abs(0.408*Dsp/1000*(Rn-(Gf))/1000+ 66.7/1000*37/(Tem[2]+273.15)
```

```
        *Um*(Vpsa-RHa*Vpsa))/(Dsp/1000+ 66.7/1000*(1+ 0.24*Um))
   else
     Trw:= abs(0.408*Dsp/1000*(Rn-(Gf))/1000+ 66.7/1000*37/(Tem[2]+273.15)
        *Um*(Vpsa-RHa*Vpsa))/(Dsp/1000+ 66.7/1000*(1+ 0.94*Um));
  if SpHai >= MwMax/vg then
     Rwater:=Abs(Ra)*(SpHao-MwMax/vg)*StrToFloat(Edit9.Text)
  else
     Rwater:=Abs(Rate)*(SpHao-SpHai)*1.2*Vg;
  {introduction of diffirential equations describing greenhouse system}

  g[1]:=(Ag*AB*Solrad(t)+Ag*Hco*(OutTemp(t)-Tem[1])-Ag*Hci*(Tem[1]-Tem[2])
       + QrCnet+Qcond)/(Mc/97*Cc);

  g[2]:=(Q+Hci*Ag*(Tem[1]-Tem[2])-0.25*Hs*Ag*(Tem[2]-Tem[3])-
0.75*Hv*Ag*(Tem[2]-Tem[6])+
 Abs(Ra)*Ca*(Outtemp(t)-Tem[2]))/(Ma/97*Ca);//+ Abs(Ra)*(Enwao-Enwai)

   g[3]:=(0.5*Solrad(t)*Tsr + Hs*Ag*(Tem[2]-Tem[3])-ks*Ag*2*((Tem[3]-Tem[4])
       /ds)+Ag*qrSnet)/(Ag*0.02*1090*cs);

   g[4]:=(ks*Ag*((Tem[3]-Tem[4])*2/ds))/(Ag*cs*1140)-(7.2*Ag*((Tem[4]-Tem[5])
   /ds))/(Ag*cs*1140*ds);

   g[5]:=(7.2*Ag*((Tem[4]-Tem[5])/ds))/(Ag*cs*1140) -(7.2*Ag*((Tem[5]-Tg)/ds))
       /(Ag*cs*1140*ds);

   g[6]:= 2*(0.5*Solrad(t)*Tsr + Hv*Ag*0.75*(Tem[2]-Tem[6])+ Ag*QrVnet)
       /(Ag*0.01*4000*1000);
   end;
```

Procedure TGrSim.Solve_System_Matrix(tinitial: Double;var yinitial:array10; nvars:integer;tstop: Double;iter:integer; var y:array10);

```
     {Matrix Runge-Kutta differential equation solving Procedure
      t-initial- initial value of time
     yinitial- array of initial values of independent variables
     nvars- number of independent variables
     tstop- final value of time
     iter- number of iterations from initial to tstop
    y- array of values of independent variables at tstop.
    Procedure System_Differential_Equations (t,y,g)
    (wherey and g are arrays must be used to define the derivatives of the
    independentvariables}
var
  t,dt,dt2,dt6:Double;
  ytemp,g1,g2,g3,g4:array10;
  i,j:integer;
begin
{initialize the values of the t and the y array and compute the value dt,dt/2,dt/6}
  t:=tinitial;
  dt:=(tstop-tinitial)/iter;
  dt2:=dt/2;
  dt6:=dt/6;
 for i :=1 to nvars do
  y[i]:=yinitial[i];
```

```
{begin outer loop to compute the nvars values of the indepentent variables
 at tstop}
for i:=1 to iter do
 begin
{compute the arrays g1,g2,g3,and g4}
  System_Differential_Equations(t,y,g1);
    for j:=1 to nvars do
      ytemp[j]:=y[j]+g1[j]*dt2;
      t:=t+dt2;
      System_Differential_Equations(t,ytemp,g2);
    for j:=1 to nvars do
      ytemp[j]:=y[j]+g2[j]*dt2;
      System_Differential_Equations(t,ytemp,g3);
    for j:=1 to nvars do
      ytemp[j]:=y[j]+g3[j]*dt2;
      t:=t+dt2;
      System_Differential_Equations(t,ytemp,g4);
{combine the arrays g1,g2,g3,and g4 to find the intermediate values of the
independent variables}
   for j:=1 to nvars do
y[j]:=y[j]+(g1[j]+2*g2[j]+2*g3[j]+g4[j])*dt6
end
end;
```

Procedure TGrSim.SimButtonClick(Sender: TObject);

```
var
 t, dt:Double;
 i, iter, j :integer;
 OldTem, Tem: array10;
 M: array of double;
 a: array of array of double;
 StrCover, StrAir, StrS_Sur, StrSoil_L1, StrSoil_L2, StrTime, StrSolrad,
 Scale, StrHum, StrVeg: Double;
begin
{clear simulated result form if any on the result sheet}
  ResultF.memo1.clear;
  ResultF.memo2.clear;
  ResultF.memo3.clear;
  ResultF.memo4.clear;
  ResultF.memo5.clear;
  ResultF.memo6.clear;
  ResultF.memo7.clear;
  ResultF.memo8.clear;
  ResultF.memo9.clear;
{initialize arrays and other variables}
  t :=0;
  dt :=0.5;
  Ue := 0.5; { is the external wind speed, m/s}
  Vg := StrToFloat(Edit7.Text); {Greenhouse volume,m^3}
  Ma := 1.2*Vg;{Mass of greenhouse volume, kg}
  Ca := 1.006; {Thermal capicity of greenhouse air, kJ}
  Q := 0; {Heat generated in the greenhouse,KJ}
  Hco := 3.6*(7.2+3.8*Ue); {Heat transfer coeffient between outside air and
          greenhouse cover}
```

```
  Mc := StrToFloat(Edit8.Text)*0.0002*800;{Mass of greenhouse Cover}
  Cc := 3.6; {The thermal capacity of the cladding material,kJ/kg}
  Ab := 0.15; { effective absorptivity of solar radiation}
  Bol := 5.67*(Power(10,-8))*3.6;{Stefan-Boltzmann constant, kJ/m^2)}
  Ag := StrToFloat(Edit9.Text)/StrToFloat(Edit9.Text);{ Floor Area of the ,m^2}
  Ac := StrToFloat(Edit8.Text)/StrToFloat(Edit9.Text);{greenhouse Cover Area,m^2}
  Ks := StrToFloat(Edit11.Text); {Thermal conductivity of soil layer kJ/hmK}
  Ds := StrToFloat(Edit13.Text)/2; { the thickness of soil layers,m}
  Cs := 1.200; { Specific heat capacity of the soil layers, KJ/kg}
  Tg := StrToFloat(Edit12.Text);
  Cd := 0.35;{ the emprical discharge coefficient}
  Cw := 0.09;{ is the emprical wind effect coefficient}
  Lo := StrToFloat(Edit10.Text);{ length of the continuous vent}
  H := 0.55; { is the vertical height of the vent,m}
  gr := 9.81;{gravitation constant,m/s^2}
  Tsr := 0.6;

 {Initial Mass of water in the air,kg}
   Mwater := (0.622*
         StrToFloat(Edit14.Text)/100*
         0.611*exp(17.27*((StrToFloat(Edit3.Text)+273)-273)
         /((StrToFloat(Edit3.Text)+273)-36))/(101.325-StrToFloat(Edit14.Text)/100*
         0.611*exp(17.27*((StrToFloat(Edit3.Text)+273)-273)
         /((StrToFloat(Edit3.Text)+273)-36))))*Vg*1.2;

  ndata :=  memo1.Lines.count;
  iter := 30;
{Initialize input data dynamic arrays}
  Setlength (tdata, ndata+2);
  Setlength (Tem_data, ndata+2);
  Setlength (Rad_data, ndata+2);
  Setlength (OutRH_data, ndata+2);
 if (memo1.Lines.count= 0) or (memo2.Lines.count= 0)
 or (memo3.Lines.count= 0)or (memo4.Lines.count= 0)then
begin
  Messagedlg ('You have not entered any or some input data!',mtError,[mbok],0);
   exit;
   end;
 if (memo1.Lines.count<>memo2.Lines.count) or
   (memo2.lines.count<>memo3.lines.count)
  or (memo3.lines.count<>memo4.lines.count) then
  begin
   Messagedlg ('The data entries are not equal',mtError,[mbok],0);
   exit;
  end;
for  j:=0 to ndata-1 do
  begin
   tdata[j+1]:=strtofloat(memo1.Lines[j]);
   Tem_data[j+1]:=strtofloat(memo2.Lines[j]);
   Rad_data[j+1]:=strtofloat(memo3.Lines[j]);
   OutRH_data[j+1]:=strtofloat(memo4.Lines[j]);
  end;

 TableF.StringGrid1.colcount:=7;
```

```
  TableF.StringGrid1.rowcount:=1000;
  Setlength (a, 8 , round (tdata[ndata]/dt +2));

  a[1,0]:=StrToFloat(edit2.text);
  a[2,0]:=StrToFloat(edit3.text);
  a[3,0]:=StrToFloat(edit4.text);
  a[4,0]:=StrToFloat(edit5.text);
  a[5,0]:=StrToFloat(edit6.text);
  a[6,0]:=StrToFloat(edit15.text);//Vegetation;
  a[7,0]:=StrToFloat(edit14.text);//humidity;

 OldTem[1]:=StrToFloat(edit2.text);
   OldTem[2]:=StrToFloat(edit3.text);
  OldTem[3]:=StrToFloat(edit4.text);
  OldTem[4]:=StrToFloat(edit5.text);
  OldTem[5]:=StrToFloat(edit6.text);
  OldTem[6]:=StrToFloat(edit15.text);

 i:=1;
while  i< tdata[ndata]/dt do
begin
   Solve_System_Matrix (t, oldTem, 6, t+dt, iter,Tem);

   a[1,i]:=Tem[1];
   a[2,i]:=Tem[2];
   a[3,i]:=Tem[3];
   a[4,i]:=Tem[4];
   a[5,i]:=Tem[5];
   a[6,i]:=Tem[6];

   OldTem[1] := Tem[1];
   OldTem[2] := Tem[2];
   OldTem[3] := Tem[3];
   OldTem[4] := Tem[4];
   OldTem[5] := Tem[5];
   OldTem[6] := Tem[6];

{Humidity Ratio is stored in the array}
   a[7,i]:= RHa*100;
   Mwater:=Mwater;//-Wbance+Rwater+Trw*Ag;
   t:=t+dt;
   i:=i+1;
   end;
ResultF.Show;
  i:=0;
  t:=0;
while i<tdata[ndata]/dt do
 begin
  StrCover := StrToFloat(Format('%8.2f',[a[1,i]]));
  StrAir := StrToFloat(Format('%8.2f',[a[2,i]]));
  StrS_Sur := StrToFloat(Format('%8.2f',[a[3,i]]));
  StrSoil_L1 := StrToFloat(Format('%8.2f',[a[4,i]]));
  StrSoil_L2 := StrToFloat(Format('%8.2f',[a[5,i]]));
  StrHum := StrToFloat(Format('%8.2f',[a[7,i]]));
```

```
    StrVeg := StrToFloat(Format('%8.2f',[a[6,i]]));

    StrTime := StrToFloat(Format('%8.1f',[t]));
    StrSolrad := StrToFloat(Format('%8.2f',[Solrad(t)]));
    Scale :=StrSolrad/100;

   ResultF.memo1.Lines.Add(floatTostr(StrTime));
   ResultF.memo2.Lines.Add(FloatToStr(StrCover));
   ResultF.memo3.Lines.Add(FloatToStr(StrAir));
   ResultF.memo4.Lines.Add(FloatToStr(StrS_Sur));
   ResultF.memo5.Lines.Add(FloatToStr(StrSoil_L1));
   ResultF.memo6.Lines.Add(FloatToStr(StrSoiL_L2));
   ResultF.memo7.lines.Add(floattostr(Scale));
   ResultF.memo8.lines.Add(floattostr(StrHum));
   ResultF.memo9.lines.Add(floattostr(StrVeg));

   TableF.StringGrid1.Cells[1,i+1]:=floatTostr(StrTime);
   TableF.StringGrid1.Cells[2,i+1]:=FloatToStr(StrCover);
   TableF.StringGrid1.Cells[3,i+1]:=FloatToStr(StrAir);
   TableF.StringGrid1.Cells[4,i+1]:=FloatToStr(StrS_Sur);
   TableF.StringGrid1.Cells[5,i+1]:=FloatToStr(StrSoil_L1);
   TableF.StringGrid1.Cells[6,i+1]:=FloatToStr(StrSoiL_L2);
   TableF.StringGrid1.Cells[0,i+1]:= format('%d',[i+1]);

   FullResultF.memo1.Lines.Add(floatTostr(StrTime)+#9+FloatToStr(StrCover)
   +#9+FloatToStr(StrAir)+#9+FloatToStr(StrS_Sur)+#9+FloatToStr(StrSoil_L1)
   +#9+ FloatToStr(StrSoiL_L2));
   i:=i+1;
   t:=t+dt;
   end;

   TableF.StringGrid1.Cells[1,0]:='Time(hours)';
   TableF.StringGrid1.Cells[2,0]:='Cover Temprature';
   TableF.StringGrid1.Cells[3,0]:='Air Temperature';
   TableF.StringGrid1.Cells[4,0]:='Soil surface Temprature';
   TableF.StringGrid1.Cells[5,0]:='First soil Layer Temperature';
   TableF.StringGrid1.Cells[6,0]:='Second soil layer Temperature';


   Setlength(M,ResultF.memo2.Lines.Count);
   for  j:=0 to ResultF.memo2.Lines.Count-1 do
   M[j]:= StrToFloat(ResultF.memo2.Lines[j]);
   GraphF.Chart1.BottomAxis.Automatic:= False ;
   GraphF.Chart1.LeftAxis.Automatic:= False ;
   GraphF.Chart1.BottomAxis.Maximum:=tdata[ndata];
   GraphF.Chart1.LeftAxis.Maximum:=Round(MaxValue(M)+1);
   end;
{Menu commands}
Procedure TGrSim.AboutBox1Click(Sender: TObject);
begin
messagedlg('A program for dynamic simulatio of a greenhouse environment'#13+
        'Developed by AGULLO O.J,UoN of Nairobi',mtinformation,[mbok],0);
end;
end.
```

```
Unit RESULT;
interface

Uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, GraphUnit, Table2, FullResult, Menus;

type
  TResultF = class(TForm)
    Memo1: TMemo;
    Memo2: TMemo;
    Memo3: TMemo;
    Memo4: TMemo;
    Memo5: TMemo;
    Memo6: TMemo;
    Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label6: TLabel;
    Label5: TLabel;
    Graph: TButton;
    Memo7: TMemo;
    ButtonTable: TButton;
    Full_Results: TButton;
    Label7: TLabel;
    Memo8: TMemo;
    Label8: TLabel;
    MainMenu1: TMainMenu;
    File1: TMenuItem;
    Open1: TMenuItem;
    SaveAs1: TMenuItem;
    SaveDialog1: TSaveDialog;
    Memo9: TMemo;
    Label9: TLabel;
    Procedure GraphClick(Sender: TObject);
    Procedure FormCreate(Sender: TObject);
    Procedure ButtonTableClick(Sender: TObject);
    Procedure Full_ResultsClick(Sender: TObject);
    Procedure Delay(Seconds,Millisec:word);
    Procedure SaveAs1Click(Sender: TObject);
  end;
var
  ResultF: TResultF;
  implementation
    Uses GrSimulation;
{$R *.DFM}

Procedure TResultF.Delay(Seconds,Millisec:word);
var
TimeOut:TdateTime;
Begin
    TimeOut:=Now+EncodeTime(0,seconds div 60,Seconds mod 60, MilliSec);
```

```
    {wait until timeout time}
        while now<TimeOut do
          Application.ProcessMessages
end;
Procedure TResultF.GraphClick(Sender: TObject);
Var
 i:integer;
Begin
 GraphF.Chart1.Series[0].Title := 'Cover Temperature';
 GraphF.Chart1.Series[1].Title := 'Air Temperature';
 GraphF.Chart1.Series[2].Title := Soil Surface Temperature';
 GraphF.Chart1.Series[3].Title := 'First Soil Layer Temperature';
 GraphF.Chart1.Series[4].Title := 'Second Soil Layer Temperature';
 GraphF.Chart1.Series[5].Title := 'Solar Radiation (kJ/hr)* 10^2';
 GraphF.Chart1.Series[6].Title := 'Relative humidity (%)* 3';
 GraphF.Show;
 for i := 0 to 5 do
  GraphF.Chart1.Series[i].Clear;
 for i:=0 to memo1.Lines.Count-1 Do
   begin
    GraphF.Series1.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo2.lines[i]));
    GraphF.series2.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo3.lines[i]));
    GraphF.series3.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo4.lines[i]));
    GraphF.series4.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo5.lines[i]));
    GraphF.series5.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo6.lines[i]));
    GraphF.series6.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo7.lines[i]));
    GraphF.series7.addxy(Strtofloat(memo1.lines[i]),Strtofloat(memo8.lines[i])/3);
    delay(0,50);
    end;
    end;
Procedure TResultF.FormCreate(Sender: TObject);
 begin
    memo1.clear;
    memo2.clear;
    memo3.clear;
    memo4.clear;
    memo5.clear;
    memo6.clear;
    memo7.clear;
    memo8.clear;
end;

Procedure TResultF.ButtonTableClick(Sender: TObject);
begin
TableF.show;
end;
Procedure TResultF.Full_ResultsClick(Sender: TObject);
begin
FullResultF.show;
end;
Procedure TResultF.SaveAs1Click(Sender: TObject);
var
ResultFile: TextFile;
j:Integer;
```

```
s1, s2, s3, s4, s5,s6, Value,T: string;
begin
 if SaveDialog1.Execute then
   begin
     AssignFile(ResultFile,Savedialog1.FileName);
      Rewrite(ResultFile);
      T:= Datetimetostr(now);
      Writeln(Resultfile,'SIMULATION DONE ON:'+' '+T);
          with TableF.StringGrid1 do
            for J:= 0 to trunc(tdata[ndata]/dt) do
   begin
     s1:=(Cells[1,j]);
     s2:=(Cells[2,j]);
     s3:=(cells[3,j]);
     s4:=(Cells[4,j]);
     s5:=(Cells[5,j]);
     s6:=(Cells[6,j]);
     Value:=s1+#9+s2+#9+s3+#9+s4+#9+s5+#9+s6;
     writeln(ResultFile,Value);
     end;
     CloseFile(ResultFile);
    end;
    end;
    end.

Unit GraphUnit;
interface
Uses
 Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
TeEngine, Series, ExtCtrls, TeeProcs, Chart, Menus, StdCtrls, CheckLst;
type
 TGraphF = class(TForm)
   MainMenu1: TMainMenu;
   File1: TMenuItem;
   Savechart1: TMenuItem;
   OpenDialog1: TOpenDialog;
   SaveDialog1: TSaveDialog;
   OpenChart1: TMenuItem;
   ButtonSim: TButton;
   CheckListBox1: TCheckListBox;
   CheckListBox2: TCheckListBox;
   Button1: TButton;
   Chart1: TChart;
   Series1: TLineSeries;
   Series2: TLineSeries;
   Series3: TLineSeries;
   Series4: TLineSeries;
   Series5: TLineSeries;
   Series6: TLineSeries;
   Series7: TLineSeries;
   BtnAdd: TButton;
   BtnRemove: TButton;
   Edit1: TMenuItem;
   CopyChart1: TMenuItem;
```

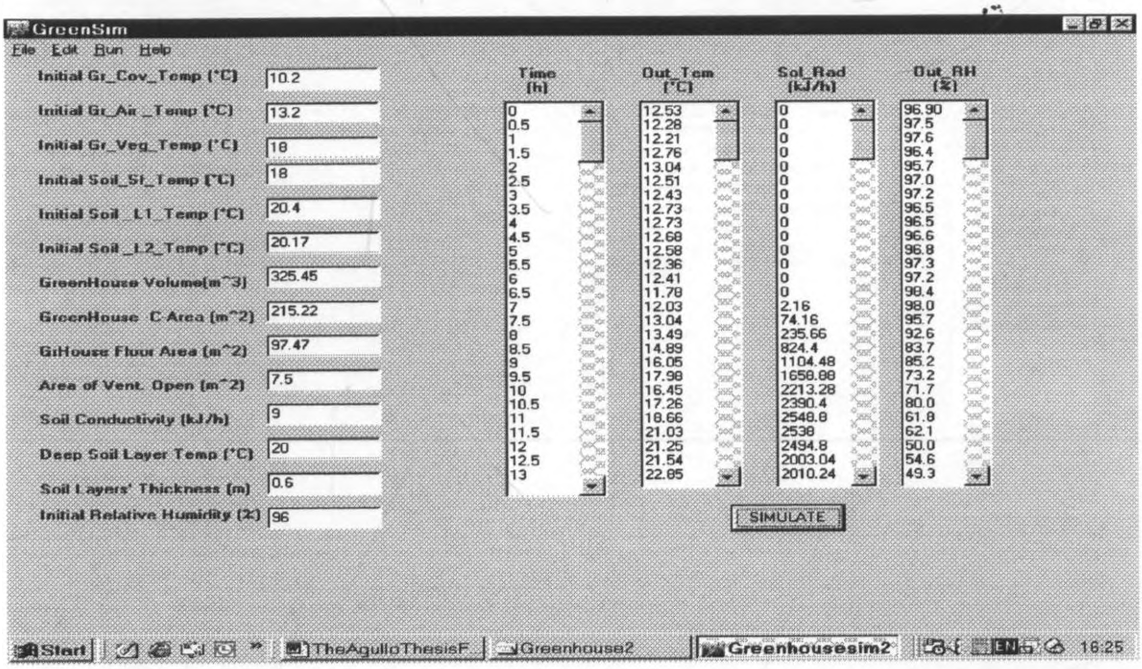
```
    Procedure Savechart1Click(Sender: TObject);
    Procedure OpenChart1Click(Sender: TObject);
    Procedure Button1Click(Sender: TObject);
    Procedure ButtonSimClick(Sender: TObject);
    Procedure CheckListBox1ClickCheck(Sender: TObject);
    Procedure BtnAddClick(Sender: TObject);
    Procedure BtnRemoveClick(Sender: TObject);
   end;

var
  GraphF: TGraphF;
implementation
 Uses GrSimulation, Result;
Procedure TGraphF.Button1Click(Sender: TObject);
begin
Chart1.UndoZoom;
end;
Procedure TGraphF.ButtonSimClick(Sender: TObject);
var
i:integer;
begin
  for i := 0 to 5 do
   GraphF.Chart1.Series[i].Clear;
  for i:=0 to ResultF.memo1.Lines.count-1 do
   begin
```

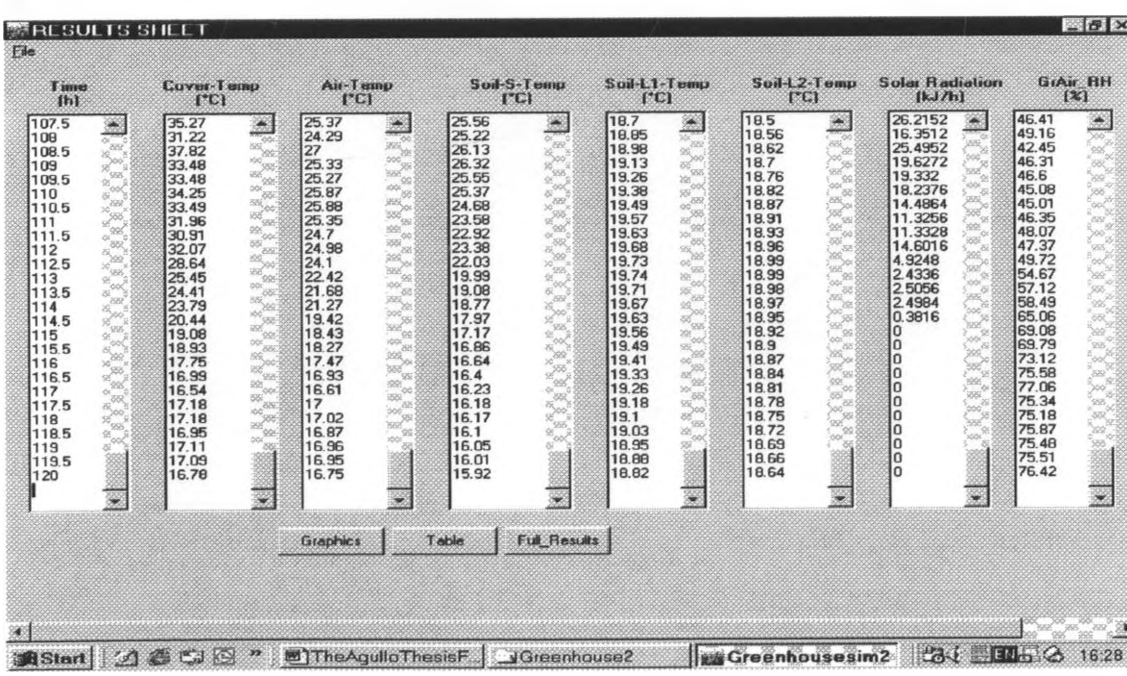
```
Series1.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo2.lines[i]));
series2.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo3.lines[i]));
series3.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo4.lines[i]));
series4.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo5.lines[i]));
series5.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo6.lines[i]));
series6.addxy(Strtofloat(ResultF.memo1.lines[i]),Strtofloat(ResultF.memo7.lines[i]));
series7.addxy(Strtofloat(ResultF.memo1.lines[i]),(Strtofloat(ResultF.memo8.lines[i]))/
3);
delay(0,250);
 end;
 end;
```

APPENDIX 2 : GREENSIM INTERFACE

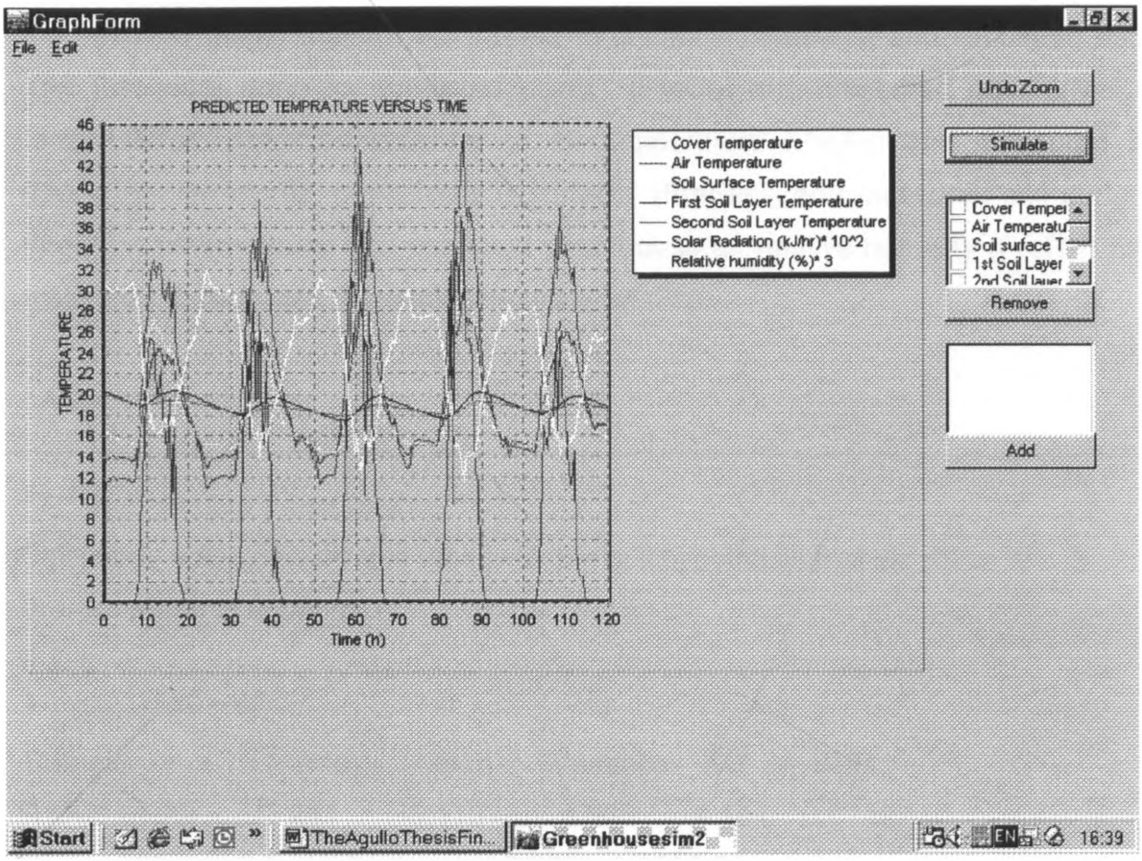
A 2.1 Input Window



A 2.2 Output window (Values)



A 2.3 output window (Graphics)



APPENDIX 3: STATISTICAL ANALYSIS

A 3.1 Two sample paired T- Test

Two sample t-tests (paired) were done to compare measured and simulated data. The test were done for predicted cover (PreCo) and measured cover (MeCo) temperatures; predicted greenhouse air temperature (PreAir) and measured air (MeAir) temperatures; predicted soil surface (PreSsur) and measured soil surface (MeSsur) temperatures and predicted greenhouse air relative humidity (PreRH) and measured greenhouse air relative humidity (MeRh).

A 3.1.1 Air

***** Two-sample T-test (paired) *****
Calculated using one-sample t-test with the null hypothesis that the mean of
PreAir - MeAir is equal to 0

*** Summary ***

Sample	Size	Mean	Variance	SD	SEM
PreAir- MeAir	241	-0.1107	1.355	1.164	0.07497

95% confidence interval for mean: (-0.2584, 0.03694)
*** Test of null hypothesis that mean of PreAir- MeAir is equal to 0 ***
Test statistic t = -1.48 on 240 d.f.
Probability = 0.141

A 3.1.2 Cover

***** Two-sample T-test (paired) *****
Calculated using one-sample t-test with the null hypothesis that the mean of
preCo - MeCo is equal to 0

*** Summary ***

Sample	Size	Mean	Variance	SD	SEM
preCo- MeCo	241	1.272	7.100	2.665	0.1716

95% confidence interval for mean: (0.9340, 1.610)
*** Test of null hypothesis that mean of preCo- MeCo is equal to 0 ***
Test statistic t = 7.41 on 240 d.f.

Probability < 0.001

A 3.1.3 Soil surface

***** Two-sample T-test (paired) *****

Calculated using one-sample t-test with the null hypothesis that the mean of PreSsur - MeSsur is equal to 0

*** Summary ***

Sample	Size	Mean	Variance	S.D	SEM
PreSsur- MeSSur	241	-1.469	5.460	2.337	0.1505

95% confidence interval for mean: (-1.766, -1.173)

*** Test of null hypothesis that mean of PreSsur- MeSSur is equal to 0 ***

Test statistic t = -9.76 on 240 d.f.

Probability < 0.001

A 3.1.4 Relative humidity

***** Two-sample T-test (paired) *****

Calculated using one-sample t-test with the null hypothesis that the mean of preRH - MeRH is equal to 0

*** Summary ***

Sample	Size	Mean	Variance	S.D	SEM
preRH- MeRH	241	-0.7161	113.6	10.66	0.6865

95% confidence interval for mean: (-2.068, 0.6363)

*** Test of null hypothesis that mean of preRH- MeRH is equal to 0 ***

Test statistic t = -1.04 on 240 d.f.

Probability = 0.298

APPENDIX 4: VALIDATION DATA

The measured values over the period of 30/06/2003 to 3/07/2003 were outside air temperature (T_{ai}), Cover (T_c), Greenhouse air temperature (T_{ai}), soil surface temperature (T_{ss}), soil layer temperature at 15cm depth (T_{s-15}), Soil temperature at 30cm depth, outside air relative humidity (Rh_{ai}) and greenhouse air relative humidity (Rh_{ai}).

Date and Time	T_{ao}	T_c	T_{ai}	T_{ss}	T_{s-15}	T_{s-30}	Rh_{ao}	Rh_{ai}	R_s(kJ/m^{2}hr)
30/06 00:00:39	11.35	10.09	13.21	17.80	21.67	20.34	97	96.9	0
30/06 00:30:39	10.52	9.59	12.73	17.36	21.57	20.31	96.5	97.5	0
30/06 01:00:39	11.83	12.01	13.01	16.94	21.32	20.17	96	97.6	0
30/06 01:30:39	12.23	11.53	13.16	16.77	21	19.97	95	96.4	0
30/06 02:00:39	12.36	12.51	13.49	16.66	20.93	19.94	94	95.7	0
30/06 02:30:39	12.46	11.14	13.21	16.64	21	20.04	94	97.0	0
30/06 03:00:39	12.51	11.57	13.16	16.62	20.98	20.04	94	97.2	0
30/06 03:30:39	12.83	11.97	13.09	16.58	20.88	20	96	96.5	0
30/06 04:00:39	13.14	12.20	13.04	16.53	20.83	20.02	98	96.5	0
30/06 04:30:39	13.21	12.60	13.06	16.52	20.71	20	98	96.6	0
30/06 05:00:39	13.06	12.18	12.93	16.52	20.73	20.04	98	96.8	0
30/06 05:30:39	12.66	11.84	12.78	16.48	20.66	20.02	97.5	97.3	0
30/06 06:00:39	12.88	12.06	12.76	16.45	20.61	20.02	97	97.2	0
30/06 06:30:39	13.04	10.60	12.28	16.43	20.63	20.04	70.5	98.4	0
30/06 07:00:39	13.26	10.83	12.91	16.40	20.41	19.92	66	98.0	2.16
30/06 07:30:39	13.51	13.54	14.39	16.34	18.69	18.89	63	95.7	74.16
30/06 08:00:39	14.17	15.37	15.3	16.40	19.27	19.24	60	92.6	235.66
30/06 08:30:39	14.62	22.27	20.34	16.87	17.68	18.39	51	83.7	824.4
30/06 09:00:39	15.45	20.28	18.04	17.21	19.04	19.32	42	85.2	1104.5
30/06 09:30:39	14.49	25.11	22.18	18.24	18.91	19.29	46	73.2	1658.9
30/06 10:00:39	19.04	29.89	23.26	19.70	17.23	18.16	50	71.7	2213.3
30/06 10:30:39	18.71	22.80	21.4	21.04	18.74	19.54	50	80.0	2390.4
30/06 11:00:39	22.4	36.78	28.91	21.63	17.51	18.76	50	61.8	2548.8
30/06 11:30:39	21.47	25.73	24.12	23.46	20.88	21.94	48	62.1	2538
30/06 12:00:39	23.85	31.74	25.33	24.26	20.17	20.58	46	50.0	2494.8

30/06 12:30:39	21.4	28.34	24.93
30/06 13:00:39	26.24	31.56	24.66
30/06 13:30:39	22.06	29.41	25.15
30/06 14:00:39	23.31	34.20	26.63
30/06 14:30:39	23.24	25.28	24.07
30/06 15:00:39	22.43	38.00	28.59
30/06 15:30:39	22.3	24.53	23.85
30/06 16:00:39	22.89	30.11	25.13
30/06 16:30:39	21.35	30.53	25.4
30/06 17:00:39	20.85	23.16	22.16
30/06 17:30:39	20.04	25.01	23.85
30/06 18:00:39	19.44	19.40	20.61
30/06 18:30:39	18.29	16.08	19.17
30/06 19:00:39	17.68	17.51	18.91
30/06 19:30:39	17.11	16.67	18.06
30/06 20:00:39	16.9	14.12	16.75
30/06 20:30:39	16.2	15.61	16.95
30/06 21:00:39	14.79	13.52	16.23
30/06 21:30:39	13.86	13.35	15.77
30/06 22:00:39	14.69	12.36	14.57
30/06 22:30:39	14.47	13.65	15.2
30/06 23:00:39	14.87	10.64	13.84
30/06 23:30:39	14.54	9.63	12.93
07/01/03 00:00	13.84	9.42	12.73
07/01/03 00:30	14.27	9.12	12.31
07/01/03 01:00	13.64	10.88	12.51
07/01/03 01:30	12.68	11.67	13.01
07/01/03 02:00	12.66	11.69	12.98
07/01/03 02:30	12.31	11.79	13.11
07/01/03 03:00	11.1	11.87	13.19
07/01/03 03:30	11.5	12.49	13.26
07/01/03 04:00	12.86	12.87	13.49
07/01/03 04:30	12.78	12.85	13.46

26.28	19.97	20.34	46	54.6	2003
26.42	20.22	20.36	46	49.3	2010.2
27.99	19.59	19.79	45.5	52.0	2260.1
27.43	19.29	19.54	45	43.9	1688.4
27.47	19.82	19.87	45	54.6	1648.8
27.10	18.89	19.07	45	44.3	1404
26.99	20.71	20.36	45.6	53.8	1960.6
26.87	20.12	19.72	46	52.5	831.6
25.82	19.49	19.07	45.5	52.3	1767.6
24.64	19.84	19.47	45	61.3	871.2
24.06	19.97	19.14	52.5	59.9	194.4
23.34	21.42	20.31	70	66.4	181.44
22.72	22.11	20.61	75	72.8	72
22.00	22.01	20.41	80	74.2	0
21.55	21.81	20.24	81.5	78.7	0
20.98	22.03	20.34	83	83.7	0
20.64	21.76	20.12	88	82.3	0
20.44	21.89	20.14	93	85.3	0
19.87	21.84	20.09	93	86.2	0
19.39	22.11	20.31	93	92.0	0
19.24	21.79	20.09	95	90.9	0
18.85	21.89	20.19	97	94.7	0
18.55	21.94	20.29	97	97.9	0
18.46	21.86	20.29	97	99.1	0
18.24	21.79	20.27	96	99.9	0
18.06	21.52	20.07	95	98.3	0
17.96	21.3	19.97	95	97.6	0
17.71	21.22	19.97	95	97.3	0
17.54	21.15	19.94	95	97.1	0
17.27	21.1	19.97	94	97.0	0
16.92	21.1	20.02	93	96.2	0
16.71	20.95	20	92.5	95.4	0
16.76	20.88	19.97	92	95.2	0

07/01/03 05:00	13.04	12.87	13.44
07/01/03 05:30	13.19	12.93	13.46
07/01/03 06:00	13.14	12.74	13.24
07/01/03 06:30	13.26	12.85	13.59
07/01/03 07:00	13.61	13.20	13.61
07/01/03 07:30	13.86	14.55	14.54
07/01/03 08:00	14.19	16.48	15.77
07/01/03 08:30	15.77	17.75	16.35
07/01/03 09:00	13.94	21.23	17.98
07/01/03 09:30	15.92	21.62	19.97
07/01/03 10:00	17.86	31.65	24.86
07/01/03 10:30	19.19	24.59	21.57
07/01/03 11:00	18.89	35.51	28
07/01/03 11:30	25.23	38.04	28.57
07/01/03 12:00	20.34	38.44	28.91
07/01/03 12:30	25.28	32.88	29.18
07/01/03 13:00	26.16	41.64	30.36
07/01/03 13:30	23.9	31.38	28.32
07/01/03 14:00	23.41	39.78	29.68
07/01/03 14:30	24.59	30.24	27.49
07/01/03 15:00	23.83	29.57	26.36
07/01/03 15:30	22.35	27.98	25.7
07/01/03 16:00	24.93	24.72	24.47
07/01/03 16:30	22.8	22.81	22.75
07/01/03 17:00	21.47	22.78	22.5
07/01/03 17:30	20.36	20.34	20.88
07/01/03 18:00	19.59	19.21	20.12
07/01/03 18:30	18.61	17.65	18.76
07/01/03 19:00	17.68	16.74	18.14
07/01/03 19:30	17.61	15.55	17.33
07/01/03 20:00	16.18	16.06	17.41
07/01/03 20:30	16	14.61	16.55
07/01/03 21:00	16.58	12.01	15.45

16.76	20.85	20.02	93.5	95.6	0
16.76	20.83	20.04	95	95.4	0
16.76	20.78	20	94.5	96.1	0
16.69	20.71	20	95	95.7	0
16.71	20.63	19.94	86	95.1	41.76
16.66	20.31	19.79	78	93.2	215.28
16.70	19.72	19.37	74	90.8	380.88
16.92	19.74	19.44	70	86.6	678.96
17.34	19.09	19.09	62.5	76.7	1632.2
17.81	17.08	17.96	55	67.1	1871.3
20.24	17.93	18.61	50	54.3	2497.7
21.98	18.96	19.39	45	62.9	1581.8
24.19	18.24	18.89	43.5	40.5	2490.5
25.95	17.78	18.89	42	38.9	2882.9
27.30	17.93	19.12	40	40.3	1945.4
27.82	17.98	19.17	38	41.7	1963.4
29.31	18.29	19.49	38	39.7	2785.7
29.92	19.84	20.27	38	42.1	1595.5
28.87	19.29	19.69	38	38.7	1530.7
28.45	20.14	20.36	38	43.7	2327
28.70	19.82	19.67	38	48.4	1497.6
28.79	20.36	19.92	45.5	52.2	1316.2
27.40	20.9	20.24	53	53.6	252.72
27.40	21.69	20.63	56.5	60.6	527.76
24.52	21.05	20.04	60	62.9	262.8
24.67	21.57	20.27	65	66.8	104.4
24.64	21.76	20.22	70	69.7	39.6
24.22	22.08	20.31	75	75.2	0
23.23	22.03	20.22	80	78.0	0
22.49	22.23	20.29	81	80.6	0
21.96	22.08	20.17	82	81.6	0
21.24	22.16	20.19	87.5	84.6	0
20.82	22.53	20.44	93	90.1	0

07/01/03 21:30	15.67	12.27	15.07
07/01/03 22:00	13.64	14.23	15.65
07/01/03 22:30	13.41	12.21	14.94
07/01/03 23:00	12.98	13.31	14.72
07/01/03 23:30	12.33	13.85	14.92
07/02/03 00:00	11.95	11.46	14.24
07/02/03 00:30	11.95	13.27	14.52
07/02/03 01:00	13.66	12.49	14.22
07/02/03 01:30	13.94	10.62	13.51
07/02/03 02:00	14.12	11.34	13.84
07/02/03 02:30	14.12	10.36	13.34
07/02/03 03:00	14.14	8.89	12.16
07/02/03 03:30	14.17	11.54	12.48
07/02/03 04:00	14.07	12.91	13.51
07/02/03 04:30	14.09	12.81	13.36
07/02/03 05:00	14.02	12.82	13.46
07/02/03 05:30	14.07	12.92	13.74
07/02/03 06:00	13.89	12.72	13.41
07/02/03 06:30	13.94	12.75	13.51
07/02/03 07:00	14.02	13.05	13.89
07/02/03 07:30	14.42	13.91	14.12
07/02/03 08:00	15.45	15.57	15.22
07/02/03 08:30	15.52	18.44	16.75
07/02/03 09:00	16.3	19.21	18.29
07/02/03 09:30	18.69	26.12	22.92
07/02/03 10:00	18.11	27.58	24
07/02/03 10:30	19.02	34.74	26.83
07/02/03 11:00	19.82	37.02	29.31
07/02/03 11:30	23.93	40.55	31.3
07/02/03 12:00	21.79	27.86	26.73
07/02/03 12:30	24.61	42.56	31.46
07/02/03 13:00	25.87	42.80	32.04
07/02/03 13:30	28.64	28.85	27.86

20.51	22.35	20.34	91.5	93.3	0
20.09	22.03	20.12	90	90.5	0
19.57	22.06	20.17	91.5	91.3	0
19.14	21.99	20.14	93	89.9	0
18.73	21.79	20.09	93	91.0	0
18.30	21.91	20.19	93	93.4	0
17.97	21.81	20.19	94.5	92.0	0
17.76	21.71	20.14	96	94.0	0
17.80	21.89	20.31	96.5	96.6	0
17.83	21.67	20.22	97	96.6	0
17.83	21.69	20.24	97	97.4	0
17.79	21.79	20.39	97	99.4	0
17.79	21.62	20.29	96.5	98.9	0
17.75	21.22	20.09	96	96.1	0
17.71	21.17	20.09	95	96.3	0
17.62	21.13	20.12	94	95.7	0
17.58	21.08	20.12	92.5	95.3	0
17.49	21.05	20.12	91	95.4	0
17.38	20.95	20.09	88	95.1	0
17.38	20.88	20.07	85	94.1	0
17.26	20.71	20	72.5	93.3	36
17.46	20.39	19.82	70	92.2	154.8
17.91	19.52	19.27	62.5	86.4	406.8
18.48	18.69	18.79	55	79.6	826.56
19.51	17.31	17.93	47.5	60.0	1669
20.48	17.66	18.59	40	63.2	2251.4
22.39	17.28	18.61	37.5	47.3	2572.6
23.78	17.76	19.02	35	41.5	3114.7
25.39	18.21	19.57	34	37.2	2992.3
26.34	19.69	20.24	33	46.7	2890.8
28.36	19.09	20	34	37.1	3003.1
30.10	18.69	19.89	35	38.7	3843.4
31.59	20.29	20.71	32.5	43.4	2800.8

07/02/03 14:00	25.97	26.72	26.51
07/02/03 14:30	24.44	26.89	26.6
07/02/03 15:00	25.89	32.98	29.09
07/02/03 15:30	24.66	24.51	25.74
07/02/03 16:00	27.66	37.01	28.08
07/02/03 16:30	25.7	23.41	24.12
07/02/03 17:00	24.59	26.38	22.85
07/02/03 17:30	22.03	22.31	23.39
07/02/03 18:00	21.1	18.40	21.17
07/02/03 18:30	19.84	15.36	19.19
07/02/03 19:00	19.19	16.78	18.61
07/02/03 19:30	18.59	16.19	18.21
07/02/03 20:00	18.19	13.38	16.98
07/02/03 20:30	16.85	14.21	16.73
07/02/03 21:00	16.25	15.50	17.08
07/02/03 21:30	15.32	12.94	15.82
07/02/03 22:00	15.1	11.31	14.79
07/02/03 22:30	14.07	10.93	14.29
07/02/03 23:00	13.84	10.66	13.91
07/02/03 23:30	14.69	10.09	13.24
07/03/03 00:00	13.24	9.83	12.96
07/03/03 00:30	12.93	11.92	13.26
07/03/03 01:00	14.04	13.31	14.24
07/03/03 01:30	14.17	13.58	14.72
07/03/03 02:00	13.74	13.68	14.54
07/03/03 02:30	13.76	13.93	14.57
07/03/03 03:00	13.76	13.99	14.79
07/03/03 03:30	13.76	13.95	14.59
07/03/03 04:00	13.61	13.86	14.59
07/03/03 04:30	13.69	13.84	14.54
07/03/03 05:00	13.71	13.70	14.34
07/03/03 05:30	13.54	13.66	14.29
07/03/03 06:00	.13.66	13.50	14.19

30.41	20.76	20.66	30	48.0	1030.3
29.59	19.84	19.59	34	46.8	2188.1
30.63	19.89	19.52	38	42.3	2792.2
29.70	21.84	21.05	39.5	48.4	1830.2
29.59	20.39	19.44	41	39.8	1510.6
28.53	22.18	20.81	43	54.0	842.4
27.36	19.74	18.96	45	60.0	947.52
26.47	20.9	19.52	47.5	61.8	559.44
25.34	22.16	20.46	50	66.6	122.4
24.37	23.02	20.85	60	73.7	35.28
23.50	22.89	20.63	70	74.6	0
22.77	22.8	20.46	77.5	77.2	0
22.21	23.04	20.61	85	84.7	0
21.73	22.85	20.49	89	85.4	0
21.37	22.57	20.29	93	83.0	0
20.99	22.7	20.36	93	86.8	0
20.47	22.85	20.54	93	94.0	0
20.08	22.8	20.54	94	94.7	0
19.65	22.77	20.56	95	95.8	0
19.18	22.67	20.54	94	97.4	0
19.06	22.6	20.54	93	98.1	0
18.81	22.4	20.46	94.5	98.1	0
18.51	22.03	20.24	96	93.9	0
18.44	21.91	20.22	96	93.1	0
18.41	21.86	20.24	96	92.5	0
18.34	21.86	20.34	95.5	92.5	0
18.26	21.76	20.27	95	92.4	0
18.25	21.74	20.31	94.5	92.3	0
18.19	21.71	20.36	94	92.6	0
18.03	21.64	20.34	94	92.6	0
17.95	21.59	20.36	94	92.8	0
17.90	21.57	20.41	92	92.6	0
17.86	21.52	20.39	90	93.2	0

07/03/03 06:30	13.14	13.55	14.24
07/03/03 07:00	14.14	13.79	14.34
07/03/03 07:30	14.64	15.20	15.27
07/03/03 08:00	15.52	17.46	16.3
07/03/03 08:30	16.78	19.99	18.06
07/03/03 09:00	15.97	20.45	19.14
07/03/03 09:30	19.44	30.58	24.44
07/03/03 10:00	19.72	32.85	25.74
07/03/03 10:30	19.82	27.42	23.78
07/03/03 11:00	21.64	24.30	23.43
03/07/03 11:30	23.21	38.69	30.07
03/07/03 12:00	22.5	26.58	25.62
03/07/03 12:30	26.11	38.66	29.72
03/07/03 13:00	23.26	41.92	32.07
03/07/03 13:30	23.9	41.85	31.66
03/07/03 14:00	25.06	31.36	29.41
03/07/03 14:30	25.67	34.10	29.77
03/07/03 15:00	25.38	38.08	31.27
03/07/03 15:30	24.37	33.42	30.02
03/07/03 16:00	24.39	36.91	30.31
03/07/03 16:30	24.59	32.49	27.64
03/07/03 17:00	22.48	29.47	25.23
03/07/03 17:30	21.67	21.46	22.43
03/07/03 18:00	21.1	20.36	21.59
03/07/03 18:30	18.46	18.77	20.17
03/07/03 19:00	17.63	18.32	19.47
03/07/03 19:30	17.63	17.52	18.61
03/07/03 20:00	16.4	17.07	18.31
03/07/03 20:30	15.77	14.70	17.26
03/07/03 21:00	15.37	14.57	16.73
03/07/03 21:30	16.1	12.50	15.55
03/07/03 22:00	16	13.39	15.8
03/07/03 22:30	15.77	12.20	14.67

17.80	21.42	20.34	82.5	93.1	0
17.64	21.4	20.34	75	92.8	0
16.98	20.95	20.07	60	91.5	58.32
18.14	20.46	19.82	55	87.7	306
19.65	20.17	19.62	50	81.8	342.72
20.88	19.19	19.14	45	78.3	843.84
22.10	18.54	18.91	46.5	49.6	1166.4
23.70	17.88	18.44	48	49.1	1963.4
23.80	18.39	19.17	49	58.7	3135.6
24.95	20.81	20.66	50	58.9	946.8
26.25	19.79	20.41	40	39.4	3226.3
27.55	19.24	20.14	30	48.3	3376.8
28.62	20	20.81	32.5	37.9	2821
29.45	19.89	21.3	35	37.4	3700.8
28.74	21.27	22.28	35	36.9	3565.4
29.51	20.85	21.27	35	40.8	2501.3
30.43	20.66	20.73	38.5	40.5	2535.1
29.55	21.44	21.91	42	37.2	2534.4
29.19	20.83	20.29	43.5	39.1	2342.9
28.47	22.23	21.64	45	38.4	1513.4
27.73	22.55	21.4	56	43.1	1260
27.21	22.26	20.85	67	46.8	1148.4
26.13	22.99	21.49	68.5	57.4	342
25.41	22.94	21.1	70	61.7	198
24.42	22.99	21	72.5	67.8	36
23.29	22.97	20.83	75	70.9	0
22.69	22.97	20.73	82.5	73.8	0
22.18	22.92	20.61	90	75.7	0
21.68	23.02	20.71	92	81.8	0
21.10	23.12	20.68	94	84.4	0
20.61	23.26	20.83	93.5	88.2	0
20.39	23.02	20.68	93	89.0	0
20.13	23.07	20.78	94.5	92.6	0

03/07/03 23:00	15.97	11.69	14.37	19.94	23.02	20.85	95	93.4	0
03/07/03 23:30	15.92	13.96	14.89	19.68	22.7	20.58	94.5	90.5	0
04/07/03 00:00	15.6	11.16	14.14	19.51	22.72	20.68	94	95.1	0
04/07/03 00:30	15.37	11.82	14.07	19.43	22.77	20.78	95.5	96.0	0