PROJECT Title

Experimental investigation and modelling of condensation of a rose crop in a greenhouse in Zimbabwe

By

MICHAEL MUBVUMA

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Agricultural Meteorology

Supervisor:
Mr. E. Mashonjowa

Department of Physics
FACULTY OF SCIENCE
UNIVERSITY OF ZIMBABWE

HARARE, June 2007

Abstract

The main aim of this study was to experimentally determine the conditions when dew forms on leaf surfaces from measured ambient conditions, and to adapt an appropriate vegetative condensation model to describe and predict the condensation of a rose crop in a greenhouse. A vegetation sub-model within the Gembloux Dynamic Greenhouse Climate Model (GDGCM), that offers the possibility to predict whether condensation is present on the leaves of plants in a greenhouse was adapted and validated. Measurements of the leaf wetness were made with different orientations of leaf wetness sensors located above and within the canopy to determine the optimum placement of the sensor for accurate measurements. Measurements were also taken at several places within the greenhouse in order to investigate spatial variability.

All measurements took place in a controlled greenhouse at the Biological Sciences Department, University of Zimbabwe Campus and in a commercial greenhouse at Floraline (Pvt.) Ltd. in Harare. Outside weather data was collected from established automatic weather stations at the sites. Relevant greenhouse meteorological and plant physiological parameters, such as air temperature and humidity, solar radiation, wind speed, leaf temperature, leaf wetness and leaf wetness duration, etc., were measured and together with outside weather measurements were used to calibrate and validate the vegetative condensation sub-model of the greenhouse climate model.

Condensation on the leaf surfaces was observed whenever the relative humidity was high and the canopy temperature of plants in the greenhouse was close to that of the surrounding air. Because of its incorporation of both temperature and humidity in its calculation, vapour pressure deficit (Δe) was found to be a convenient indicator of the condensation potential. Condensation on plant surfaces inside the greenhouse was observed to occur at different vapour pressure deficit thresholds (Δe_{th}), depending on the season and the night temperatures. During summer nights (November-March), the greenhouse air temperature was observed to range from 15°C – 18 °C, and the Δe_{th} was observed to range from 0.1 kPa to 0.27 kPa, corresponding to relative humidity threshold range of 83 % to 87 %. During winter nights, the air temperatures were observed to range from 9°C – 12 °C and the Δe_{th} was observed to range from 0.15 kPa to 0.3 kPa, and was corresponding to relative humidity threshold of 75 % to 80 %. When the greenhouse air temperature was maintained within the range of 22 °C - 25 °C, the Δe_{th} range from 0.2 kPa to 0.45 kPa, corresponding to relative humidity threshold of 84 % - 90 % was observed. Plant temperature was mostly below air temperature during the day and mostly close to air temperature just before sunrise. Comparison of measured and calculated temperatures and saturation deficits in the plant canopy showed a good agreement. In general, night-time air and plant temperatures, calculated by the model, compare quite satisfactorily with the measured temperatures. The comparison with measurements shows that the model allows prediction of condensation to within 82 % of the occasions when dew occurred. The fact that the mean temperature of the plant differs from that of the air and thus produces a quite different saturation deficit has important implications for disease control. The model gives Δe values, which can be used to predict disease-causing climate conditions, while taking into account different temperature levels.

Acknowledgements

I would like to extend my sincere gratitude to my project supervisor, Mr. Mashonjowa, for his tireless technical guidance and moral support which is unparalleled and encouraging. His comments were fruitful, stimulating and enriching.

My profound thanks also go to my scholarship project co-coordinator, Mr. Chipindu, all the MAGM members of staff and all the MSc Agricultural Meteorology students for their friendship and support during the entire course.

I am gratefully indebted to the UZ-Flemish University link program for awarding me a scholarship; their financial contribution in facilitating this research is greatly appreciated.

Last but not least, my heart-felt love and happiness goes to my family; Stanford, Tawanda, Tamare, Teclah and Pheris for their unmeasurable and priceless support in the entire programme.

Dedication

To my Parents

List of Figures

List of Tables

List of symbols and abbreviations

Roman symbols

Symbol	Description	Unit
a	thermal diffusivity	[m^2 s^{-1}]
A_l	Surface area	[m^2]
C	Water vapour content	[kg m^{-3}]
c	heat capacity	[J(kg.K)$^{-1}$]
c'	heat capacity per unit area	[J(m^2.K)$^{-1}$]
d	Characteristic length	[m]
D	diffusion coefficient	[m^{2}s^{-1}]
g	acceleration by gravity	[m s^{-2}]
h	heat transfer coefficient	[W/(m^2 K)]
H	solar time	[hr]
h'	mass transfer coefficient	[m s^{-1}]
i	enthalpy	[J (kg)$^{-1}$]
J	Ventilation setpoint temperature change/unit time	[K/hr]
l	thickness	[m]
k	attenuation coefficient	[m^{-1}]
I/K_ζ	translation factor for parameter ζ	[-]
LAI	leaf area index	[-]
m	mass	[kg]
m'	mass surface density	[kg/m^2]
n	refractive index	[-]
p	fraction	[-]
p'	partial vapour pressure	[Pa]
q	heat flux density	[µmol m^{-2} s^{-1}]
Q_R	heat flux	[W]
q'	mass flux density	[kg/(m^2.s)]
q''	heat developed in a unit volume and time	[W/m^3]
r	mass transfer resistance	[s/m]
$\mathrm{R_a}$	air renewal rate	[hr^{-1}]
R'_a	ventilation rate	[m^3/s]
t	time	[s]
T	absolute temperature	[K]
T_d	dew point temperature	[°C]
$T_{(l)}$	leaf temperature	[°C]
u	air velocity, wind speed	[m/s]
v	specific volume	[m^3/kg]
V	volume	[m^3]
x	distance along the first axis of an orthonormized coordinate system	[m]
x'	absolute air humidity	[kg/kg]
y	distance along the second axis of an orthonormized coordinate	[m]
z	distance along the third axis of an orthonormized coordinate system	[m]

Greek symbols

Symbol	Description	Unit
α	absorptance	[-]
A	absorptance for solar radiation, incl. multiple reflections	[-]
$\acute{\alpha}$	opening angle of the ventilation windows	[^{o}]
β	thermal expansion coefficient	[K^{-1}]
β'	inclination angle	[rad]
γ	elevation angle of the sun	[rad]
δ	boundary layer thickness	[m]
δ'	declination angle of the sun	[rad]
δ''	diffusion conuctance	[m^2/s]
ε	emittance	[-]
λ	thermal conductivity	[W/(m.K)]
λ'	wavelength	[m]
μ	diffusion resistance factor	[-]
v	angle of incidence	[rad]
v'	coefficient of cinematic viscosity	[m^2/s]
ρ	reflectance	[-]
p	reflectance for solar radiation, incl. multiple reflections	[-]
ρ'	density	[kg m^{-3}]
τ	transmittance	[-]
T	transmittance for solar radiation, incl. multiple reflections	[-]
$\acute{\omega}$	hour angle of the sun	[rad]
ψ	degree of saturation	[-]
ψ'	azimuth angle of the sun	[rad]
φ	relative air humidity	[%]
φ	latitude	[rad]
θ	Celsius temperature	[°C]
θ'	Orientation angle	[rad]

Subscripts

a	air
b	bulk fluid
bl	boundary layer
bm	direct (solar radiation)
c	cover
ce	outer cover surface
ci	inner cover surface
cf	condensation
cl	clouds

ct	cuticle
D	conduction
day	day, defined as the period between sunrise and sunset
dc	dry cover
d	diffuse (solar radiation)
e	external air
F	diffusion
Fr	greenhouse frame
g	gas
gr	greenhouse
ha	humid air
heat	heating
HS	heating system
i	internal air
int	internal greenhouse environment
l	lower
L	latent heat transfer
lim	limit
m	middle (with δ:mass)
M	momentum
P	phase change
R	far infrared radiation
s	soil surface
S	solar radiation
sd	solid
set	setpoint
sky	sky, treated as a full radiator
ss	subsoil
st	stomatal
s1, s2, s3, s4	four soil layers
s12, s23, s34	interfaces between the soil layers
s4s	interface between soil layer 4 and the subsoil
T	temperature
Tr	transpiration
U	upper
v	vegetation
V	convection
Vent	ventilation
Vp	vapour
w	water
wd	(ventilation) window
π	parallelly polarized
σ	perpendicularly polarized

Constants

C	light speed in a vacuum	$3.00.10^8$m/s
h	planck constant	$6.63.\ 10^{-34}$J.s
h_{fg}	latent heat of condensation of water	±2500 kJ/kg
k	Boltzmann constant	$1.38.\ 10^{-23}$J/K
R_a	gas constant for dry air	462 J/(kg.K)
R_{vp}	gas constant for water vapour	287 J/(kg.K)
σ	Stefan-Boltzmann constant	$5.67.\ 10^{-8}$ W/($m^2.K^4$)

Dimensionless groups

Bi	Biot number	$\frac{h_{V+R}.d}{\lambda}$
Gr	Grashof number	$\frac{b.g.d^3.\lvert T_{sd} - T_b \rvert}{V'^2}$
Le	Lewis number	$\frac{a}{D}$
Nu	Nusselt number	$\frac{q_V}{\lambda.\frac{T_{sd} - T_b}{d}}$
Pr	Prandtl number	$\frac{V'}{a}$
Re	Reynolds number	$\frac{u.d}{V'}$
Sc	Schmidt number	$\frac{V'}{D}$
Sh	Sherwood number	$\frac{q_{P}'}{D.\frac{C_{sd}* - C_b}{d}}$

CHAPTER 1

BACKGROUND AND JUSTIFICATION

1.1 Economic importance of roses in Zimbabwe

Roses (*Rosa spp*) of the Rosacea family are grown throughout the world under different climatic conditions as as cut flowers in greenhouses and as garden roses outdoors. The ornamental crop provides a valuable source of foreign currency and employment in many African countries. In Zimbabwe, the industry has contributed significantly to the country's foreign currency earnings and has a projected annual growth of 20 %. Roses are grown by commercial producers, intensively in farms which are located around Harare. The country's climate is conducive to a broad spectrum of different types of roses (Davies, 2000).

Recently, the county's monetary authorities have identified the floriculture industry as a highly export-oriented sector, with close to 100 per cent of commercially grown flowers finding their way into foreign markets. The industry has also been viewed as an extremely fast growing sector, when compared to other Zimbabwean exports and in terms of its rise in its world share of the cut-flower market. For example, between 1990 and 1997, the US$ value of cut-flower exports increased by an average of 87 per cent per year. In the year 1995, the country was reported to be the third largest supplier of roses to the European Union (Liemt, 1998). By the year 2000, Zimbabwean floriculture industry had grown to be the second largest exporter of cut-flowers in Africa after Kenya (Davies, 2000).

Among the total flowers grown in the country, roses constitute approximately 70% of Zimbabwe's flower exports (Sembja and Mbelwa, 1999, Davies, 2000). The hectrage of roses under cultivation in the country has enormously increased over the past years, mainly as a result of the exponential growth rate that has been registered in the 1980s and late 90s. Currently the industry has over 1600 ha of land under rose cultivation.

Roses have the advantage of having an international market, and provide the needed foreign currency in to the country. In addition, roses are not affected by subsidies that have been a problem in the cotton industry for example. The market for roses is readily available locally and international through the auction system. Both skilled and unskilled labour is readily available locally. It is clear that the floriculture industry is vital in the discourse of the country's economic recovery. However, more research is still required in the area of disease control so as to achieve successes of the industry (Davies, 2000).

Recently the rose industry has been affected by fungal diseases to the detriment effect of efficient development of a quality product (Anon, 1998). The three important fungal diseases namely powdery, downy mildew, and botrytis blight have been identified as the biggest challenge in the rose pathology sector. Currently, roses are chemically sprayed everyday so as to control the above mentioned diseases. Infestation and development of the diseases is proliferant especially under greenhouse conditions where moisture from condensation is often available. Therefore, it is imperative to understand the environment of the greenhouse in relation to disease control, as will be outlined below.

1.2 Greenhouse and disease control

The understanding of environmental conditions in a greenhouse is very important for the timely management of roses, especially under conditions of high humidity and cool temperatures which are commonly experienced in the greenhouse at night (Yang, 1995). Epidemics occur in warm and humid conditions, which favour infection, and may predispose the host to become susceptible. High relative humidity in the greenhouse and free moisture on plant surfaces are considered the most important environmental factors which influence infection by most pathogens (Shtienberg and Elad, 1996).

In Zimbabwe, diseases present a serious hazard to the production of quality greenhouse crops. Fungal diseases such as botrytis, downy mildew and powdery mildew are common in greenhouse crops, and can account for a crop yield loss of up to 50%, when conditions favourable for their development occurs (Shtienberg and Elad, 1996). For the majority of pathogenic fungi and bacteria, development and infection requires wet vegetation, i.e. a film or drops of water on plant surfaces (Epton and Richmond, 1980). Surface wetness of greenhouse crops results mainly from condensation, which occurs when the surface temperature becomes lower than the dew point of the air. This moisture promotes the germination of fungal pathogen spores. Avoidance of foliar wetting can therefore significantly reduce plant damage by both bacterial and fungal pathogens (Elad and Shtienberg, 1995, Shtienberg and Elad, 1996)

Cultural and meteorological crop protection measures, with limited use of chemicals, can be a powerful means to suppress plant pest and diseases in a greenhouse. Such measures are usually aimed at altering the microclimate in the canopy and around susceptible plant organs. It is therefore important to determine the critical environmental conditions under which dew starts to accumulate on the plant surfaces and the period when it completely evaporates from the leaf. The study will provide information to help control of plant diseases.

A dynamic greenhouse climate model; the Gembloux Dynamic Greenhouse Climate Model (GDGCM) within the Transient System Simulation program (TRNSYS), has been adapted to describe and quantify the microclimate in typical Zimbabwean greenhouses in relation to the outside environment (Mashonjowa, 2001). The model offers the possibility to predict whether condensation is present on the leaves, but has only been used with tomatoes (Pieters, 2002). Therefore, this study also seeks to adapt and validate an appropriate vegetative condensation model to describe the condensation of a rose crop in a greenhouse so as to solve the problem which is outlined below.

1.3 Problem statement

The major constraint faced by all commercial rose farmers in the production of flowers in a greenhouse is the control of three important diseases which are botrytis, downy mildew and powdery mildew. Crop yield losses of up to 50% have been recorded as a result of the mentioned diseases. Use of chemicals in controlling the diseases has been discouraged because of increase in costs and their environmental side effects. A cultural approach to disease control based on monitoring the leaf wetness using micrometeorology parameters, and sensors has been identified as a solution to the problem. However, the solution still needs to be introduced to the Zimbabwean environmental conditions through timely monitoring the conditions when condensation occurs on plant leaves under different temperature and humidity levels, and hence the justification of this study.

1.4 Justification

Over the years, studies on the microclimate of a greenhouse, when considered as a relatively homogeneous entity have been done and seem to be well understood (Jewett and Jarvis, 2001). However, control of the microbial activities (pathogens) in the boundary layer on the phylloplane is poorly understood, and cultural disease escape measures are not yet incorporated into automatic environment control systems. In some cases where research on crop disease protection on roses in a greenhouse has been done, the studies have been found limiting and not exhaustive for a full understanding of the leaf wetness management on diseases control using micrometeorology. No research has modelled condensation development in rose plant leaves using meteorological parameters. Therefore, this research work is expected to fill the missing gap through experimentally determining and forecasting the conditions when dew forms on leaf surfaces from measured ambient conditions.

1.5 Aims and Objectives

The overall aim of the study is to investigate ways of improving environmental management in Zimbabwean greenhouses.

The specific activities are to:

a) Experimentally determine and predict the conditions under which dew forms on leaf surfaces from measured ambient conditions;

b) Adapt an appropriate vegetative condensation model to describe and predict the condensation of a rose crop in a greenhouse.

c) Monitor greenhouse and leaf conditions to provide data for calibrating and validating the model.

1.6 Expected Benefits

The use of dynamic models to describe the greenhouse climate and the condensation of crops should help in the forecasting of microclimatic conditions and prediction of disease epidemiology for greenhouse crops. Economic benefits are expected through reduced loss to disease and a reduced need for fungicide treatment for disease control on greenhouse roses.

1.7 Project Layout

The project is made up of six chapters. The first chapter is the introductory topic, and outlines the problem statement and the objective of the study. Chapter 2 includes the literature review relevant to the study and an overview of the Gembloux Dynamic Greenhouse Climate Model (GDGCM). The materials and the methods used in the study are outlined in chapter 3. Chapter 4 lays out the results obtained and also the discussion on these findings. Chapter 5 summarizes the results before the conclusion and recommendations are made in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In line with the main objective of the study, which is to experimentally determine and predicts the conditions when dew forms on leaf surfaces from measured ambient conditions, the literature review was structured to include the physics of the greenhouse, which explains the energy and mass balance inside the greenhouse. Sources of moisture on plant leaves in a greenhouse were reviewed first before looking at the vapour balance inside the greenhouse. The GDGC model to be adapted was outlined so as to enhance the knowledge on how the model operates. However, before looking at the greenhouse physics and the crop microclimate, it was seen imperative to review the previous work that has been done recently so as to understand all possible areas of improvement.

2.2 Previous work on modelling leaf wetness

In general, the presence of wetness on the plant surfaces above a minimum duration provides the free water required by pathogens to germinate and infect foliar tissue (Wallin, 1967, Kim *et al*, 2004, Magarey *et al*., 2004, Magarey *et al*., 2006, Sentelhas *et al*, 2006). Leaf-surface wetness, produced by dew has been one of the most significant agro meteorological pest-promoting factors that trigger fungal and bacterial plant diseases in a greenhouse (Schuh, 1993, (Magarey *et al*., 2006). Most phytopathological models uses leaf-wetness parameters in combination with other factors in order to assess the infection risk and severity of diseases, so as to manage and control their development in an efficient way (Sentelhas *et al*, 2006). Surface wetness is important for many agricultural and environmental applications including plant disease management, the deposition of atmospheric pollutants and the survival of some arthropods (Magarey *et al*., 2006)

Intensive research has been done on modelling leaf wetness for disease control on foliar plants in a greenhouse. One literature review listed at least 16 models capable of simulating surface wetness (Huber and Gillespie, 1992). Disappointingly, most of these researches were concentrating on horticultural crops other than roses, and this has left the rose industry with the only option of spraying chemicals daily so as to control the fungal and bacterial diseases. Recently, the Gembloux Dynamic Greenhouse Climate Model (GDGCM) was developed and has been tested and used in tomato plants. Although, there are possibilities of adapting this same model to rose plants, no model has been developed specifically for monitoring leaf wetness in roses, particularly for the tropical environment use (Mashonjowa, 2001).

Models based on environmental-physics have been developed and used to model dew development on leaf surfaces of different crops (Huber and Gillespie, 1992, Pedro and Glillespie, 1982a,b, Rao *et al*., 1998 Kim *et al*. 2002, and Kim *et al*, 2004). These models use the energy budget method that drives condensation and evaporation of water from the plant leaves by calculating latent heat flux of that particular area (Anderson *et al*., 2001, Kim *et al*. 2002, Papastamati *et al*., 2003, Kim *et al*, 2004). The most important advantage of the models based on environmental physics approach is that, the model's mathematical computations are representations of the physical principles; they can be utilized wherever the required input weather data is available (Kim *et al*, 2004).

Empirical models have also been developed and validated as alternatives to Physical models (Francl and Panigrahi, 1997, Chtioui *et al*., 1999, Kim *et al*., 2002 and Kim *et al*., 2004). Wilks and Shen (1991) developed an empiracal model based on the statistical relationships between weather variables and leaf wetness. Although Wilks and Shen's empirical studies were successful, researchers such as Papastamati *et al*. (2003) have considered physical models to have a general applicability on different environmental sites than statistical models, which tends to be more accurate only at the site where the data comes from.

Kim *et al*, (2004) developed and validated an empirical Fuzzy model based on the fuzzy logic, using the hourly weather measurements at 15 sites in the U.S. Magarey *et al*., 2006). The Fuzzy model incorporated both energy balance principles and empirical computation methods in a fuzzy logic system. A comparison of the Fuzzy model and the CART/SLD/ Wind model, which is an empirical model that used the same weather variables showed that the Fuzzy model classified presence or absence of wetness more accurately than the CART/SLD/WIND model.

Pedro and Gillespie (1982 a, b) have also developed a leaf wetness model, which has been successfully applied by several authors. However, the weakness to the model has been its failure to rely on locally available meteorological data only in its forecasts. Papastamati *et al* (2003) also modelled leaf wetness duration during the rosette stage of oilseed rape. This later model appeared different from the single layer energy budget approach which has been used in the past, and has the advantage of being simple and relying on locally available meteorological data. However, the model has been found limiting when it tends to underestimate leaf wetness duration by about 0.5h (Papastamati *et al*., 2003).

Having looked at the previous work on modelling leaf wetness and its duration, it is important to review the physics and microclimate inside the greenhouse so as to understand the conditions which are likely to cause dew development inside the greenhouse.

2.3 The greenhouse physics and the crop microclimate

Greenhouses are a means of overcoming climatic diversity, using a free energy source, which is the sun (Hanan, 1998). Considerable research has shown microclimatic differences between the greenhouse environment and the outdoor climate (Jewett and Jarvis 2001). Variations also exist between the canopy microclimate for a rose crop and the air inside the greenhouse. Development of dew inside the greenhouse is a function of the mass and energy balance of the greenhouse microclimate. Therefore, it is important to review the literature on the mass and energy budget in the greenhouse in the paragraphs below.

2.3.1 Radiation energy in a greenhouse

Radiation refers to the continual emission of energy from the surface of all bodies of a given temperature (Bakker *et al.,* 1995). It is energy that propagates through free space or through a material medium in the form of electromagnetic waves. It is the main input energy in the green house structure (Pasipanodya, 2005). The heat from the sun excites or disturbs electric and magnetic fields, setting up a wave-like activity in space exhibit characters of both electric and magnetic fields. The electromagnetic Radiation can be described in terms of a stream of mass-less particles that travel at the speed of light in wave-like patterns (3×10^8 m/s). Radiation is in different forms, and can be distinguished by their wavelength, frequency and also the levels of energy found in their photons. The important types of radiation in a greenhouse structure can be classified as shortwave and or longwave radiation (Hanan, 1998). These radiation types are discussed below.

2.3.1.1 Shortwave radiation

Shortwave radiation is radiation emanating from the sun in the wavelength band of 0.3 to 3 μm. It is this type of radiation that is most significant in a greenhouse structure because it determines the fraction available for crop growth and development as well as influencing the energy and mass balance of the greenhouse air, crop and the media (Hanan, 1998). Previous research has shown that 70% of the solar radiation that penetrates the greenhouse is used for transpiration by plants, while 10% is utilized for photosynthesis process (Wang and Boulard, 2000; Mashonjowa, 2001).

The radiometric properties of the greenhouse cover influence the microclimate inside the greenhouse because they determine the amount of energy that enters the greenhouse to warm the air and also the energy losses from the greenhouse. The radiation transmittance of a greenhouse cover varies with the following factors: (Monteith and Unsworth, 1990; Hanan, 1998).

- wavelength and incidence angle of the radiation reaching it
- The refractive index of the material and its extinction co-efficient
- The shape and height of the structure
- Design of superstructure
- Slope of the roof, orientation (i.e. N-S or E-W)
- Time of the day and year
- Proportion of diffuse and direct radiation
- Latitude of the structure; and
- The general climatic conditions of the area

2.3.1.2 Thermal radiation (Longwave radiation)

Long wave radiation is energy emitted by the earth-atmosphere system. It is radiation emitted by the atmosphere or by bodies at temperatures above zero Kelvin. Thus radiation, if originating from the ground is referred to as terrestrial radiation (Duffle and Beckman, 1991). The energy is better explained by the Stefan Boltzmann's law

$$(Q_{LR} = \varepsilon\sigma T^4) \qquad (2.1)$$

Where: ε is the emissivity

σ is the Stefan-Boltzmann constant

T is the absolute Kelvin temperature of the body.

Q_{LR} is the heat flux due to longwave radiation.

A direct effect of longwave radiation on the condensation process is evident in a greenhouse. Long longwave radiation on leaf surfaces when compared to the surrounding greenhouse air tends to promote condensation process (Hanan, 1998). This usually occurs under clear night skies which promotes maximum energy losses so that leaf temperature will be lower than the air temperature. It is under such conditions that condensation will take place. However, radiation is only one of the three methods of heat transfer, it therefore important to look at the other two methods in which heat is transferred inside the greenhouse, so as to relate the temperature difference between the greenhouse air and the plant leaves. These methods of heat transfer include conduction, and convection, and are outlined below.

2.3.2 Conductive heat transfer process in a greenhouse

Conduction is the mechanism of transport of energy in a resting medium. The mechanism, in itself is on a molecular scale, but for overall calculations the process is considered at a macroscopic scale in measurable quantities (Bakker *et al.,* 1995). Conduction involves the exchange of kinetic energy among molecules or atoms between two different parts of an object. In a greenhouse, the process occurs in the soil and green house cover materials. In general, energy flows from high to low temperature for all mechanisms. For conduction not only the change in temperature is taken into account but also the distance over which the temperature changes (Bakker *et al.,* 1995). The flux density, which is the amount of heat energy transferred per unit distance in a specified direction, across a unit area and a normal temperature gradient to the surface is expressed by the empirical law of Fourier as:

$$Q_D = h_D \left(T_2 - T_1\right) \qquad (2.2)$$

where:

Q_D is the conductive heat flux density (W m^{-2})

(T_2 –T_1) is the temperature gradient (K)

h_D is the conductive heat transfer coefficient and is calculated using the equation below:

$$h_D = \frac{\lambda}{l} \qquad (2.3)$$

where λ is thermal conductivity (W m^{-1} K^{-1}) and *l* is the thickness (m) (Bakker *et al.,* 1995).

2.3.3 Advection and convection heat transfer process in a greenhouse

Advection is the transport of energy and mass by a flow from one place to the other in the direction of flow. In a greenhouse, the ventilative exchange of energy and mass is transport by advection (Bakker *et al.,* 1995). Convection may be defined as the transfer of heat and mass by moving air (Monteith and Unsworth (1990). It is a mechanism by which transport of energy is by a flowing medium in the flow direction or between a resting medium and a flowing medium (Bakker *et al.,* 1995). The method is more efficient in transferring heat energy over longer distance when compared to conduction. Convective heat transfer from a plant leaf surface can be described by the following equation: (Monteith and Unsworth, 1990)

$$Q_v = K \frac{(T_S - T)}{\delta} \qquad (2.4)$$

where Q_v is convective heat transfer

K is the thermal conductivity of the fluid,

Ts is the plant leaf surface temperature,

T is fluid temperature; and

δ is an equivalent laminar boundary layer of uniform thickness

There are two types of convective transfer, forced and free convection. Forced convection is transfer through a boundary layer of a leaf surface exposed to an air stream, proceeding at a rate, which depends on the velocity of the flow (Monteith and Unsworth, 1990). This method of convection is defined by the Reynold's number (Re), or the Nusselt's number (Nu). The Re defines the boundary layer thickness for momentum and is expressed as the ratio of inertial to viscous forces. The Nu depends on the rate of heat transfer through a boundary layer from a surface, which may be either hotter or cooler than the air passing over it.

Free or natural convection involves the airflow within the greenhouse as a result of density differences brought about by a temperature differential (Pieters, 2002). Natural convection can be described by Grashof number (Gr) or Nu as a function of Gr and the Prandtl-number (Pr). Gr is a non-dimensional group and is dependent on the ratio of the product of the buoyancy and inertial forces to the square of the viscous forces (Pieters, 2002). In a greenhouse, local air velocities are in the order of 0.3 ms^{-1} ($Re = 10^4$) and the temperature differences of about 10 K ($Gr = 10^{10}$), so it can be expected that natural convection is the prevailing form of heat transfer. Forced convection can be expected on the outside of a greenhouse (Bakker *et al.,* 1995).

Having looked at energy fluxes as important forms of energy inside the greenhouse, it is imperative to review the vapour balance in the greenhouse, so as to relate the effect of radiation and temperature on the vapour state in the greenhouse. Therefore the following paragraphs will focus on the moisture in a greenhouse and the vapour balance.

2.4 Moisture in a greenhouse and the water vapour balance

2.4.1 Sources of moisture on plant leaves in a greenhouse

The main source of liquid water on plant leaves in a greenhouse other than irrigation water is dew. Dew is prevalent when conditions favourable for condensation process are in place in the greenhouse. However, reports have pointed out the existence of water on plant surfaces at night under conditions that can not be conducive to dew formation (Rosenberg *et al*, 1983).

Noffsinger (1965) reported that phenomena other than dew can be involved as sources of plant leaf surface moisture. Liquid water seen on plant surfaces may be irrigation residual water, or dew (the deposit of vapor condensed from the air on radiationally cold leaf surfaces), or it may be distillation (the condensation of vapor originating from the plant media. Water from guttation (water expressed through the organs of translocation in leaves) may also be another source of liquid water on plant leaves (Rosenberg *et al*, 1983). Therefore, creation of an even drier greenhouse environment is a powerful defence against plant disease (Prenger and Ling, 2000).

2.4.2 Vapour balance in a greenhouse

Humidity describes the amount of water vapour in the air, but this parameter depends strongly on air temperature. The amount of vapour contained in a parcel of air can be quantified in many ways, and some of the ways includes: (Bakker *et al.,* 1995).

- Relative humidity
- Absolute humidity or vapour concentration, which is defined as the mass of vapour per unit volume of air,
- Specific humidity, which is defined as the mass of vapour per unit mass of air.
- And finally, the *e,* which is partial pressure.

Vapour balance in a greenhouse is a function of the greenhouse height, mean vapour content, evaporation, condensation and the greenhouse ventilation. The balance is shown by the equation below (Bakker *et al.,* 1995).

$$h\frac{dx_a}{dt} = E - C - V \text{ (kg m}^{-2}\text{ s}^{-1}\text{)} \tag{2.5}$$

Where h (m) is the ratio of the greenhouse volume to its ground area, that is, the mean height of the greenhouse, and x_a is the mean vapour content of the air within the greenhouse (kg m^{-3}), E is the Vapour flux density, C is condensation and V is ventilation (Bakker *et al.,* 1995).

2.4.3 Vapour pressure deficit in a greenhouse

Vapour pressure deficit Δe is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated. The parameter is best explained by the equation below:

$$\Delta e = e_s - e \qquad (2.6)$$

Where Δe is the vapour pressure deficit, e is the actual vapour pressure and. e_s (kPa) is the saturation vapour pressure ($e_s = 6.100 * 10^2 e^{(\frac{17.3T}{T+237.3})}$) (2.7)

where T is air temperature (K) (Monteith and Unsworth, 1990).

Vapour pressure deficit functions as a convenient indicator of the condensation potential because it quantifies how close the greenhouse air is to saturation. The parameter can also be used to evaluate the disease threat, condensation potential and irrigation needs of a greenhouse crop.

Higher values of Δe indicate an increased transpiration demand, and this influences how much moisture is transferred from the plant leaves into the greenhouse air. In contrast, very low Δe indicates closer proximity to the dew point, meaning harmful condensation can begin to develop. Vapour pressure deficit (Δe) is an improvement over relative humidity (RH) measurement alone, because Δe takes into account the effect of temperature on the water holding capacity of the air, which roughly doubles with every 20 degrees Celsius increase in temperature (Prenger and Ling, 2000). Therefore, rather than giving a relative measure of the water content of the air, Δe gives an absolute measure of how much more water the air can hold, and how close it is to saturation. In a greenhouse, Δe can be used to identify disease-causing climate conditions. For example, several studies that explore disease pathogen survival at different climate levels reveal two critical values of Δe. Studies have shown that fungal pathogens survive best below <0.43 kPa. Furthermore, disease infection is most damaging below 0.20 kPa. Thus, the greenhouse climate should be kept above 0.20 kPa, to prevent disease and damage to crops (Prenger and Ling, 2000).

A summary of the previous findings on the relative humidity thresholds at several temperatures, which corresponds to the 0.20 kPa disease prevention threshold, is shown in table 2.1 below.

Table2. 1: Relative Humidity thresholds for disease prevention, corresponding to 0.20 kPa (Prenger and Ling, 2000)

Degrees Celsius	Relative humidity Thresholds
10	83.0%
16	89.0%
20	91.5%
30	95.5%

2.4.4 Development of dew on plant leaves

Dew is defined in the Glossary of Meteorology as "water condensed onto grass and other objects near the ground, the temperatures of which have fallen below the dew point of the surface air due to radiational cooling during the night, but are still above freezing."

Dew point temperature is best defined by the equation below:

$$T_d = \frac{237.7 * \log\left[\frac{e_s * rh}{611}\right]}{7.5 - \log\left[\frac{e_s * rh}{611}\right]} \tag{2.8}$$

(www.wrh.noaa.gov/saltlake/projects/wxcal/formulas/vaporPressure.pdf)

Where T_d is the dew point temperature, (^oC)

e_s is the saturation vapour pressure (kPa), and

rh is the relative humidity.(%)

The period during which dew (mm) is deposited and its duration on the foliar plant is of major importance in the pathology of fungus disease (Schuh, 1993). Certain pathogens, for example, can only penetrate the stomata of leaves if they are enveloped in liquid water; others require free water for a length of time in order for the spores to germinate (Blad *et al*., 1978; Weiss *et al*., 1980). For example, studies conducted in West Virginia University, have shown that powdery mildew germination process does not occur under free moisture conditions (Schuh, 1993). In some cases, research has also shown that high relative humidity condition in a greenhouse is also one of the best meteorological methods of controlling powdery mildew.

Baier (1966) found that plants may remain moisture-coated for 12-15 hours, from the onset of dew or distillation. Burrage (1972), in a separate experiment also found that dew can last from 4-14 hours on a wheat crop. The duration of dew on plant surfaces was found to be longer in hot and arid conditions such as in Israel (Lomas, 1965).

2.4.5 Dew point depression (DD)

The dew point depression (DD) is a useful indicator of how moist the greenhouse air is. It is calculated by taking the difference between the temperature of the air the dew point temperature. Lower dew point depression values mean that the air is very moist, and an increased likelihood that condensation may occur. According to Sentelhas *et al*. (2004) dew point depression values under 2^0C can be used as an indicator of dew presence on plant leaves in a greenhouse.

2.4.6 Condensation process in rose plants

Condensation is the liquification of vapour. It is the forming of liquid water from water vapour. On plant leaves in a greenhouse, it takes place when warm, moisture-laden air comes in contact with a colder leaf surface. The condensation process takes place when the leaf temperature is lower than the air temperature ($T_{leaf} < T_{air}$) = *condensation*. If the saturated air in a greenhouse starts to cool, its capacity to hold water vapour would decrease, but the actual amount of water vapour would not change. If the cooling continues, the capacity of the air to hold water vapour would continue decreasing until it could hold no more moisture. At that point, the air would then (by definition) be saturated, and would have reached the dew point temperature. Further cooling below the dew point temperature will result in deposition of a film of dew on the plant leaf surfaces. Practically, this occurs at night particularly when humidity is very high in the greenhouse (Bakker *et al.,* 1995).

Research has shown that at a particular vapour pressure, the dew point temperature depends only on how much water vapour is actually in the air. The more water vapour there is in the air, the high the dew point temperature is. If saturated air cools further (below its dew point) then the air can not hold as much water vapour as it actually contains, and the excess vapour must condense to become liquid water. It is that liquid water and its duration which is of fundamental importance in the development of a disease in roses.

(www.Dew point temperature upper air station reports)

2.5 Evaporation from a wet surface in a greenhouse.

The duration of dew on the leaf surface is a function of a number of factors. The rate at which evaporation takes place within the greenhouse is very important and is also affected by temperature and ventilation of the greenhouse. It is therefore important to examine the process of evaporation and ventilation and temperature inside the greenhouse so as to have a clear understanding on the connection between leaf wetness duration, temperature, evaporation and the ventilation process of the greenhouse (Hannan,1998).

According to Bakker *et al.* (1995), for evaporation from a wet surface to take place in a greenhouse, two conditions have to be met.

- The energy necessary for the phase change has to be brought to the surface.
- The layer of saturated air in contact with the surface has to be constantly removed and replaced by non saturated air. This condition is governed by a conservation law or the surface energy budget equation which state that:

$$R_n - G = H + \lambda E \qquad (2.12)$$

Where R_n is the mean flux density of available radiation (W m^{-2}); H is the flux density of sensible heat transferred between the canopy and the air (W m^{-2}); and λE is the flux density of latent heat due to transpiration (W m^{-2}); λ being the heat of vaporization of water (latent heat in J kg^{-1}); and E is the vapour flux density (kg m^{-2} s^{-1}); G is ground heat flux(W m^{-2}) (Montieth and Unsworth, 1990).

From the surface energy budget equation, the evaporation from a wet surface can be calculated using either the eddy correlation technique or the flux gradient techniques, which include the aerodynamic approach or the Bowen ratio energy balance (BREB) approach. The flux gradient techniques are based on the assumption that the vertical transfer of latent heat (λE) and sensible heat (H) can be expressed in terms of the vertical gradients of vapour pressure and greenhouse air temperature, where the following equations hold:

$$H = \rho CpK_H \frac{\Delta T}{\Delta Z} \tag{2.13}$$

and

$$\lambda E = \lambda \rho \frac{\rho C_P}{\gamma} K_W \frac{\Delta e}{\Delta z} \tag{2.14}$$

Where:

ρ is the density of air

λ is the latent heat of vaporization

C_P is the specific heat capacity of air at constant pressure

K_W is the eddy diffusivity for water vapour (W m^{-2});

K_H is the eddy diffusivity for (W m^{-2});

Δz is the distance (m) between the two sensor readings

Δe is the vapour pressure differences (kPa) between the two humidity sensor readings

ΔT is the air temperature differences (^{o}C) between the two temperature sensor readings

In most cases, evaporation is combined with transpiration, to form evapotranspiration (ET). This combined water loss is calculated by Penman Monteith's equation and is shown below

$$ET = \frac{A}{\lambda} \frac{\delta R_N + c_p \rho_a \frac{(e_s - e)}{r_a}}{\delta + \lambda (1 + \frac{r_c}{r_a})} \tag{2.15}$$

Where:

- A constant to convert units from kg m^{-3} s^{-1} to mm d^{-1} (C = 86400)
- R_N is the mean flux density of available radiation (W m^{-2});
- λ latent heat of vaporisation (J kg^{-1})
- δ slope of the temperature-saturation vapour pressure curve (kPa K^{-1})
- C_p specific heat of air at constant pressure (c_p = 1004.6 J kg^{-1} K^{-1} at normal atmospheric pressure)

- ρ_a density of air
- e actual vapour pressure of the air at 2 m height in k Pa
- e_s saturation vapour pressure for the air at 2 m height in kPa
- r_a aerodynamic resistance in s m^{-1}.

2.6 Ventilation process of a greenhouse

Air exchange through openings of a greenhouse is called ventilation, and is expressed in terms of volumetric flow (m^3 s^{-1}). The driving force of ventilation process is the pressure differences between the two environments, which may be as a result of either an external airflow (wind effect) or temperature differences (Bakker *et a.l,* 1995). Ventilation is one of the most important tools for controlling the greenhouse climate. The air exchanges between the inside and the outside of a greenhouse influences the environmental conditions such as the temperature, humidity and carbon dioxide concentrations that affect the development and production of the crop (Pasipanodya, 2005; Bakker *et al.,* 1995). Two types of ventilation can be distinguished and these are natural and forced ventilation. Natural ventilation is the principal and least expensive method used in greenhouses to prevent excessive temperatures. Pressure differences or natural buoyancy forces cause natural ventilation through ventilators arranged on the sides of the structure, the top or both. Forced ventilation involves the use of fans and or air conditioning systems to drive the circulation of the air (Montieth and Unsworth, 1990).

2.7 Leaf temperature and its effect on condensation in a greenhouse

The understanding of leaf temperature is very important as it determines the conditions necessary for the development of moisture on the plant leaf during the condensation process. The temperature of a leaf determines the rate and amount of dew development, evaporation of dew from the leaf surface, and the temperature which is conducive for disease development on that particular leaf. The leaf temperature is determined by the interplay of a set of environmental variables which includes air temperature, humidity, radiant flux density and wind velocity. The effect of some of the variables has already been discussed above. The temperature of the leaf is also depended on: (Fitter and Hay, 1989)

- Time of the day (regular diurnal variation);
- Month of the year (regular seasonal variation);
- Cloudiness and wind speed (irregular, short-term variation);
- Position in the canopy (e.g. a combination of factors such as” age sun or shade leaves”);
- Height above the soil surface;
- Leaf shape and dimension.

A higher temperature within the plant canopy and around the leaf tends to maintain leaf surface temperature at a level which is above the dew point temperature, and hence preventing condensation process to take place. Conversely, lower canopy temperatures may results in leaf surface temperatures below the dew point temperature. It is at that temperature point when the moisture in the air condenses on the leaf surface to form droplets of free water.

Another close determinant of the temperature of a leaf is the plant canopy structure. The canopy of a rose plant is a complex mosaic of rapidly fluctuating thermal regimes such that each group of leaves does respond to a unique pattern of temperature fluctuation. This variability makes it very difficult to carry out field studies as it affects the exact position upon where measurements ought to be taken. Yang (1995) in his studies on greenhouse micrometeorology and estimation of heat and water vapour fluxes, also found that the big-leaf and perfectly-stirred-tank approximation of greenhouse canopy and air, not only implicitly assumes homogeneity of thermal conditions within and above the canopy, but also nullifies the differences in airflow between these two distinct domains. The air temperature above the canopy may differ from that within the canopy by several degrees Celsius depending on the vertical temperature profile and hence affecting dew development and amount to different positions in the same greenhouse. Therefore, development of dew during condensation and its duration tend to be different within a canopy of the same plant.

2.8 Control of condensation on plant leaves in a greenhouse

A variety of simple and practical methods, which growers can use when reducing greenhouse moisture problems, have already been put in place. These methods includes, heating dehumidification, air circulation and thermal insulation (Prenger and Ling, 2000).

a) Heading

This method relies on raising the temperature of the cold surface so that it stays above the dew point temperature. Electrical wraps, infra-red heaters and warm air blowers are sometimes used for this purpose.

b) Dehumification

This method relies on reducing the relative humidity of the air by drying it or absorbing the moisture out of it. As the relative humidity drops, the dew point temperature is lowered. Surfaces that were previously below the dew point temperature are now above it and condensation does not occur. Desiccants are used for this and work well in a contained area.

c) Air Circulation

This method relies on the continuous supply of air of the same or lower relative humidity than the air in the vicinity of the cold surface. This is a good method to use in conjunction with other methods.

d) Thermal insulation

The method involves insulating the greenhouse so as to minimize heat loss and maintain the greenhouse temperature above the dew point temperature so as to prevent condensation to taking place.

Having looked at the greenhouse physics and the and its effects on the prevailing microclimate inside the greenhouse, a review of the Gembloux Dynamic Greenhouse Climate Model will be outlined in the paragraphs below so as to understand how it simulates the inside climate of the greenhouse.

2.9 The Gembloux Dynamic Greenhouse Climate Model

The Gembloux Dynamic Greenhouse Climate Model (GDGCM) is a dynamic, semi-one dimensional greenhouse climate model, that describes the energy and mass exchanges between several layers. It consists of seven internal layers that form the system: (Pieters, (2002).

- one cover;
- one inside layer;

- one vegetation layer; and
- four soil layers.

The model is also made up of three external layers, which together with solar radiation constitute what are referred to as the boundary conditions for the model. These outside layers are:

- the sky;
- the outside air; and
- the subsoil.

2.9.1 The model

Fig. 2.1 shows the interactive exchanges of energy and mass between the various greenhouse layers.

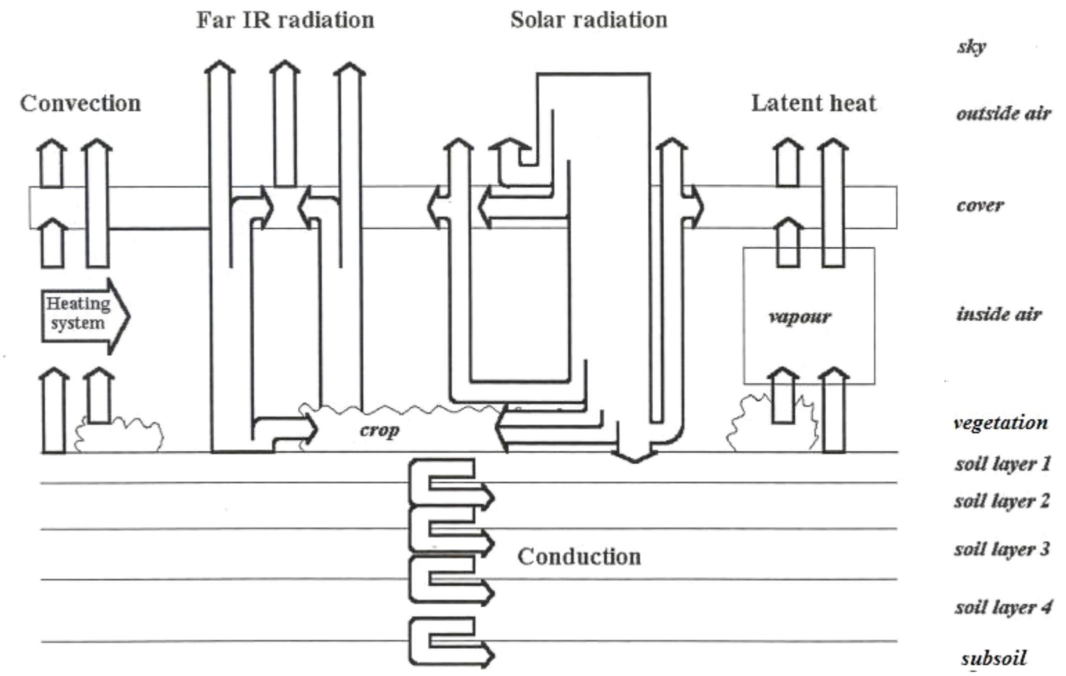

Figure 2. 1 The schematic diagram showing the heat and mass exchanges between the greenhouse layers (Pieters, 2002)

The model incorporates various interactions between the different layers, and this includes heat transfers by conduction, convection, solar radiation and thermal radiation as well as the latent heat exchanges. For the greenhouse cover, heat is gained and lost through absorbed solar radiation, radiative exchange with the sky, the interior of the greenhouse and the soil, convective exchange between the cover and both the greenhouse air and the outside air and latent heat, released by condensation of water vapour within the greenhouse (Pieters and Deltour, 1997 and Wang and Boulard, 2000).

The greenhouse air exchanges heat by convection with the cover, the vegetation, the soil and the heating system (artificial heaters for example). Air exchange with the outside air is by advection and the ventilation process. For the soil, the gains and losses of the energy are through the absorption of solar radiation, radiative exchange with the cover and the crop, and the heating system, convective exchange with the greenhouse air and conductive exchange with the underlying soil layers. To allow the simulation of the effect of control procedures for regulating the inside air, several possibilities of heating and ventilating strategies among which the user can choose are built into the model. (Pieters, 2002; Zhu *et al*, 1998; Hanan, 1998; Pieters and Deltour, 1997 and Wang and Boulard, 2000).

The model has a mass balance for the simulation of the relative humidity of the greenhouse air. For each of the layers, heat loss or gain by solar radiation, far infrared radiation, conduction, convection, ventilation and phase change are described mathematically. Furthermore, a mass transfer equation for water vapour is considered. In this way, a system of eight heat balances for the cover, the inside air, the vegetation and the five soil layer surfaces and one vapour balance for the inside air are obtained. For the greenhouse cover, heat is gained and lost through absorbed solar radiation, radiative exchange within the sky, the inside of the greenhouse and the soil, convective exchange between the cover and both the inside and outside air and latent heat released by condensation of water vapour within the greenhouse Pieters and Deltour, 1997 and Wang and Boulard, 2000).

The GDGCM uses the TRNSYS software for the simulation of the heat and mass transfer process. TRNSYS is a transient simulation programme developed at the Solar Energy Laboratory of the University of Wisconsin-Madison. TRNSYS is a suite of programs designed to simulate transient energy systems. With the current version of TRNSYS (Version 16) users create a text file describing the system being simulated and then launch a FORTRAN program to run it. This TRNSYS programme runs the simulation using the deck files. The deck file consists of several modules, which are described in separate units. A unit refers to a component of the greenhouse system to be simulated such as the air or vegetation. The types in the deck file are FORTRAN subroutines, which can be used for the description of several units. Therefore a type can be used once in a simulation in relation to different units. The deck file should be prepared carefully as in-built control procedures which detect errors in it and prevent simulation runs (Pieters, 2002)

The inputs of the GDGCM include ventilation, outside climate variables, characteristics of the greenhouse, crop and soil; the outputs include inside climate variables, vegetation and soil temperatures and other vegetation characteristics, such as stomatal resistances and whether or not condensation occurs on the leaves. The inputs are read into the programme by means of specific data files. These files normally have a DAT extension such as the CHARACT.DAT or CLIMAT.DAT files that are used in the present version of the GDGCM.

The CHARACT.DAT contains data stored in COMMON blocks such that they can be used anywhere in the programme. Each block contains characteristics of a specific element within the greenhouse. The blocks used in the GDGCM include:

CHRSOIL	block containing some of the soil characteristics
CHRCONSTR	block containing the construction characteristics
CHRAIR	block containing the air characteristics
CHRVEG	block containing the vegetation characteristics
COND	block containing characteristics that are influenced by the processes of condensation and evaporation

The data from the CHARACT.DAT file is read into the model using type 60 (the greenhouse construction data reader).

CLIMAT.DAT contains the external weather data (air temperature, relative humidity, wind speed, total solar radiation and cloud cover). The data from the CLIMAT.DAT file is read by Type 9; the data reader card.

2.9.2 Boundary Conditions

The model has two components: boundary conditions and the greenhouse system. Boundary conditions are found at the limits of the greenhouse system and are independent of the greenhouse environment. Boundary conditions include the sky, outside air and the greenhouse subsoil. The sky forms the upper boundary condition with lower boundary condition being the subsoil. The subsoil tends to have a constant temperature, whose value is assumed to be equivalent to that at the soil depth where there is little temperature variation for small greenhouses whilst with infinitely large greenhouse; it is given as the yearly mean value of the outside air temperature.

The sky interacts with the greenhouse environment through the exchange of radiation. The exchanges of total solar radiation between the sky and greenhouse system can be simulated using the subroutine, Type 16 (solar radiation processor). The simulation of the radiation data is done using the curve for extraterrestrial radiation. Solar radiation should not be simulated linearly because this introduces errors particularly at sunset and sunrise. The simulation of insolation requires two radiation data sets, which in most cases are the global solar radiation and diffuse solar radiation such that the direct solar radiation is obtained as their difference. However, where only the global radiation measurement is available, Type 16 has the provision of simulating the distribution of the solar radiation over beam and diffuse radiation. The selection of the radiation mode to be used in Type 16 is thus dependent on the set of radiation data that is available as input data.

The longwave (far infrared) radiation from the sky is described using its radioactive properties and temperature. In the present version of the model, the radiative properties of the sky are constants whilst the radiative sky temperature, determined by the equation of Swinbank is simulated using Type 61. Type 61 not only simulates the radiative sky temperature but other variables related to the position of the sun such as the beam radiation flux density and the day length (Pieters, 2002).

2.9.3 Greenhouse Layers

The greenhouse layers refer to the components of the greenhouse system which include the cover, air, vegetation and the soil with its sub-layers. The state variables of individual layers can be simulated from their respective heat balances and the mass balance in the case of the greenhouse air. These heat and mass balances are derived in different units. There is an interlinking of these units because the output in one unit may become input in other units. The heat and mass balances for the greenhouse layers will therefore be described in this section (Pieters, 2002).

2.9.4 Cover

In the modelling of the cover temperature, the cover is assumed to have the same temperature on both its inner and outer side of the cover because of its low conducive resistance, which is given a *Bi* critical value of 0.1. *Bi* is calculated as the ratio of the conductive resistance to the combined convective resistance and radiative heat resistance.

The radiative properties of the cover for diffuse solar radiation and thermal radiation are constants whilst those for direct solar radiation are influenced by the angle of incidence.

Radiation is the only method of heat transfer between the sky and the cover or vice versa. Heat transfer through phase change (evaporation of rainfall) has not yet been incorporated in the model.

Condensation is regarded as a rare phenomenon on the outer cover, and it only occurs inside the cover (Pieters and Deltour, 1997).

In the model, the subroutine that calculates the heat balance equation for the cover is Type 62. The heat balance for the greenhouse cover is expressed as

$$C'_{c'}\frac{dT_c}{dt} = \frac{A_{gr}}{A_c}.(q_{v(i,c)} - q_{v(c,e)} + q_{p(i,c)} + q_{R(s,c)} + q_{R(v,c)} - q_{R(c,sky)} + q_{s(c)}) \tag{2.16}$$

where $C'_{c'}$ is the greenhouse cover, A_{gr} is the surface area of the greenhouse, A_c is the surface area of the greenhouse cover, $q_{v(i,c)}$ is the convective heat flux density from the inside air to the cover (Wm^{-2}), $q_{v(c,e)}$ is the convective heat flux density from the cover to the outside air (Wm^{-2}), $q_{p(i,c)}$ is the heat transfer by phase change (Condensation), $q_{R(s,c)}$ is the radiative heat flux density from the soil to the cover (Wm^{-2}), $q_{R(v,c)}$ is the radiative heat flux density from the crop to the cover (Wm^{-2}), $q_{R(c,sky)}$ is the radiative heat flux density from the cover to the sky (Wm^{-2}).

Heat exchange between the cover with the sky, vegetation and soil by radiation is mainly influenced by the radiative properties: absorptivity(α), reflectivity (ρ) and transmissivity (τ) of the respective model components. It should be noted that for diffuse solar radiation, the radiative properties tends to be constant while those for direct solar radiation are dependent on the angle of incidence (Pieters, 2002).

In the model, heat exchange between the cover with the greenhouse air and outside air occurs by convection. Heat exchange by convection is influenced by the characteristics of the air such as its temperature and velocity. It is assumed that air velocity inside the cover is constant and was given a value of 0.3ms^{-1} in this model (Pieters, 2002). The greenhouse cover and the inside air also exchange heat by phase change where water vapour condenses onto the cool greenhouse cover. Condensation is defined in the model by the following equation:

$$P_{cf} = \frac{L_{cf}}{L_{cf,\max}} \tag{2.17}$$

Where P_{cf} is the equivalent water-covered surface factor (wetted fraction of the cover), L_{cf} is the condensate film thickness and $L_{cf,\max}$ is the maximum condensate film thickness.

The presence of condensate increases both the heat capacity and opaqueness of the cover to thermal (infrared) radiation, such that more is trapped within the greenhouse. Where condensation has occurred, the thermal (infrared) radiative properties of the covering material are replaced with those of water α =0.93; ρ = 0.07; τ = 0.

2.9.5 Vegetation

In the determination of heat and mass transfer between the vegetation and other layers of the model, information on the fraction of the greenhouse surface area covered by the vegetation (ρ_v), vegetation mass density (m_v) and the leaf area index (LAI) is required. In the study, ρ_v was calculated for a fully developed crop. In the model, ρ_v value was determined as the total projected area of the vegetation on the soil surface and related to the total greenhouse area. The leaf area index was calculated as a ratio of the total leaf area to total ground surface area. Similarly the vegetation mass density is also expressed with respect to the total greenhouse surface area (Pieters, 2002).

The vegetation covered fraction of the soil, LAI and vegetation mass surface density increase during the growing season until their maximum values are reached. Although these time-dependent changes are not linear, the use of forcing functions (Type 14) by the model forces the time-dependent changes to assume a linear pattern (Pieters, 2002).

The FORTRAN subroutine Type 64 is used for the simulation of the heat balance of the vegetation microclimate variables based on the following equation:

$$C'_{v} \, m'_{v} \, \frac{dT_v}{dt} = q_{v(v,i)} - q_{p(v,i)} - q_{R(v,c)} - q_{R(v,sky)} + q_{R(s,v)} + q_{s(v)}) \qquad (2.18)$$

where m'_{v} is mass density, and C'_{v} is the greenhouse surface cover.

According to equation 2.18, heat exchange by radiation occurs between the vegetation and the cover, soil and sky. The vegetation receives solar radiation from the sky and longwave radiation from the soil whilst in turn losing longwave radiation to the sky and cover. The amount of solar radiation absorbed by the crop will depend on the crop's radiative properties as has been previously mentioned. Here the crop's reflectance ρ_{sv} is assumed to be constant and its value corresponds to that for the soil. The transmittance τ_{sv} of the crop will vary depending on the position within the canopy and is described based on Beer's Law as:

$$\tau_{sv} = (1 - \rho_{sv}).e^{-k_v.LAI} \qquad (2.19)$$

where ρ_{sv} is the reflectance for solar radiation and k_v canopy attenuation coefficient (Monteith and Unsworth, 1990).

Heat energy by convection is assumed to occur on both surfaces of the leaves within the canopy to the inside air. Differences in the orientation of the upper and leaf surfaces results in differences in the convective transfer coefficients.

2.9.5.1 Model of stomatal resistance

In the GDGCM, the leaf stomatal resistance (r_l) was considered to be primarily a function of solar irradiance, vapour pressure deficit, air temperature and the soil/water potential (Jarvis, 1989; Stanghellini, 1987; Baille *et al*, 1994; Kittas *et al*, 1999).

$$r_l = r_{l\,min} \cdot f_1(QS_{int}) \cdot f_2(VPD) \cdot f_3(T_a) \cdot f_4(\Psi) \qquad (2.20)$$

where r_l is the leaf stomatal resistance;

QS_{int} is the solar irradiance incident on the crop;

Δe is the air vapour pressure deficit;

T_a is the air temperature; and

Ψ is the soil water potential;

f_1, f_2, f_3 and f_4 represent dimensionless functions, quantifying the relative increase of stomatal resistance whenever one of the parameters is limiting the exchange rate.

Because the plants are assumed to be always well-watered, the influence of soil plant water potential on r_l is assumed to be negligible (Baille *et al.*, 1994). The surface or canopy resistance is assumed to include most of the characteristics of the leaf stomatal behaviour, so that we can normalize the above equation by the leaf area index, *LAI*:

$$r_s = \frac{r_l}{LAI} = r_{s,min} \cdot f_1(QS_{int}) \cdot f_2(VPD) \cdot f_3(T_a) \qquad (2.21)$$

where r_s is the leaf stomatal resistance. The response of r_s to QS_{int} was estimated using the hyperbolic relationship suggested by Jarvis, (1989) and Stanghellini, (1987).

$$f_1(QS_{int}) = \frac{a + QS_{int}}{b + QS_{int}}$$

where a and b are model-specific parameters determined from experimental data by fitting an algorithm.

(2.22)

The functions f_2 and f_3 were the response functions suggested by Stanghellini (1987) and Baille *et al.*(1994), respectively.

$$f_2(\Delta e) = 1 + \exp\left[c(\Delta e - \Delta e_m)^2\right] \qquad (2.23)$$

when $\Delta e < \Delta e_m$, $f_2(\Delta e) = 1$.

$$f_3(T_a) = 1 + d(T_a - T_m)^2 \qquad (2.24)$$

when $T_a < T_m$, $f_3(T_a) = 1$.

where Δe_m and T_m are the vapour pressure deficit and the temperature of the air, respectively, at which the resistance is minimal.

In the equations above *a*, *b*, *c* and *d* are model-specific parameters determined from experimental data by fitting an algorithm.

$r_{l,\text{min}}$ can be chosen as the average of several lower values of r_l obtained at maximum solar irradiance.

Because the greenhouse conditions are usually such that $T_a < T_m$, $f_3(T_a) = 1$, the canopy resistance can then be written as:

$$r_s = \frac{r_{s\,\min}}{LAI}\left(\frac{a+QS_{\text{int}}}{b+QS_{\text{int}}}\right)\left\{1+\exp\left[c(\Delta e-\Delta e_m)^2\right]\right\} \tag{2.25}$$

where $r_{s,min}$ $\left(=\frac{r_{l,min}}{LAI}\right)$ is the minimum possible value for r_s in conditions of optimal water supply and environment and Δe_m is the vapour pressure deficit at which the resistance is minimal and can be taken to be 2.5 kPa (Baille *et al*, 1994; Kittas *et al*, 1999).

In the GDGCM the whole canopy is treated as a "big leaf" and the transpiration flux density, $T_r'(t)$, expressed per unit area of the ground, is given by (Pieters, 2002):

$$T_r'(t) = h_{Tr}\left[C^*(T_v) - C_a\right] \tag{2.26}$$

where

$C^*(T_v)$ is the saturation water vapour concentration at the temperature of the vegetation, T_v [kg m^{-3}]

C_a is the water vapour concentration of the surrounding air [kg m^{-3}], and h_{Tr} is the transpiration heat flux coefficient, defined for hypostomatal leaves as:

$$h_{Tr} = LAI\left[h_{P1} + h_{fg}\cdot\frac{1}{\frac{h_{fg}}{h_{P2}} + r_s}\right] \tag{2.27}$$

where h_{P1} and h_{P2} are the phase change heat transfer coefficients for the upper and lower faces of the leaves, respectively,

h_{fg} is the latent heat of condensation of water, and

r_s is the canopy stomatal resistance as determined by equation (2.25).

2.9.5.2 Condensation

The model also offers the possibility to verify whether condensation is present on the leaves and fruits, that is whether the vegetation temperature is below the dewpoint of the inside air. To this end, a state variable has been introduced within the model. When condensation is going on, its value is 1; when condensation is not going on (dry leaves or leaves that are drying, but still wet because of condensation in the past), its value is set to 0 (Pieters, 2002). Simulation of condensation inside the greenhouse is based on the vapour pressure deficit *(Δe)* of the air in the greenhouse. See equations (2.6) and (2.7). The model simulates condensation to be present inside the greenhouse when $\Delta e \leq 0.5$ kPa.

2.9.6 Soil surface layer

The soil surface is assumed to form a barrier to the exchange of water vapour and water with the greenhouse air due to the presence of a covering. The assumption is on the basis that most greenhouse floors are covered with a plastic film, concrete or quarry stones are mostly common in commercial greenhouses.

The soil surface has the following properties:

- It receives mostly diffuse solar radiation and will only have one reflectance (ρ_{Ss}) value; that for diffuse solar radiation.
- There is no transmission of radiation in the soil such that the far infra-red radiative exchange between the soil surface and other components of the greenhouse are influenced by its emittance and reflectance properties.
- The characteristic length for the convective exchanges between the soil surfaces and other greenhouse components is taken as the distance between subsequent rows.
- Since it is assumed that all the water vapour that condenses on the soil surface evaporates, the condensate film thickness has no maximum value as in the case of the greenhouse cover.

The heat balance for the simulation of the temperature of the greenhouse soil surface (using Type 65) is as follows:

$$\rho_s.C_s.l_s.\frac{dT_s}{dt} = -q_{v(s,i)} - q_{p(s,i)} - q_{R(s,c)} - q_{R(s,sky)} - q_{R(s,v)} + q_{s(s)} - q_{D(s1)} = 0 \qquad (2.29)$$

Where C_s is the capacity (J kg^{-1} K^{-1}), l thickness (m) and ρ density (kg m^{-3}) and all other terms are as defined before.

2.9.7 Soil sub-layers

The GDGCM divides the soil into four sub-layers so as to increase the accuracy in the simulation of the conductive heat transfer in the soil. The temperature variations within the soil sub layers are still sinusoidal but associated with depth. As a result, the thickness of the lower soil layers should be greater such that they cover the same temperature difference between the upper and lower edges. Each soil layer is thus assumed to be homogeneous with respect to its thermal conductivity, heat capacity and density.

The temperature of a soil sub layer is simulated at its interface with an underlying soil layer. In order to determine the soil temperature, the thermal properties for the interface are calculated as weighted mean values of these characteristics for the two sub layers involved. The weighted factors used in the calculations are the relative thicknesses of the two adjacent layers. The following equations are used for the calculation of the thermal properties at the interface of two soil layers:

$$\rho_{s23} = \frac{l_{s2.}\cdot\cdot\rho_{s2} + l_{s3}\cdot\rho_{s3}}{l_{s2} + l_{s3}} \tag{2.30}$$

$$C_{s23} = \frac{l_{s2.}.C_{s2} + l_{s3}.C_{s3}}{l_{s2} + l_{s3}} \tag{2.31}$$

$$l_{s23} = \frac{l_{s2.} + l_{s3}}{2} \tag{2.32}$$

The conductive heat flux density at the interface of two soil sub-layers (eg, 2 and 3) is simulated using equation (2.29)

$$\rho_{s23}.C_{s23}.l_{s23}\cdot\frac{dT_{s23}}{dt} = -q_{D(s2)} - q_{D(s3)} \tag{2.33}$$

This simulation of the soil layer temperature uses FOTRAN subroutine Type 66 of the present version of the model. However, the assumptions to the model, where the greenhouse is considered to have four soil layers, it is important to highlight the fact that the four soil layers may not be appropriate for a crop in pots or even for row crops with walkways between. Therefore results in this study may be affected by that assumption.

2.9.8 Inside air

The simulation of the air temperature and relative humidity inside the greenhouse is done by FORTRAN subroutine Type 63. The respective heat and mass balance equations involved in the simulation of these state variables are expressed as follows**:**

$$\rho_a c_{i'} \frac{V}{A_{gr}} \cdot \frac{dT_i}{dt} = q_{v(s,i)} + q_{v(v,i)} - q_{v(v,i)} - q_{v(i,e)} + q_{HS} \tag{2.34}$$

$$h_{fg} \frac{V}{A_{gr}} \frac{dC_i}{dt} = q_{p(s,i)} + q_{p(v,i)} - q_{p(i,c)} + q_{L(i,e)} \tag{2.35}$$

where *V* is the greenhouse volume (m^3) and $c_{i'}$ is the water vapour concentration of the inside air (kg m^{-3}) and all other terms are as defined before.

2.9.9 Ventilation system

Ventilation plays an important role in greenhouse in determining the greenhouse microclimate as it influences temperature, humidity and CO_2 concentration. Through ventilation heat and mass are transferred simultaneously by the replacement of inside air by outside air. Ventilation is characterized by the air renewal rate R_a, which expresses the ratio of the total volume of fresh air supplies in one hour to the greenhouse volume. The equations for the convective heat flux density, Q_V, and latent heat flux density, Q_L, can be written (Pieters, 2002; Pieters and Deltour, 1997):

$$Q_V = \frac{R_a}{3600} \cdot \frac{V}{A} \rho_a \cdot c_{ha} \cdot (T_i - T_o) \tag{2.36}$$

$$Q_L = \frac{R_a}{3600} \cdot \frac{V}{A} \cdot \rho_a \cdot h_{fg} \cdot (x_i' - x_o') \tag{2.37}$$

where:

R_a: air renewal rate [hr^{-1}]

c_{ha}: specific heat capacity of humid air [J $kg.^{-1}K$]

x_i': absolute humidity of inside air [kg water vapour/kg dry air]

x_o': absolute humidity of outside air [kg water vapour/kg dry air]

$T_i - T_o$: temperature difference between inside and outside air [K or °C]

V: greenhouse air volume [m^3]

A: greenhouse floor area [m^2]

ρ_a: the density of the air [kg m^{-3}]

h_{fg}: latent heat of condensation of water [kJ kg^{-1}]

The air renewal rate is related to the ventilation rate, G, by the equation:

$$R_a = \frac{3600 \cdot G}{V} \tag{2.38}$$

Usually, the air renewal rate can be measured using the tracer gas technique or the water vapour balance of the greenhouse air for a range of conditions and expressed by regression as a function of wind speed and ventilation window opening angle for a given greenhouse. For some commonly used greenhouse types, however, ventilation functions from literature can be used.

2.9.9.1 Ventilation rate measurement

The tracer gas technique

The ventilation rate can be measured using the tracer gas technique, which is based on the mass balance of natural or artificial constituents of the greenhouse air. Assuming a uniform distribution of the gas in the greenhouse and a perfect mixing with the air, the following relation can be used (Kittas *et al.*, 1999):

$$V \frac{dC_i}{dt} = -G(t)\left[C_i(t) - C_o(t)\right] + F_i(t) \tag{2.39}$$

where:

G: ventilation rate [m^3 s^{-1}]

V: greenhouse air volume [m^3]

C_i, C_o: the inside and outside concentration of the tracer gas [kg m^{-3}]

F_i(t): the rate of supply or removal of the tracer gas (kg s^{-1})

Using equation (2.39) the ventilation rate, and hence the air renewal rate, can be deduced if the inside and outside concentrations of the tracer gas and its rate of supply or removal are known.

Carbon dioxide (CO_2) or nitrous oxide (N_2O) are the most commonly used tracer gases. As N_2O is inert for plants, it can be used in a greenhouse with or without crops whereas CO_2 balance needs an empty greenhouse.

2.9.9.2 The water vapour balance method

The balance of water vapour in the greenhouse air can also be used to deduce the ventilation rate. Assuming a uniform distribution of water vapour in the greenhouse, perfect mixing with the air and that soil evaporation is negligible (justified by the presence of a plastic mulch on the soil surface and the soil cover offered by the crop); the ventilation rate can be calculated from the following relation for the mass balance of water vapour in the greenhouse air (Boulard and Draoui, 1995):

$$\rho' V \frac{dx_i'}{dt} = \rho' G(t)\left[x_o'(t) - x_i'(t)\right] + T_r(t) \qquad (2.40)$$

where:

G: ventilation rate [$m^3\ s^{-1}$]

V: greenhouse air volume [m^3]

x_i', x_o': the inside and outside air absolute humidity [kg water vapour/kg dry air]

ρ': density of air [kg m^{-3}]

$T_r(t)$: the greenhouse crop transpiration rate (kg s^{-1})

For small time steps Equation (2.40) can also be expressed as:

$$\rho' V \frac{\Delta x_i'}{\Delta t} = \rho' V \frac{x_i'(t) - x_i'(t-\Delta t)}{\Delta t} = \rho' G(t)\left[x_o'(t) - x_i'(t)\right] + T_r(t) \qquad (2.41)$$

2.9.9.3 Ventilation Functions

To allow the simulation of ventilation, several ventilation functions, among which the user can choose, are built into the GDGCM (Pieters and Deltour, 1997; Pieters, 2002). For a greenhouse equipped with both roof and side openings the following ventilation function, based on the two driving forces for natural ventilation: thermal buoyancy and wind forces; can be assumed (Kittas *et al*., 1997; Fatnassi, *et al* 2004; Harmanto *et al*., 2006; Katsoulas, *et al*., 2006):

$$R_a = \frac{3600}{V} C_d \left[\left(\frac{A_R\, A_S}{\sqrt{\left(A_R{}^2 + A_S{}^2\right)}} \right)^2 \left(2g\, H_c \frac{\Delta T}{T_e} \right) + \left(\frac{A_T}{2} \right)^2 C_W\, Ue^2 \right]^{0.5} + R_{a,0} \qquad (2.42)$$

where:

V: greenhouse volume [m^3]

C_d: discharge coefficient [dimensionless]

A_R: roof openings area [m^2]

A_S: side openings area [m^2]

g: gravitational constant [$m\ s^{-2}$]

H_c: vertical distance between the midpoint of side and roof openings [m]

ΔT: difference between inside and outside air temperature [K]

T_e: outside air temperature [K]

A_T: total area of vents = $A_R + A_S$ [m^2]

C_w: global wind pressure coefficient [dimensionless]

U_e: wind speed at 4.5 m above ground [$m\ s^{-1}$]

$R_{a,0}$: the air renewal rate (or leakage) when vents are closed (or $A_T = 0$) [h^{-1}]

In greenhouse structures with a chimney, If either ΔT or H_c are small, then the wind effect is much more important than the chimney effect so that:

$$R_a = \frac{3600}{VOL} \left(\frac{A_T}{2} \right) C_d \sqrt{C_W}\, Ue + R_{a,0} \qquad (2.43)$$

To describe the performance of a natural ventilation system in a greenhouse with continuous roof vents only, the dimensionless ventilation function, G(α'), can be used (Boulard and Draoui, 1995, Kittas *et al*., 1999). The ventilation function is defined as the ratio of the actual ventilation rate to the ventilation rate that would occur when the wind blows perpendicularly through the ventilation window openings and is given as:

$$G(\alpha') = \frac{G}{U_e \cdot A_{wd}} \qquad (2.44)$$

where A_{wd} is the total ventilation windows surface area, measured in the plane of the roof [m^2]

G is the ventilation rate [$m^3\,s^{-1}$]

u_e is the wind speed [$m\,s^{-1}$]

α' is the opening angle of the ventilation windows [°]

The following linear expression of Fernandez and Bailey (1992) for the ventilation function was adopted:

$$G(\alpha') = C_1 \cdot \alpha' + C_2 \tag{2.45}$$

where C_1 and C_2 are constants that can be determined statistically from measured data of ventilation rates, ventilation windows surface area and opening angles.

Comparing equations (2.38), (2.44) and (2.45), the air renewal rate, R_a, is therefore related to the ventilation function by:

$$Ra = \frac{3600}{V} \cdot (C_1 \cdot \alpha + C_2) \cdot u_e \cdot A_{wd} \tag{2.46}$$

The temperatures for the periods, which govern the ventilation rate during the course of the day, are calculated under Type 70. These ventilation set point temperatures are determined for six periods of the day, which are related to the sunrise and sunset periods. These periods are defined as:

$$H_{p1} = H_{srise} + \Delta t_{p1} \tag{2.47}$$

$$H_{p2} = H_{srise} + \Delta t_{p2} \tag{2.48}$$

$$H_{p3} = H_{srise} + \Delta t_{p3} \tag{2.49}$$

$$H_{p4} = H_{sset} + \Delta t_{p4} \tag{2.50}$$

$$H_{p5} = H_{sset} + \Delta t_{p5} \tag{2.51}$$

$$H_{p6} = H_{sset} + \Delta t_{p6} \tag{2.52}$$

where H is the hour of the day (hr), Δt is the time interval between the beginning of the period and the moment of sunrise or sunset (hr) and the subscriptions p1, p2, p3, p4, p5 and p6 represent the six ventilation periods with the subscripts srise and sset representing sunrise and sunset respectively.

2.9.10 Running a simulation using the Gembloux Dynamic Greenhouse Climate Model (Pieters, 2002)

The simulation is run with a time step of one minute (Pieters, 2002). This means that for $t_0 = 0$ the weather data for the previous day (2400 hours) is used.

To use the GDGCM the following files should be copied to a separate directory on the hard disk of a PC.

UDGCM.EXE

CLIMAT.DAT

CHARACT.DAT

REPET.DAT

FLORALINE.DEK

To run the simulation, the following steps should be carried out after adjustments to the climate, model characteristics and deck files:

Step 1: run the program UDGCM.EXE

Step2: the following questions appear:

HAS YOUR TRNSYS DECK ALREADY BEEN PROCESSED? (Y, N)

Type N↵

(Note: The symbol↵ stands for ENTER key)

Step 3: the following questions appear on the screen:

WHICH FILE FOR SIMULATION DECK?

Type FLORALINE.DECK (the name of the deck file)

In the deck file, the card reader is told to read the weather data from the CLIMAT.DAT file. The deck configuration will be processed and when no errors are found the simulation starts. If something in the deck file is not correct or if the data file is missing or has errors, the cause of the error can be found in the file EXAMPLE.OUT.

During the first loop of type 60, the file containing the greenhouse, soil and other model characteristics must be specified.

Step 4: the following questions appears:

NAME OF FILE CONTAINING MODEL CHARACTERISTICS:

Type CHARACT.DAT↵

The simulating is then completed and the outputs are written to four output files which are made during the simulation in UNITS 20, 23, 24 and 25. The first output files gives the temperatures of most greenhouse layers as well as the inside air relative humidities. The second one gives most of the variables that are related to condensation and evaporation as well as the heating flux density. The other two files contain most of the other flux densities. These files can be opened in Notepad or exported to a spreadsheet, such as MS Excel, for analysis (Pieters, 2002)

.

2.9.11 Modifying the program

Modifying the simulation program is possible only for those who have the TRNSYS software and a FORTRAN compiler. The present version of the model was originally written for TRNSYS Version 13, but has since been modified to work with Version 16 and Compaq Visual FORTRAN Version 6.6 compiler.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental sites/ location

The experiments were all carried out within Harare, Zimbabwe, at approximately 17.8 °S, 31.1°E and altitude 1483 m. The project included two phases. The first was the experimental phase, during which the conditions when dew forms on leaf surfaces were investigated. It was carried out in an experimental greenhouse at the Biological Sciences Department, University of Zimbabwe. The second phase, of calibrating and validating the vegetative condensation sub-model of the GDGCM, was carried out in a commercial greenhouse at Floraline (Pvt.) Ltd., about 5 km from the University of Zimbabwe campus. The sites are in natural region 2a, which receives an average rainfall amount of 850 mm per annum, and with mean annual temperatures of 19 ^{o}C, which are relatively low for efficient rose production; hence the need to use greenhouses.

3.2 The greenhouses and experimental set up

3.2.1 The experimental greenhouse

The experimental greenhouse was located at the Biological Sciences Department, University of Zimbabwe and was a single-span, Venlo-type greenhouse whose cladding material was single-layered glass. The floor of the greenhouse was concrete. The greenhouse structure and its orientation is shown in Fig 3.1 below. It was oriented North-South, and was divided into two compartments, each with a floor area of 10 m × 12 m. Each compartment was equipped with two air conditioners, an exhaust fan, an electric heater and a humidifier for regulating the air temperature and relative humidity.

Figure 3: 1: The experimental greenhouse at the Biological Sciences Department, at University of Zimbabwe

3.2.1.1 Planting of roses and agronomic operations

Rose seedlings, (cultivar 'Cupido') were planted in 32 uniformly spaced flower pots supported by metal stands, which were 30 cm in height. Two plants were planted in each pot on the 19th June 2006 in a soil less medium (vermiculite). The set up and orientation of roses in the greenhouse is shown in Fig 3.2.

A basal application of compound J fertilizer was done during the planting stage. After 4 weeks other different types of fertilizers were applied once every week in solution with the irrigation water (fertigation). These fertilizers and their application rates are shown in Table 3.1 below.

Weeding was done mechanically using the hand pulling method. Bending process of roses was done in the 4th week after planting. Cutting of flowers was carried out in batches and this entailed the cutting of all stems that had half-open buds. Pest and disease control was done using the normal chemicals in the industry. Localized drip irrigation system was used for watering, and this was done following commercial grower recommendations.

Figure 3: 2: Planted roses in the experimental greenhouse at the Biological Sciences Department, University of Zimbabwe

Table 3: 1 The fertilizer that were applied in the trial (Source: company journals Floraline (Pvt.) Ltd.)

Types of Fertilizers	**Amount in g/ m^3**	**Per 1000 litres**
Tank A		
Potassium Sulphate	115	6325
Ammonium Sulphate	175	9625
Ammonium Nitrate	175	9625
MAP	115	6325
Magnesium Sulphate	115	6325
Iron chelate 7%	70	3850
Tank B		
Magnesium Nitrate	230	12650
Patassium Nitrate	460	25300
Calcium Nitrate	460	25300
BMX Microfeeb	60	3300
Nitic Acid	25	

3.2.1.2 Experimental design and layout

The experimental phase of the study was divided into two parts. In the first part of the study, preliminary experiments were carried out inside the greenhouse in order to investigate the homogeneity of the greenhouse so as to determine the appropriate positions for instruments to measure temperature, humidity and leaf wetness in the greenhouse. These preliminary experiments were carried out using three combined relative humidity, temperature and pressure sensor instruments (serial numbers: 510806927, 510806930, 510806932) respectively. (Fig 3.3) which were placed at different positions within the greenhouse. The sensors were placed at different places longitudinally along the length of the greenhouse and diagonally across the greenhouse compartments at a height of 1.5 m so as to test horizontal homogeneity. Vertical gradients were also investigated by placing the sensors at different heights, at an interval height of 0.5 m from the ground up to a height of 3.5 m. This was achieved by tying the sensors at different marked heights along a 4m long stick. The stick was held vertically at 90^o from the ground and was moved to different predefined positions in the greenhouse after an interval of 30 minutes.

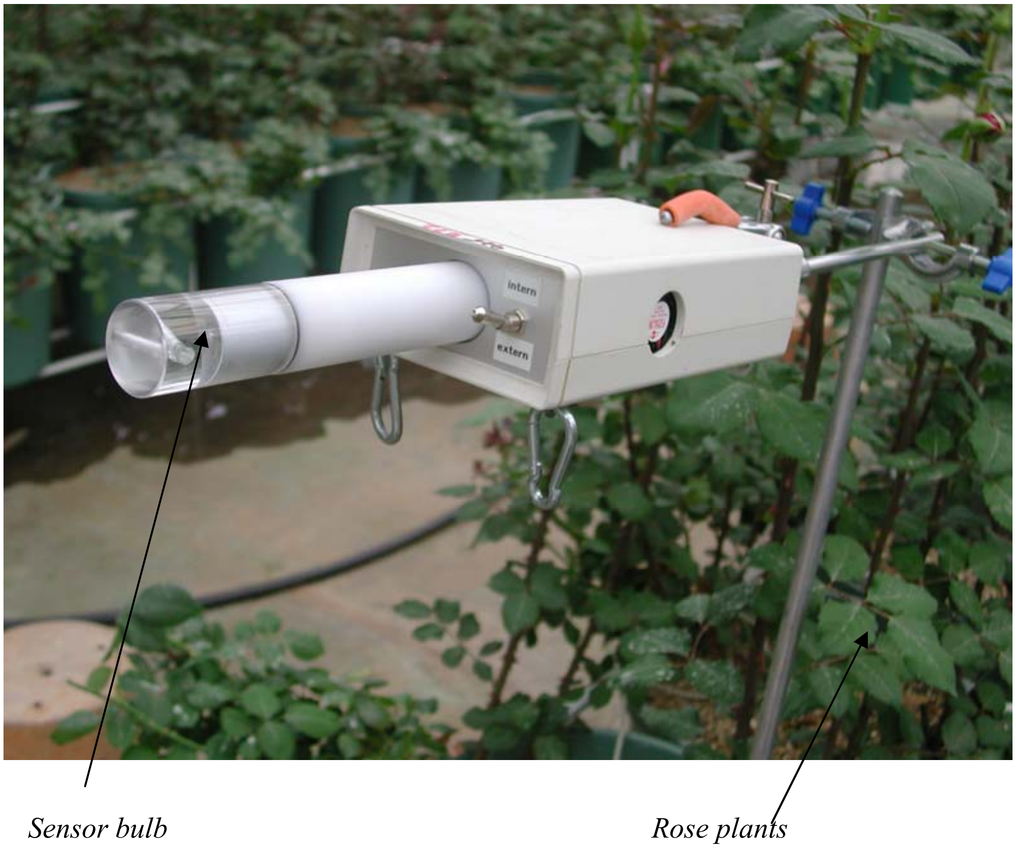

Figure 3: 3: A relative humidity, temperature, and pressure sensor used to evaluate greenhouse homogeneity in the experimental greenhouse at University of Zimbabwe

Final placement of the instruments in the greenhouse as a result of preliminary experiments is shown in Fig 3.4 below.

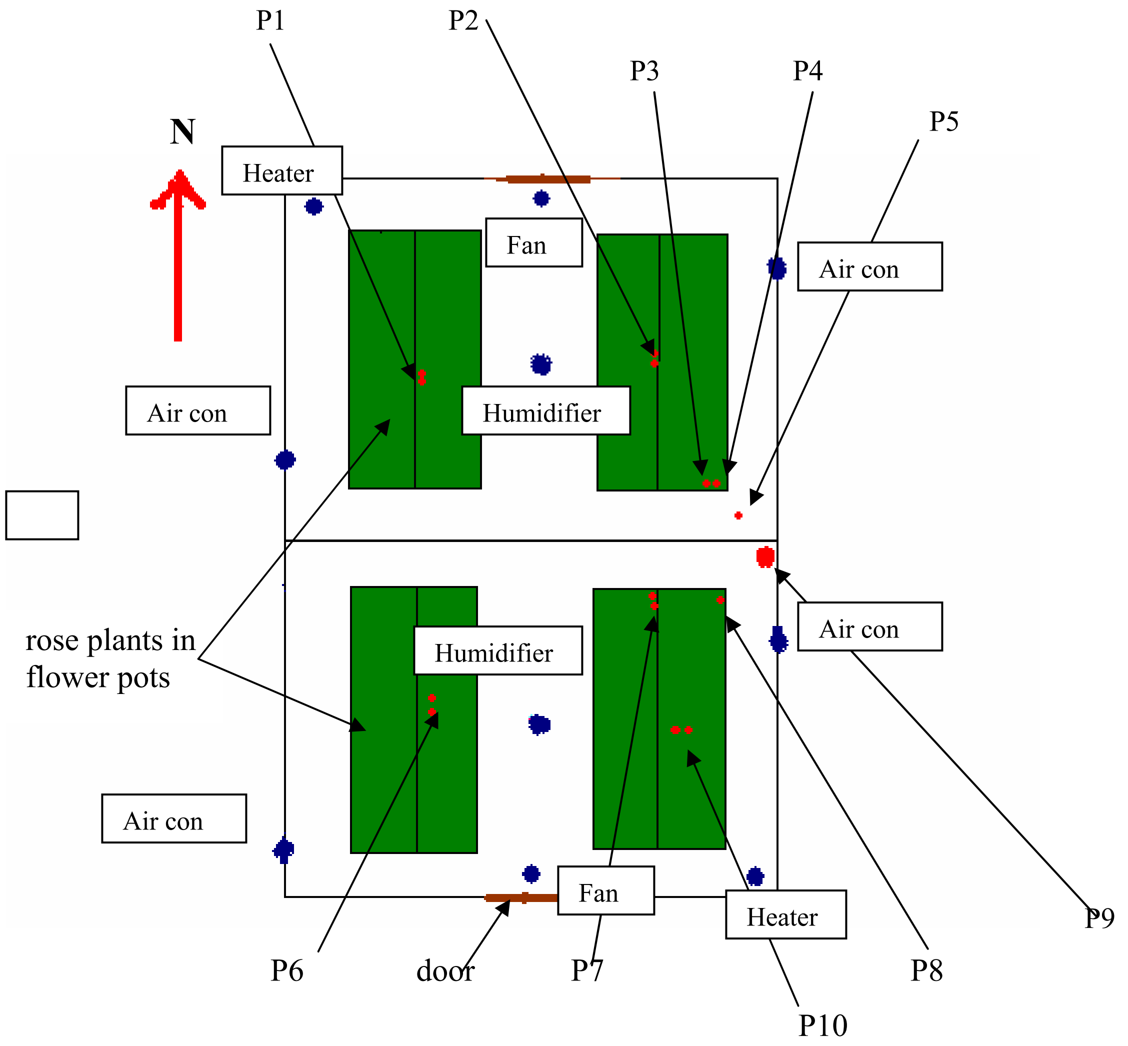

Figure 3: 4: Schematic of sensor positions within the experimental greenhouse (Not drawn to scale)

Key

P1	Leaf wetness sensor number (s/n 0311-0418) + Thermocouple K type
P2	Leaf wetness sensor (s/n 0311-422)
P3	Thermocouple K type
P4	Thermocouple K type
P5	Relative humidity and temperature (model RHT2nl s/n)
P6	Leaf wetness sensor (s/n 0311-0420) + Thermocouple K type
P7	Relative humidity and temperature (RHT2nl s/n 899)
P8	Thermocouple K type
P9	Data logger (model DL2e, Delta-T Devices, Cambridge, UK)

P10 Leaf wetness sensor (s/n 0311- 0419) + Thermocouple K type

☐ Outside weather station

N.B All environmental controlling devices used in the greenhouse are labeled in text boxes and are coloured in blue.

Having determined the optimum positions for the meteorological instruments in the greenhouse, a series of experiments to determine the effect of humidity, temperature and vapour pressure deficit (Δe) on the condensation process was carried out during the period from November 2006 until May 2007. The sampling times were 10 days for each treatment. Data was averaged after every 30 minutes for all parameters expect for the leaf wetness sensors where a minute averages were stored during winter experiments at the Bio science greenhouse. In these later experiments, the greenhouse was divided into 2 equal compartments, one of which was used as a control and in which the temperature and humidity was maintained at levels that were not conducive for the formation of dew on the leaves. In the other compartment (which was used as the test compartment), the climatic parameters were varied to investigate the conditions favourable for condensation according to the schemes outlined below. The greenhouse environments were regulated with air conditioners, fans, heaters and humidifiers.

3.2.1.3 Experimental investigation of the effect of relative humidity and Δe on condensation

Experiments were conducted to investigate the occurrence, amount and duration of leaf wetness on foliage with relative humidity and vapour pressure deficit and hence establish the relative humidity and Δe thresholds which are conducive for dew development on rose plants in a greenhouse under different conditions. Three experiments were conducted. In the first experiment the air temperature in the test compartment was regulated at the optimum temperature range for rose production (22 °C to 25°C), which also coincides with optimum temperatures for fungal and bacterial disease development. This was done by turning on the heater when the temperature fell below 22 °C and turning on the air conditioners and fan when it rose above 25 °C. In the other two experiments the temperatures were those that prevailed under natural conditions during the night in the period February to March (15 – 18 °C) and May (9 – 12 °C), respectively (Day time temperatures for the summer and winter periods were ignored in these experiments because condensation process is not expected to occur during day time). In all cases the test compartment was kept closed (except the roof openings) and the experiments were done in various relative humidity levels (70 % – 100 %). The humidity was regulated by means of different settings on the humidifier. The vapour pressure deficit was calculated using the leaf temperature, air temperature and relative humidity readings recorded by the data logger every 10 minutes during summer and 1 minute during winter (see §3.4.2 and §3.5)

The roof vents of the control compartment were kept open during the whole period to ensure that free air circulation occurred and natural conditions prevailed, except when the temperature was too hot (or cold) when the air conditioners and fan (or heater) were activated. The fans and air conditioners and vents were also activated when it got too humid or too hot in the control compartment. This was done so that the conditions were those that are known to prevent condensation taking place. Leaf wetness was monitored continuously by leaf wetness sensors as described in §3.5.1 and at certain times (in the evenings and mornings) by visual inspection.

3.2.2 The commercial greenhouse

Input and calibration data for the model were collected in a 3-span Azrum type test greenhouse that was a partition of a 9-span greenhouse (Fig. 3.5 and Fig. 3.6) at Floraline (Pvt.) Ltd. in Harare, Zimbabwe. Each span was 9.6 m wide by 44.5 m long, with ridge (eaves) and gutter heights of 6.5 and 4.1 m, respectively. The ridges were oriented north-south. The cladding material was a 200 μm polyethylene film with terrestrial infrared and UV absorbing additives (Ganeigar Co., Israel). The polyethylene sidewall roll-up curtains could be rolled up from 2 m above the floor to 3.45 m on the south wall and to 3.35 m on the north wall. Plastic nets (50 mesh, that allows the passage of 0.35 mm diameter spheres) covered the openings. A ventilation window (0.8 m wide) opened along the gutter, on the west side of each roof span. The roof vents were kept open throughout the day, and only closed during rain and wind storms, while the side curtains were opened (manually) every morning at 0400 hours (local time) and closed at sunset; i.e. at about 1800 hours (local time) and also during rain and wind storms.

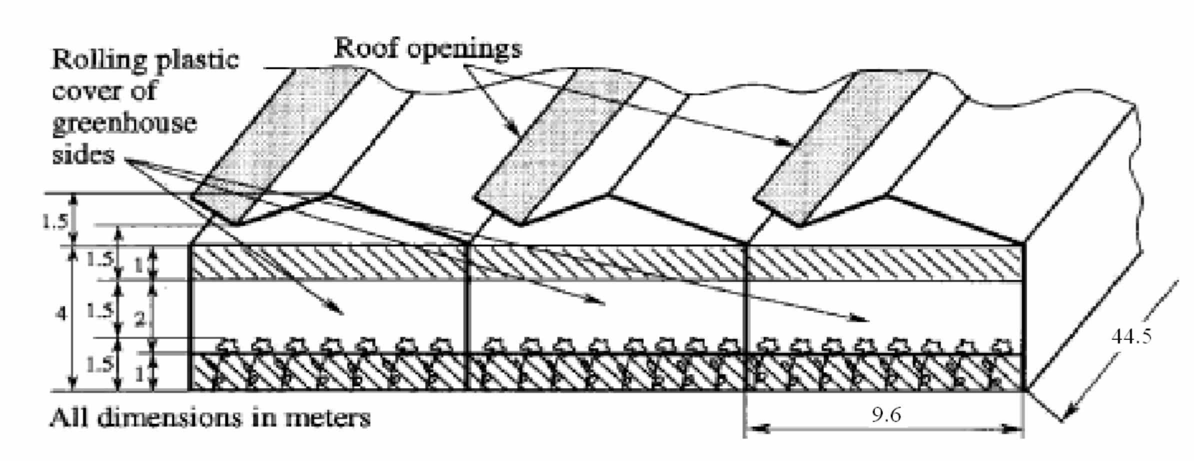

Figure 3: 5: The scheme of the Azrum type greenhouse

Figure 3: 6: The commercial greenhouse at Floraline (Pvt.) Ltd.

The crop included several cultivars of roses at different growth stages, grown in 0.5 m × 20 m × 0.4 m (width × length × depth) troughs filled with vermiculite and watered at ground level through a drip system of two drip lines 25 cm apart. The plants (1.2 m to 1.5 m in height) were planted in two rows 35 cm apart in each trough and 20 cm apart within each row. The troughs were laid parallel to the gutters in twelve 20 m rows in each span. The ground surface of the greenhouse was covered with plastic film, with the exception of a 2 m wide, concrete path running east-west along the centre of the greenhouse. The area between the troughs was covered with concrete stones. Blind and weak shoots were bent over to the side so as to provide full ground cover, resulting in an overlap of 10 cm on either side of the trough width edge.

Two circulation fans, 0.75 m diameter with a rated flow of 16000 m^3/h at zero static pressure, were installed at a height of 3.2 m above the greenhouse floor (2.8 m above the trough bed) in the first and third span and facing in opposite directions along the ridges.

To the north of the greenhouse and 8 m away was another greenhouse; to the south and 10 m away was a wall 2 m high. There was a building (over 5 m high) 6 m to the east of the greenhouse.

3.3 Meteorological Measurements

Meteorological measurements were taken both in the greenhouse and outside the greenhouse so as to allow comparison of the two environments. These measurements are outlined in section 3.41, and were continuously taken from November 2006 up to May 2007.

3.3.1 Outside meteorological measurements

An automatic weather station was set up outside each greenhouse (Fig. 3.7). At the Biological Sciences Department station, weather parameters that were measured include air temperature and relative humidity (1.5 m), global solar radiation, wind speed and direction at 2 m from the ground. All the above mentioned parameters as well as diffuse solar radiation were also measured at Floraline (Pvt.) Ltd. The main objective of these stations was to provide meteorological data which was used to run the model and to compare with the conditions taking place inside the greenhouse.

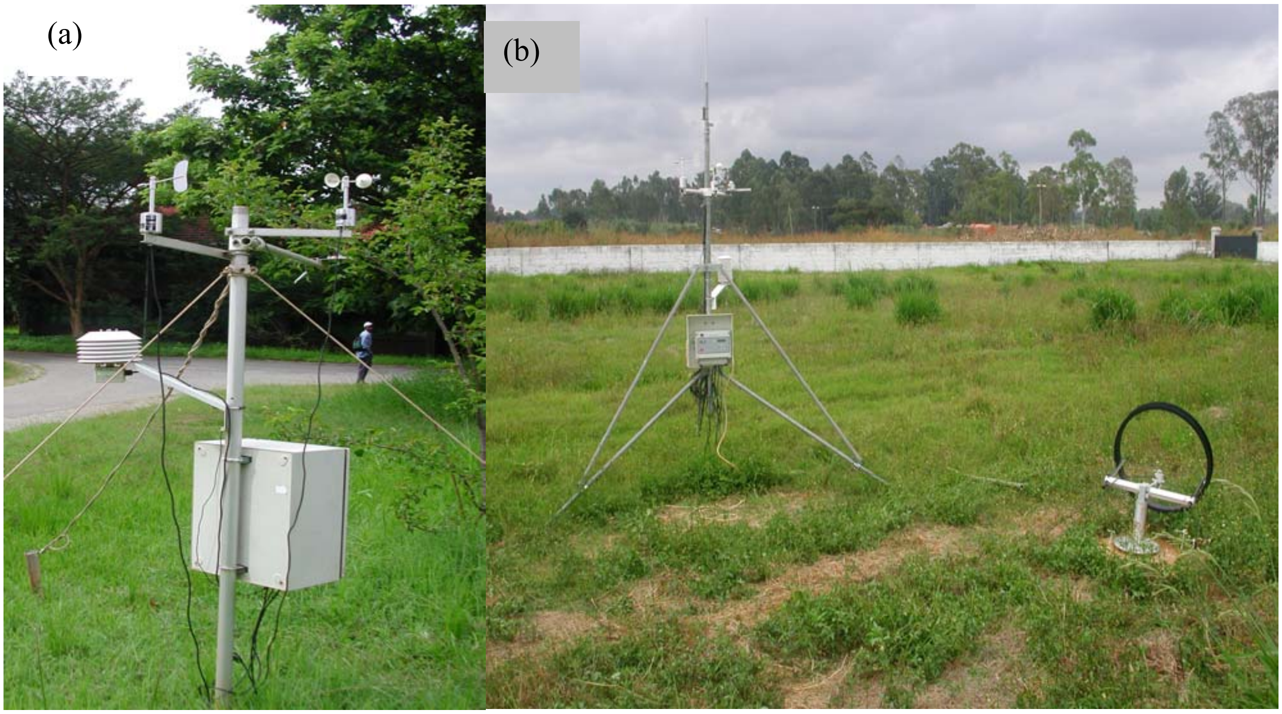

Figure 3: 7: Outside Automatic Weather Station at (a) Biological Sciences Department, University of Zimbabwe; (b) Floraline (Pvt.) Ltd, showing the shade ring for measuring diffuse solar radiation.

The air temperature and relative humidity at the Biological Sciences Department and Floraline (Pvt.) Ltd. outside weather stations were measured using temperature and humidity probes (types RHA1 and RHT2nl; respectively, Delta-T Devices, Cambridge, UK). Each of these probes contain a Platinum Resistance Temperature (PRT) detector and a Vaisala HUMICAP® 180 capacitive relative humidity sensor in a plug-in module. The probes were installed in radiation shields to protect them from radiation effects and were mounted at 1.5 m above the ground (screen height). Measurement of the total solar radiation was done using pyranometers (model CM3, Kipp and Zonen, Delft, Netherlands). The sensor uses a silicon photodiode for the measurement of solar radiation. The Pyranometer was mounted at a height of 2 m above ground level. Wind speed was measured using anemometers (type AN1, Delta-T Devices, Cambridge, UK). The rotor cups of the anemometer are made out of ABS plastic, giving strength and sensitivity. Wind direction was measured using potentiometer wind vanes (type W200P, Delta-T Devices, Cambridge, UK). The anemometers and wind vanes were mounted at a height of 2 m above the ground.

All these sensors were connected to data loggers (model DL2e, Delta-T Devices, Cambridge, UK) that were programmed to take measurements at 5-second intervals and calculate the mean values of all the measured quantities over 30-minute intervals and store these values.

3.3.2 Climatic measurements within the greenhouses

Climate parameters that were continuously monitored in both greenhouses included air temperature and relative humidity. These were measured by temperature and humidity probes (model RHT2nl, Delta-T Devices, Cambridge, UK) at 1.5 m above ground floor (Fig. 3.8). Radiation shields protected the sensors from direct radiation, while allowing air circulation.

Figure 3: 8: The probes used to measure the greenhouse air temperature and humidity in the experimental greenhouse, Biological Sciences Department, UZ.

Net radiation, incoming solar radiation above the canopy, airflow and the temperature of the medium were only measured in the commercial greenhouse. The net radiation was measured with a net radiometer equipped with Teflon coated sensor surfaces (Model NR-LITE , Kipp and Zonen, Delft, Netherlands), while the solar radiation was measured with a tube solarimeter (Model TSL, Delta-T Devices, Cambridge, UK). Both instruments were set up just above the canopy. The temperature of the medium (vermiculite) was measured at depths of 10 and 20 cm below the surface using soil temperature probes (type ST1, Delta-T Devices, Cambridge, UK). All the measurements were automatically recorded by data loggers (model DL2e, Delta-T Devices, Cambridge, UK) every 5 s and averaged over 5 minutes before being stored.

3.4 Physiological measurements within the greenhouses

Leaf temperature measurements in both greenhouses were made using fine Type K thermocouples stuck to the underside of the leaves with plastic clips (as shown in Fig. 3.9). The measurements were performed at different locations within the canopy: three thermocouples were attached on leaves of the bent shoots (lower part of the canopy), and three on leaves of the flower stems. The canopy temperature (T_c) was calculated as the mean value of the six leaf temperatures in each compartment. The thermocouples were checked once a day and were moved from one leaf to another leaf of the same plant after every 5 days.

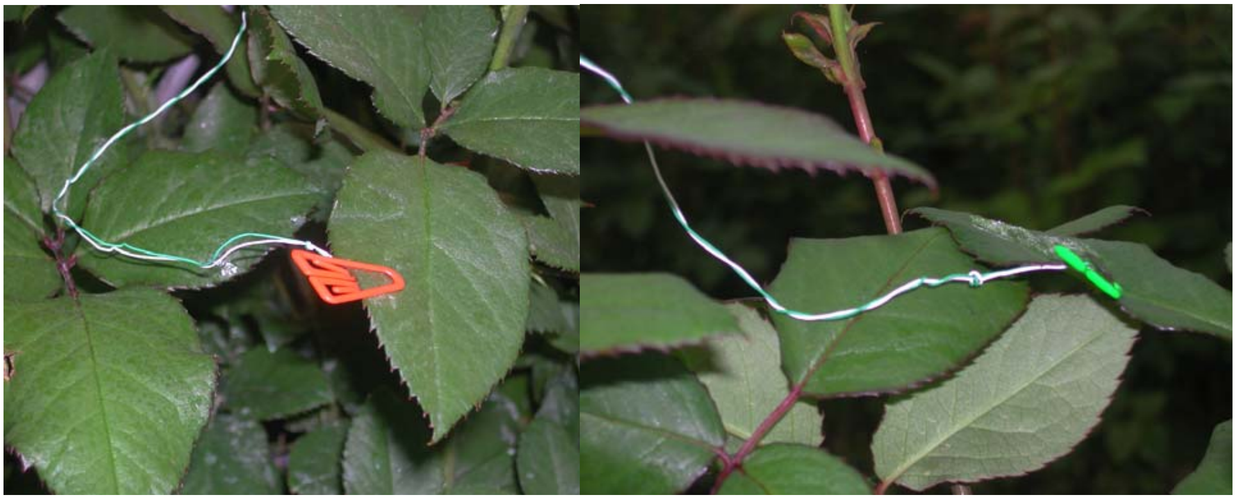

Figure 3: 9: Attachment of the thermocouples on the underside of leaves in the greenhouse

Daytime stomatal resistances of several leaves above and within the canopy were measured on selected clear days in the commercial greenhouse using a diffusion porometer (Model AP4, Delta T Devices, Cambridge, UK). However, only the daytime stomatal resistances were measured as night time stomatal resistances could not be measured due to the presence of condensation on the leaf surfaces. Frequent calibrations of the AP4 were done in order to account for temperature effects when the cup to leaf temperature differences and the cup and set relative humidity differences approached ± 2 °C and ± 5 %, respectively. Leaf area Index

(LAI) was estimated non-destructively once a week during the measurement period using a sunscan canopy analysis system (model SS1-TM, Delta-T Devices, Cambridge, UK).

3.5 Leaf wetness measurement

The moisture level on a natural rose leaf surface was measured using two methods. These methods include an electronic sensor instrument and the visual inspection method and are explained below.

3.5.1 Electronic sensor method

Leaf wetness and leaf wetness duration measurements within the canopy and at the top of the crop canopies were done with dual leaf wetness sensors (Model LW12, Environdata, Logan, Australia) connected to data loggers (Model DL2e, Delta T Devices, Cambridge, UK and CR23X, Campbell Scientific, Logan, USA) programmed to measure the percentage of time in which the sensors were wet during each 5-min interval during summer period and 1 minate during the winter period.

The sensor measures the electrical conductivity between the two wires sewn into the sensor's surfaces. The measurements were made by orienting the leaf wetness sensors parallel to the plant leaves, and were located above and within the canopy to determine and record moisture development in those areas. The LW12 sensor's output is equal to the wetter of the two sensors, hence providing a safe, conservative wetness reading that gives a "worst case scenario for disease prediction. The placement and orientation of the sensors in the field is shown by Fig 3.10 below. No scientific method was used in determining where to place the sensors within the greenhouse since preliminary experiments made had shown the greenhouse environment to be generally uniform enough for the experiments not to be affected by errors due to environmental variability. Therefore placement of the sensors was done based on convenience of the location in the greenhouse.

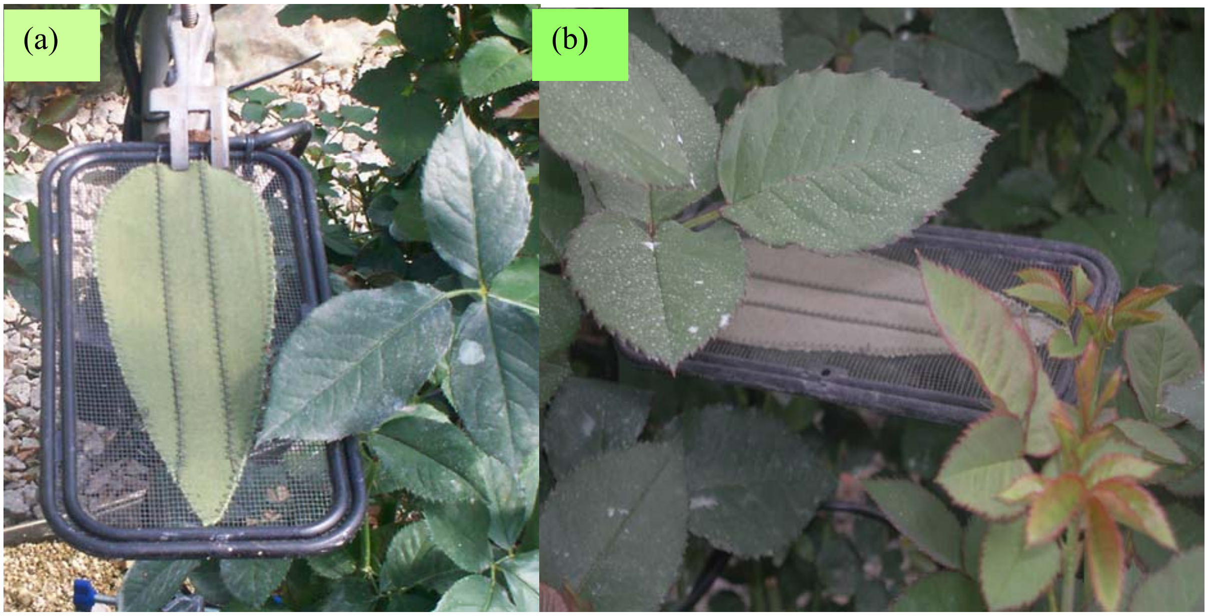

Figure 3: 10: Measurement of leaf wetness using the LW12 dual sensor instrument in a rose greenhouse (a) outside the canopy, and (b) within the canopy.

3.5.2 Visual inspection method

The other method which was used involved caring out a visual inspection and developed an index. This indexing process involved defining the leaf surface wetness parameter and explains how it was measured, its units and the scoring technique. The leaf surface wetness used in this study is defined below.

Definition of leaf surface wetness

Two variables were used for describing surface wetness. The first variable described the observed wet fraction of the plant canopy (LW) when dew was noticeable using the naked eye at any given time. The second variable described the Canopy Surface Wetness duration (CSWD). These variables are described in detail below.

Definition of observed fraction of wet surface area

The observed fraction of the canopy wet surface area (LW) was defined as the ratio of branches with more than 10% of wet leaves to the total number of branches of a single plant for duration of more than 10 minutes. The ratio was expressed as a percentage. It was noticed that, significant moisture was observed on plant leaves when the sensor instrument was recording 5 % wetness or more. Therefore, leaf wetness percentages less than 5%

were considered insignificant and the leaves were considered dry when such readings were recorded in the study.

Definition of Canopy Surface Wetness Duration

The canopy Surface Wetness (CSW) was defined as the presence of water that is visible to the human eye for 10 minutes or more on 10 % of leaves in a canopy. A score of one (1) was used to show the presence of wetness, while a score of zero (0) was used to show absence of wetness on the canopy. These scoring values of (1) and (0) were chosen mainly because the GDGC Model also gives its output in the same format. Scoring of the measurements was done at 30 minutes interval. Therefore, the total number of hours in a day during which a canopy is wet was defined as the canopy surface wetness duration (CSWD). Therefore, the CSWD uses time and existence of wetness as its variables.

Estimation of the surface wetness duration (CSWD) for the model was based on the vapour pressure deficit (Δe). Significant wetness was initially observed on plant leaves when the Δe had fallen below a certain threshold level. CSWD was estimated from the period when Δe was less than a specified threshold Δe_{th} where:

CSW= 0, for $\Delta e > \Delta e_{\text{th}}$

CSW= 1, for $\Delta e < \Delta e_{\text{th}}$

where CSW is the canopy surface wetness, dimensionless, Δe_{th} (0.3 kPa) is the vapour pressure deficit threshold below which dew starts.

The threshold of 0.3 kPa was established from the experiments described in §3.2.1.3 and it takes into account the existence of small traces of water that may persist in the canopy for extended periods. So the vapour pressure deficit threshold Δe_{th} was defined as the threshold level above which the canopy is considered to be dry. The leaf temperature and air temperature and relative humidity values were used to calculate the vapour pressure and saturation vapour pressure of the air (and at the leaf temperature) and used to determine the vapour pressure deficit (Δe) between the leaf surface and the greenhouse air.

3.6 Instrument Calibration

Prior to any field experiments, and during the measurement campaign, instruments need to be compared and standardized through the process of calibration. Calibration of sensors is usually carried out against an in-house standard sensor instrument, and ensures that the deviations from the standard are within the accuracy limits advertised by the manufacturers of the sensors. Calibration reduces instrument related errors.

The process of calibration and the instruments that were calibrated is detailed in the paragraphs below:

3.6.1 Temperature and relative humidity probe

Two relative humidity and temperature probe sensors (RHTn2*l*, serial numbers 635 and 261 respectively) were calibrated against the standard WALZ (Dewpoint system TS-2, Mess-unit and GegelTechnik) in house sensor. This process was done using the dew-point mirror measuring system. The temperature and relative humidity probes together with the WALZ instrument probes were immersed in the flow chamber. Control of chamber temperature was done by setting the GRANT LTD 9G at a constant temperature. Relative humidity in the chamber was controlled using the Portable dew point generator (model L1-610). Temperature and humidity probe sensors were connected to a Delta T logger device, while the WALZ were connected to the CRX 23 data logger to give 5 minutes averages. Regressions of the outputs of the tested sensors against the WALZ were plotted. The regression plots were used to obtain the calibration factors for the sensors. These are given in Table 3.2

Table 3: 2: Calibration factors for temperature and humidity probes

Sensor	Serial Number	Calibration equation
RHT2nl (RH output)	635	$RH_{(WALZ)} = 1.0252 * RH_{(635)} + 1.6198$
RHT2nl (RH output)	261	$RH_{(WALZ)} = 1.1314 * RH_{(261)} - 0.5978$
RHT2nl (Temp output)	635	$TM_{(WALZ)} = 1.1006 * TM_{(635)} - 3.0179$
RHT2nl (Temp output)	261	$TM_{(WALZ)} = 1.0769 * TM_{(261)} - 2.5397$

During the measurement period, the temperature and relative humidity readings from the probes were calibrated on site regularly (in the mornings, afternoons and evenings) by checking against an aspirated pychrometer.

3.7 Solar radiation sensors

The solar radiation sensors, including the tube solarimeter, were tested against a pyranometer (type CM11, Kipp & Zonen Delft, Netherlands) that has been designated as the in-house standard (serial number 997082). The calibration was done at the University of Zimbabwe on the roof of the Physics Department. To test the sensors against the standard, all of the sensors were exposed and the mean output over consecutive 15 minute periods were recorded for a complete day by a data logger (model CR10X, Campbell Scientific, Cambridge, UK; serial number 15834). A new calibration constant (or multiplier) for each sensor was determined as follows:

The apparatus was set up with the sensors being well away from obstructions and level. The tube solarimeter was oriented North-South in line with the recommendations by Monteith (1993). The output of the test sensor in mV was plotted against the output recorded by the standard (in W/m^2). The gradient (or slope) of such a graph was taken as the calibration constant for each sensor.

3.8 Modelling process

The second part of the study involved the visual inspection of the leaf conditions and monitoring of the greenhouse microclimate so as to provide data for calibrating and validating the vegetative sub-model within the GDGCM. The calibration of the model involved making adjustment of some of the model parameters in the deck and character files and ensuring that it could still work after the changes. The model was run using data for the period from 14th of May 2007 to 24th of May 2007.

In the validation of the model, data recorded from the outside weather station, which includes air temperature, relative humidity, radiation, wind speed and direction was used in the GDGCM to produce simulated events (relative humidity, leaf and air temperature) when condensation developed on plant leaves in the greenhouse. These results were then compared and validated with the observed results from the leaf wetness sensors and visual inspection. A calibration curve of the observed leaf wetness events from the leaf wetness sensors against the model simulations was produced before adapting the GDCM model as an appropriate vegetative condensation model to describe and predict the condensation of a rose crop in a greenhouse. Table 3.3, below gives the values of the parameters used in the current version of the GDGCM.

Table 3: 3: Values for the Gembloux Dynamic Greenhouse Climate Model parameters (after Wang and Boulard, 2000; Uchida Frausto *et al.*, 2003; Pollet, 2002)

Soil Characteristics	***First Layer***	***Second layer***	***Third Layer***	***Fourth layer***
Thermal conductivity [W $m^{-1}K^{-1}$] :	0.70	1.95	1.9	1.9
Layer Thickness [m] :	0.05	0.15	0.3	0.7
Density of soil layer [kg m^{-3}] :	1300	1450	1600	1650
Heat capacity of soil layer [J$kg^{-1}K^{-1}$] :	3350	1250	1250	1200

Floor reflectance for solar radiation [-] : 0.25
Floor emittance for far infrared radiation : 0.85
Subsoil temperature [°C] : 18.0
Thickness of the subsoil layer [m] : 8.8
Characteristic length of greenhouse floor [m] : 1001

Cover Characteristics

Material: 200 μm Diffused Polyethylene (DPE)
Outer cover emittance for far infrared radiation [-] : 0.82
Inner cover emittance for far infrared radiation [-] : 0.82
Transmittance for far infrared radiation [-] : 0.18
Cover absorptance for diffuse solar radiation [-] : 0.040
Dry cover transmittance for diffuse solar radiation [-] : 0.537
Wet cover transmittance for diffuse solar radiation [-] : 0.426
Frame transmittance for solar radiation [-] : 0.95
Dry cover heat capacity per unit area [kJ m^{-2} K^{-1}] : 725.00
Maximum condensation water film thickness [mm] : 0.120

TRANSMITTANCES AND REFLECTANCES AT 0, 15, 30, 45, 60, 75 AND 90°
EXPRESSED IN THE FORMAT #.### [-]

Dry cover transmittance for beam radiation:	0.597	0.592	0.569	0.547	0.498	0.368	0.000
Wet cover transmittance for beam radiation:	0.486	0.482	0.472	0.470	0.456	0.370	0.000
Dry cover reflectance for beam radiation :	0.363	0.368	0.391	0.413	0.462	0.592	1.000
Wet cover reflectance for beam radiation :	0.474	0.478	0.488	0.490	0.504	0.590	1.000

Vegetation Characteristics

Reflectance for solar radiation [-] : 0.22
Canopy attenuation coefficient [-] : 0.6093
Characteristic length of the leaves [m] : 0.06
Emittance for far infrared radiation [-] : 0.95
Specific Heat Capacity [J $kg^{-1}K^{-1}$] : 4180

Air Characteristics

Humid air density [kg m^{-3}] : 1.25
Volumetric heat capacity of humid air [kJ m^{-3} K^{-1}] : 1256
Latent heat of condensation of water [kJ kg^{-1}] : 2437000
Inside air velocity [m s^{-1}] : 0.30
Lewis Number [-] : 0.89

3.9 Data Analysis

The data from the data loggers were collected using a portable computer with the Ls2Win software and stored as ASC files and then downloaded to Excel for processing and analysis. Ls2Win is computer software that facilitates communication with Delta-T data loggers through the RS232 serial interface. The data collected from the simulation model and calibration regression was analysed using the Excel Data Analysis Tool Pack (statistical regression).

Model evaluation

The leaf wetness, relative humidity, air and plant temperatures predicted by the GDCM were compared with the observed values from the field experiments at Floraline (Pvt.) Ltd, which were independent data sets. The statistics used to test model performance was the root mean square error (RMSE), calculated as (Streck *et al.,* 2002).

$$RMSE = \left[\frac{\sum (p_i - o_i)^2}{N} \right]^{0.5}$$

where, *p* is the predicted data; *o* the observed data; and N is the number of observations. The smaller the RSME, the better the prediction.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results and the discussion hereunder were determined using the data collected during the period of September 2006 and May 2007 at the Biological Sciences greenhouse, University of Zimbabwe campus, and at Floraline (Pvt.) Ltd.; situated 5 km from the UZ campus.

Limited control of the experimental greenhouse temperature and humidity provided challenges in coming up with data that would adequately address the objectives of the study. Data processing and sorting was carried out so as to provide results which addresses the main objective of experimentally determining and predicting the conditions when dew forms on leaf surfaces from measured ambient conditions. The results are a combination of recorded sensory instrument data, visual inspection, and simulated data from the model. Field results from the greenhouse are discussed first before the discussion of results from the simulated model.

Experiments to investigate the homogeneity of the greenhouse were carried out at the Biological Science greenhouse on the 28th to 27th of September 2006. Experiments to investigate the conditions when dew forms of the leaf surface, were carried out at Biological Science greenhouse, on the 17th to 27th of December 2006 (for the summer season) and between 14th and 24th May 2007 (for the winter season). Experiments to collect data for validation and calibration of the model were carried out at Floraline (Pvt.) Ltd on the 14th to the 24th of May 2007.

4.2 Homogeneity Tests

The results below are from preliminary experiments that were carried out inside the experimental greenhouse in order to investigate the homogeneity of the greenhouse so as to determine the optimal placement positions for instruments which were used to measure temperature, humidity and leaf wetness in the greenhouse. These experiments were carried out on the 27th to 28th September 2006. Sensory instruments used to test uniformity of the greenhouse were placed longitudinally along and diagonally across the greenhouse compartment floor so as to test horizontal homogeneity. Vertical measurements at different heights were also carried out, at an interval height of 0.5 m from the ground up to a height of 3.5 m to investigate vertical homogeneity.

4.2.1 Air Temperature inside the greenhouse

Fig 4.1 depicts air temperatures that were measured (simultaneously), when the sensor instruments were placed diagonally across the greenhouse, at a height of 1.5 m above the ground. The observations made were measured from 27th to 28th of September 2006, in the Biological science department experimental greenhouse, University of Zimbabwe. High temperature variations at the initial time period of the experiment (27 September 2006 at 1500 hrs) and the temperature variations at the end of the experiment (28 September 2006, at 1200 hrs) were ignored because of errors which occurred during the programming of the sensor instruments in the laboratory before taking the instruments to the experimental site.

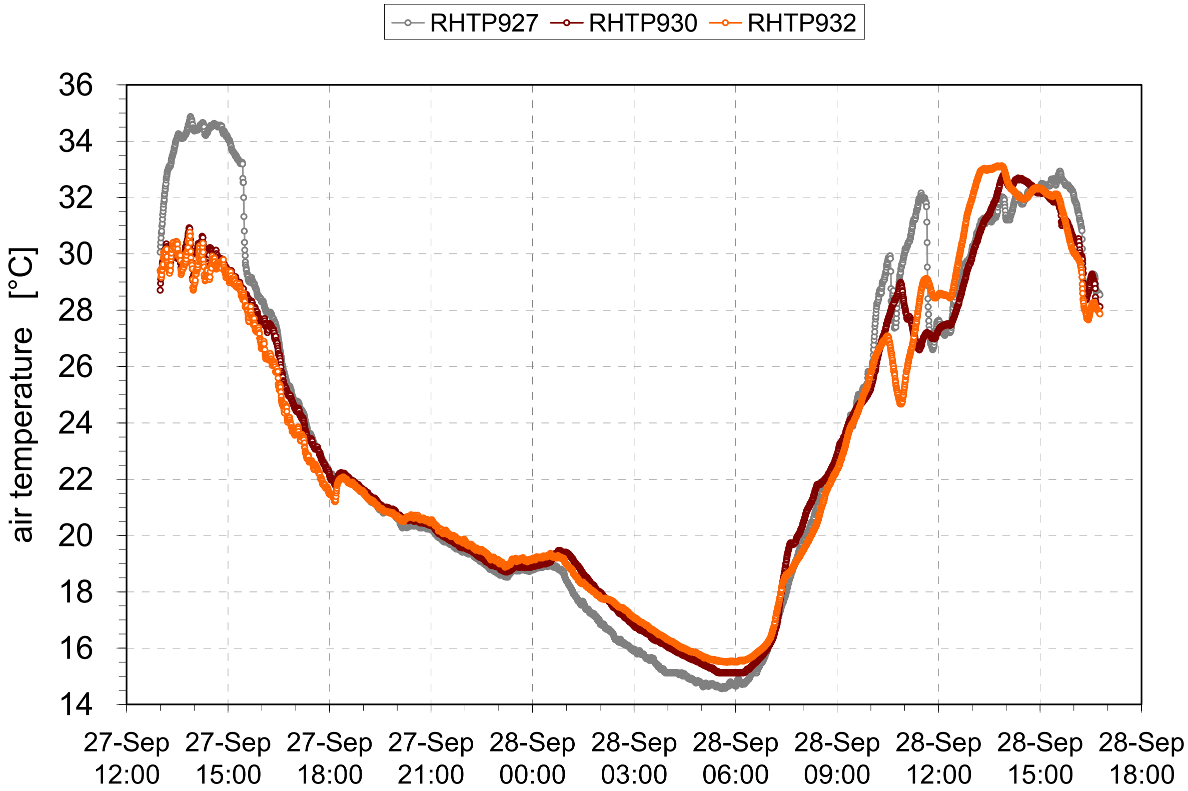

Figure 4. 1: Inside greenhouse air temperatures measured when the sensor instruments were placed diagonally across the greenhouse, at a height of 1.5 m from the ground, from 27th to 28th of September 2006 at Biological Science Department, University of Zimbabwe.

Maximum air temperature variations of less than 1 °C across the greenhouse were observed towards sunrise when temperatures were low. Minimal air temperature differences of less than 0.5 °C were observed during the afternoon when temperatures were higher. When the same experiment was repeated with the sensor instruments placed horizontally along the greenhouse, the observed results were similar to the results observed when the arrangement was diagonal.

In general, these variations are small and insignificant. Therefore, the greenhouse climate was considered horizontally homogeneous. Measuring instruments could therefore be placed at convenient (random) places inside the greenhouse.

Fig 4.2 shows measured vertical air temperatures that were observed at different heights within the greenhouse. Vertical height measurements were also replicated at different positions, diagonally across the greenhouse. Three sensors were used at any one time for the results in Fig 4.2 and 4.4.

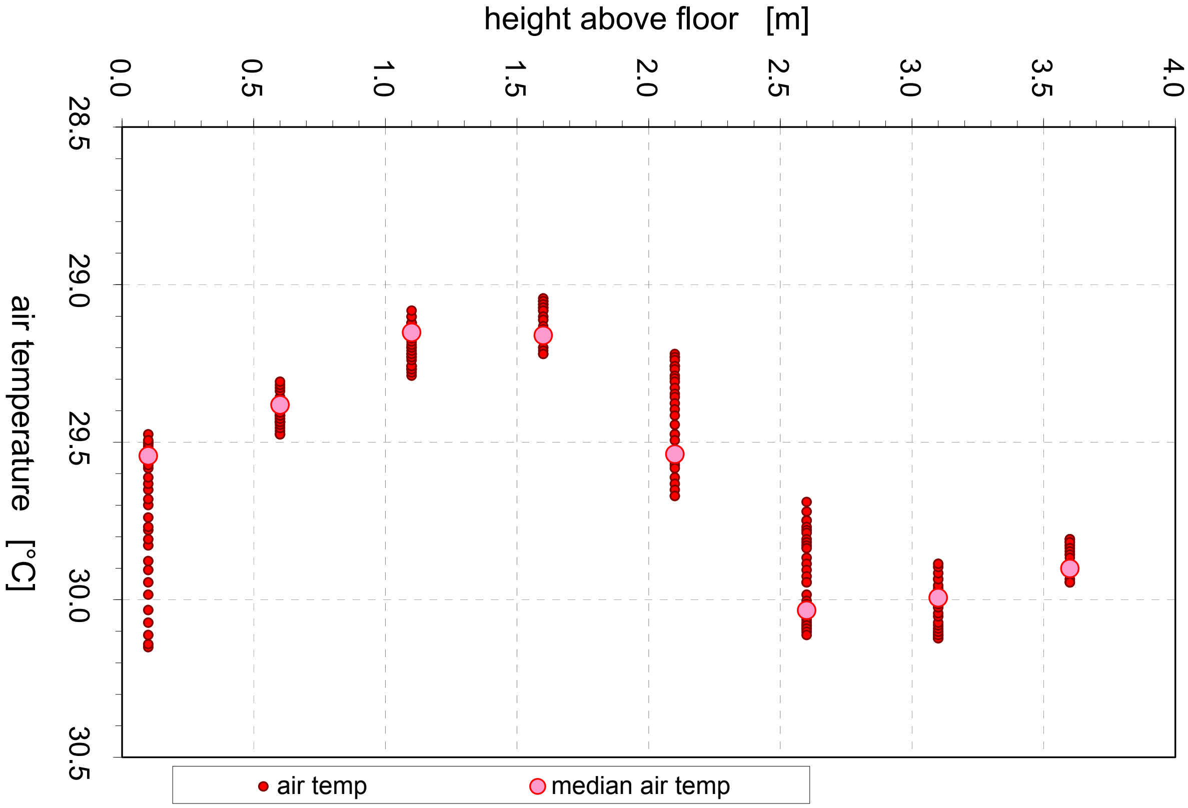

Figure 4. 2: Vertical air temperatures measured when the sensor instruments were placed at different heights above the ground, recorded on the 27th to 28th of September 2006 at Biological science department greenhouse, University of Zimbabwe.

Maximum air temperature variations of less than 0.5 °C were observed within the first 2 m above the ground, with the exception of ground temperature which was subjected to an error of ± 0.5 °C. Maximum variations of 1.8 °C (30.0 ± 0.5 °C -29.2 ± 0.5 °C) were noticed when the height was increased to 3.5 m above the ground. The main problem with these results is that they are not consistent, they are not random and the variability is not easily predicted. It was noticeable that little variations occurred between 1m and 2m above the ground level. Having looked at temperature variations inside the greenhouse, all the measuring instruments that were used in the study were placed at a vertical height of less than 1.5 m so as to avoid errors due to temperature variations with height.

4.2.2 Air relative humidity inside the greenhouse

Fig 4.3 depicts air relative humidity values that were measured when the sensor instruments were placed diagonally along the greenhouse ground floor. The results were recorded on the 27th to 28th of September 2006 at Biological Science Department Greenhouse, University of Zimbabwe.

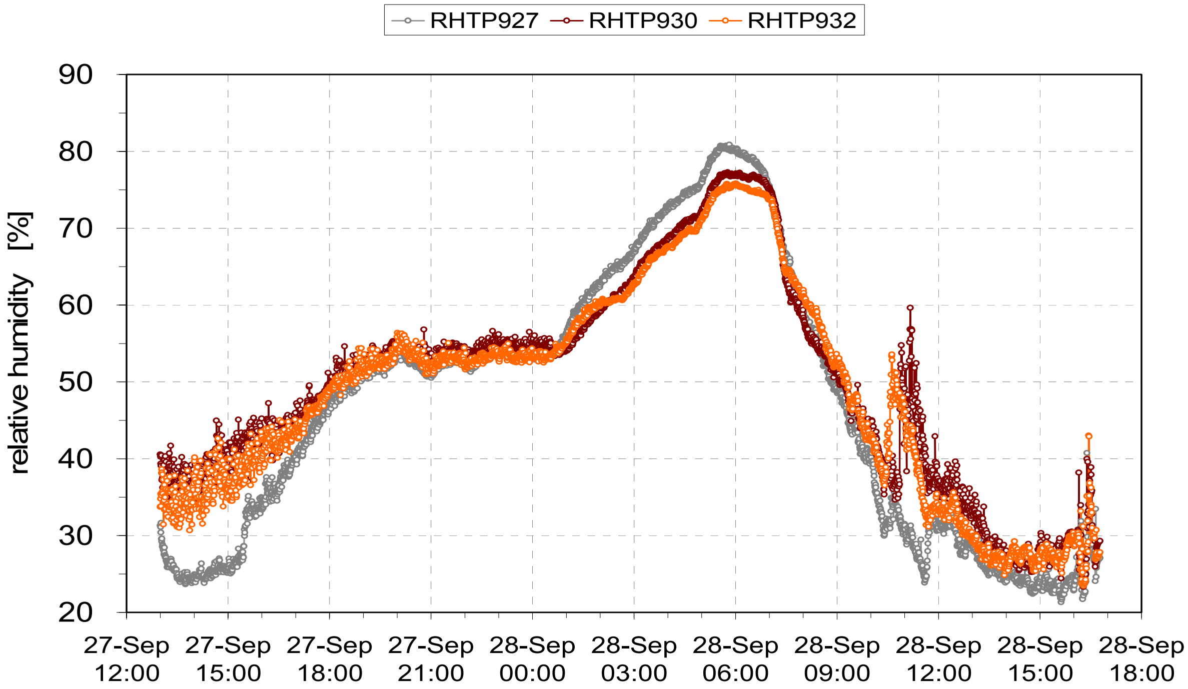

Figure 4. 3: Inside greenhouse air relative humidity measured when the sensor instruments were placed diagonal across the greenhouse, at a height of 0.5m from the ground, from 27th to 28th of September 2006 at Biological science department, University of Zimbabwe.

Minimal relative humidity variations of ± 8 % across the greenhouse were observed towards sunrise when relative humidity was high. Maximum relative humidity differences of ± 15 - 20 % were observed during the afternoon when the relative humidity was low. When the same experiment was repeated with the sensor instruments place horizontal along the greenhouse, the observed results were similar to the results observed when the arrangement was diagonal.

In general, the relative humidity variations during sunrise period were significant and the relative humidity and temperature probes which were used in the study were placed at a central position so as to reduce the variations.

Fig 4.4 shows air relative humidity values that were measured when the sensor instruments were placed at different heights above the ground. The results were recorded on the 27th to 28th of September 2006 at Biological science department greenhouse, University of Zimbabwe.

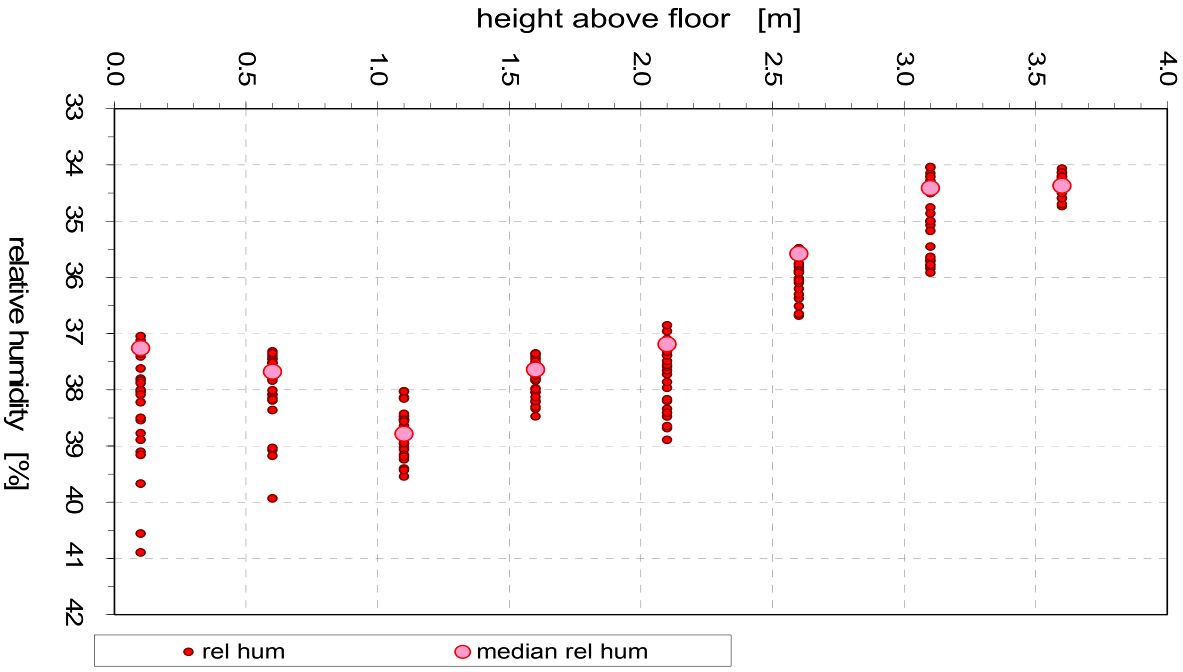

Figure 4. 4: Vertical air relative humidity values, measured from 27th to 28th of September 2006 at Biological science department weather station, University of Zimbabwe

Maximum relative humidity differences of ± 4 % were observed at the greenhouse ground floor. The variations were reduced, with the minimum variations of 2.0 % being observed and recorded at a height of ± 1.5 m.

Having looked at relative humidity variations inside the greenhouse, all the measuring instruments that were used in the study were placed at a vertical height of 1.5 m so as to avoid errors due to relative humidity variations with height.

Theory suggests that a measurement sensitivity of ±1 ºC is sufficient for studies of plant growth and other physiological processes (Jones, 1993). Thus the greenhouse can not be assumed to be well-mixed and homogeneous and any errors resulting from the placement of the temperature sensors may not affect the accuracy of this study results. However greater variations of relative humidity sensors may affect the results.

4.3 The environmental conditions

The environmental conditions which prevailed during the period when the results were recorded are presented in this section. The weather conditions at the Biological Sciences department were outlined separately:

a) For the summer season, (27th to 28th September 2006 and 17th to 27th December 2006).

b) For the winter season (14th to 24th May 2007).

4.3.1 Environmental conditions during the summer season

4.3.1.1 Outside and inside air temperature

Fig 4.5 depicts the outside and inside air temperatures, measured continuously, at 30 minutes averages from 17th to 27th of December 2006, at Biological Science Department weather station, University of Zimbabwe. The period was mostly cloudy.

The air temperature inside the greenhouse was always higher than the outside air temperature during the day, and was almost close to or slightly below the outside air temperature during the night. Maximum temperature (36 °C) was experienced in the greenhouse at around 1400 hours, local time, when the maximum temperature outside the greenhouse was 29 °C. The lowest temperatures (16 °C) were observed outside the greenhouse just before sunrise, whilst the lowest temperature in the greenhouse was 17 °C and was recorded at sunrise.

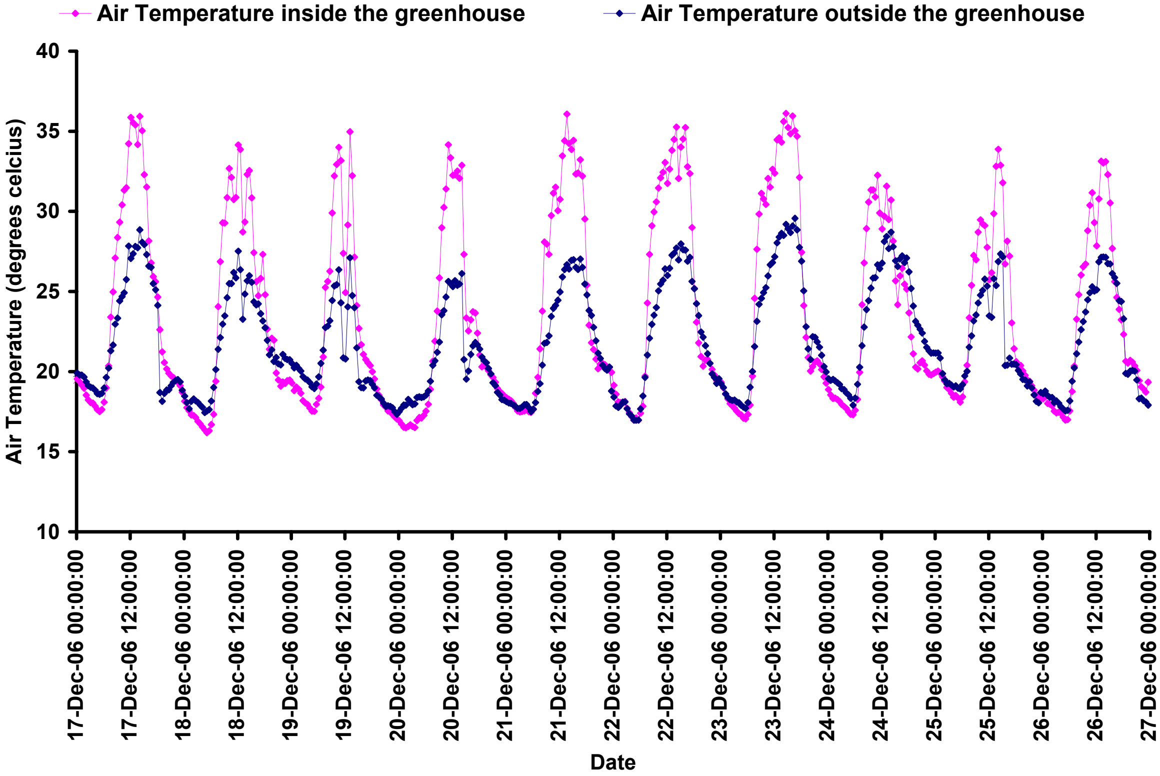

Figure 4. 5: Outside and inside air temperature measured continuously at 30 minutes averages from 17th to 27th of December 2006 at Biological Science Department weather station, University of Zimbabwe

4.3.1.2 Outside and inside air relative humidity

Fig 4.6 shows the outside and inside air relative humidity, measured continuously at 30 minutes averages from 17th to 27th of December 2006, at Biological Science Department weather station, University of Zimbabwe. The relative humidity inside the greenhouse was always lower than the outside relative humidity during the day, and almost close to, but slightly below the outside air relative humidity during the night. Maximum relative humidity values (100%) were experienced outside the greenhouse during rainy days, whilst the maximum relative humidity inside the greenhouse was only 92%. Lowest relative humidity values (29%) were observed inside the greenhouse, when the relative humidity outside the greenhouse was 35%.

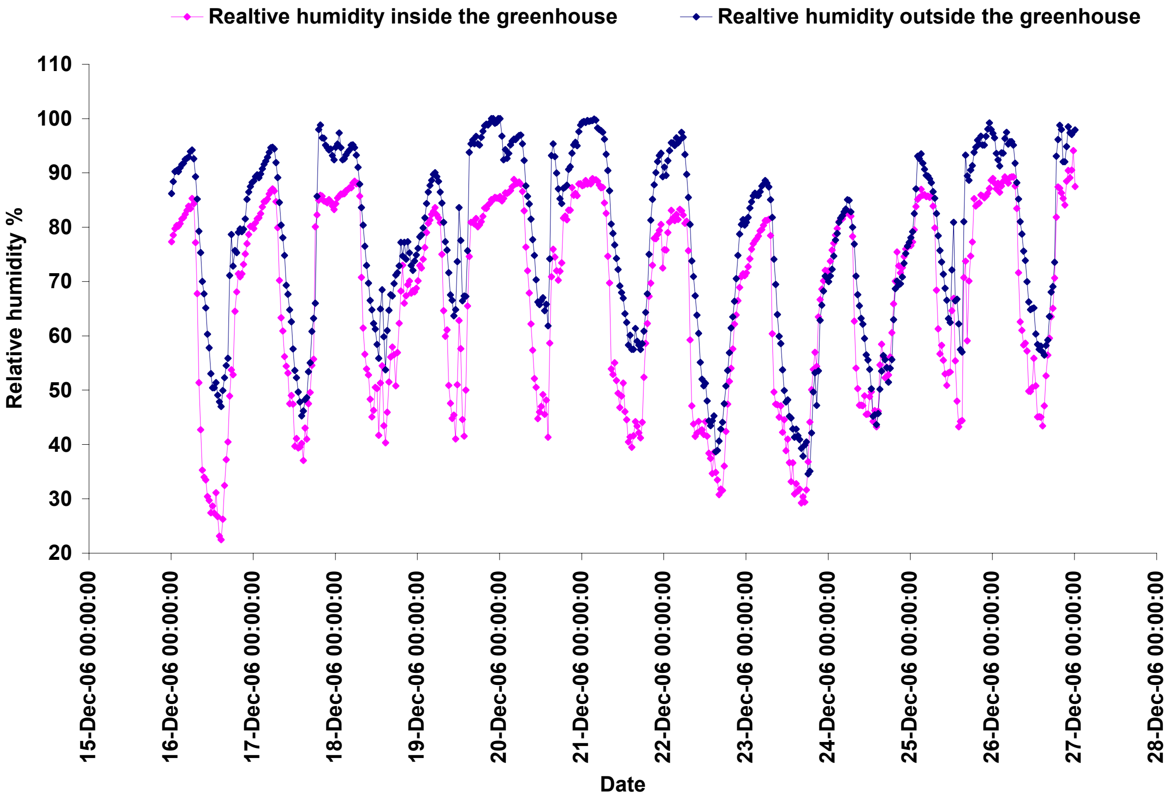

Figure 4. 6: Outside and inside air relative humidity measured continuously at 30 minutes averages from 17th to 27th of December 2006 at Biological Science Department weather station, University of Zimbabwe

4.3.2 Environmental conditions recorded during the winter season

4.3.2.1 Outside and inside air temperature

Fig 4.7 shows the outside and inside air temperatures, measured continuously on cloudless days at 30 minutes averages from 11th to 21st of May 2007, at Biological Science department weather station, University of Zimbabwe.

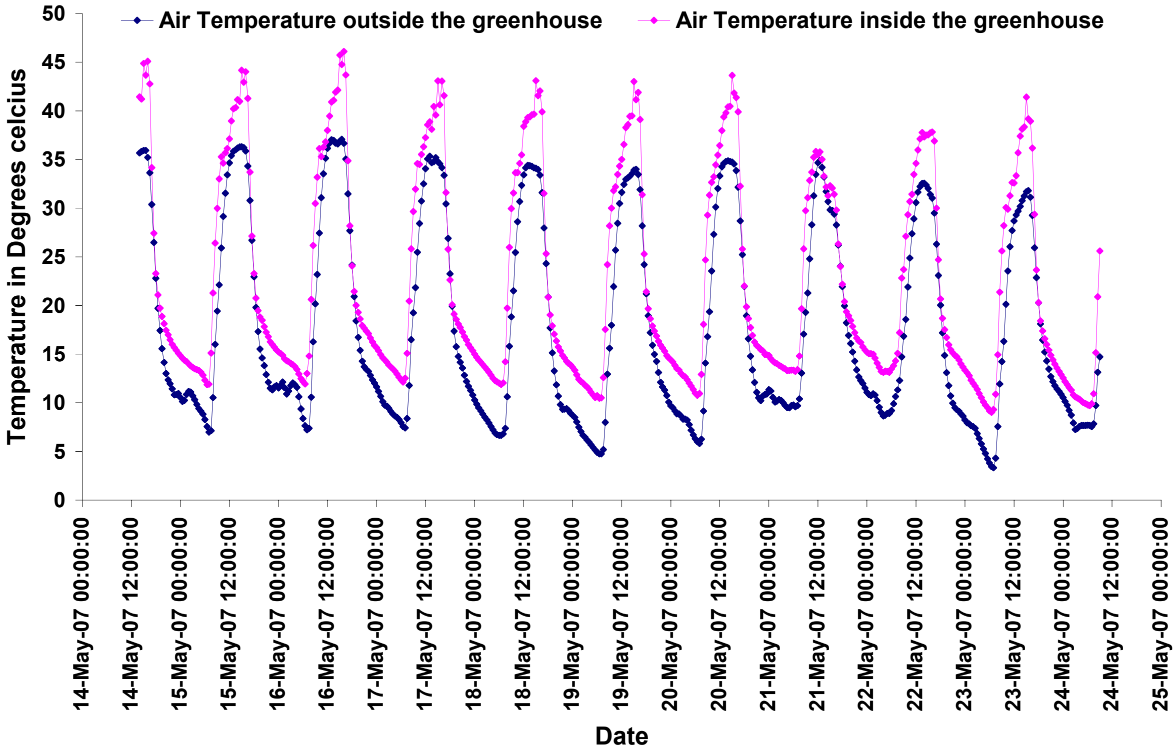

Figure 4. 7: Outside and inside air temperature measured continuously at 30 minutes averages from 11th to 21st of May 2007at Biological science department weather station, University of Zimbabwe

The air temperature inside the greenhouse was always higher than the outside air temperature during the day and also at night. Maximum temperature (46 °C) was experienced in the greenhouse during the day, when the maximum temperature outside the greenhouse was 36 °C. Lowest temperatures (3 °C) were observed outside the greenhouse around sunrise, whilst the lowest temperature in the greenhouse was 9 °C, confirming the "greenhouse effect" suggested by theory.

4.3.2.2 Outside and inside air relative humidity

Fig. 4.8 shows the outside and inside air relative humidity, measured continuously on cloudless days at 30 minutes averages from 11th to 21st of May 2007, at Biological Science Department weather station, University of Zimbabwe.

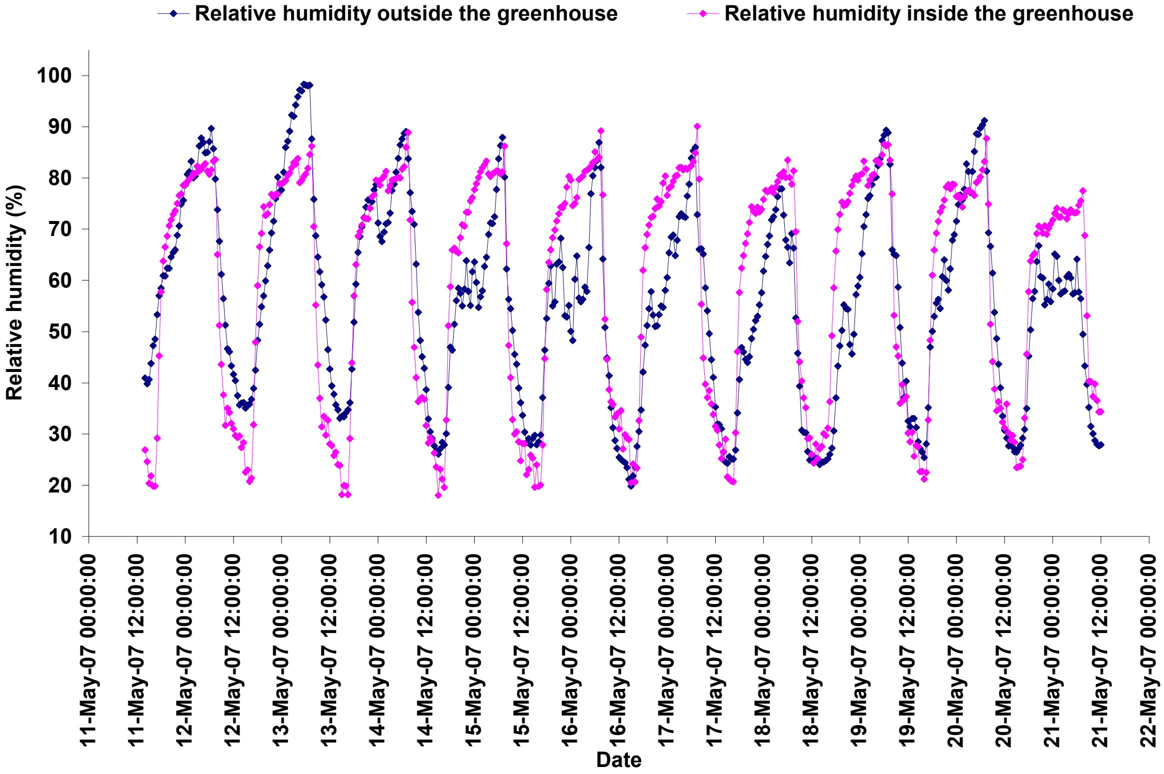

Figure 4. 8: Outside and inside air relative humidity measured continuously at 30 minutes averages from 11th to 21st of May 2007 at Biological science department weather station, University of Zimbabwe

The relative humidity inside the greenhouse was always lower than the outside relative humidity during the day, and almost close to, but slightly lower than the outside air relative humidity during the night. Maximum relative humidity values (98 %) were experienced outside the greenhouse towards sunrise, whilst the maximum relative humidity inside the greenhouse was 91 %, at the same time. The lowest relative humidity value of 21 % was observed outside the greenhouse in the late afternoon, whilst the lowest relative humidity value in the greenhouse was 18 %.

4.4 Conditions for condensation at Biological Science Department greenhouse

Experiments were conducted to investigate the occurrence, amount and duration of leaf wetness on foliage with relative humidity and vapour pressure deficit and hence establish the relative humidity and Δ*e* thresholds which are conducive for dew development on rose plants in a greenhouse under different conditions. These experiments were done in the following temperature ranges: 22 – 25 °C (optimum temperatures for rose production), 15 – 18 °C (night time temperatures under natural conditions in summer) and 9 – 12 °C (night time temperatures under natural conditions in winter)

The results on the occurrence and duration of leaf wetness, observed in the experimental greenhouse at the biological science department were outlined separately in two parts:

a) for the summer season, and

b) for the winter season.

4.4.1 The relative humidity, air and leaf temperature conditions observed when leaf wetness developed inside the greenhouse during summer season

Fig 4.9 and 4.10 depict the greenhouse relative humidity, air and plant temperature conditions which prevailed in the test compartment (Fig 4.9), where conditions were manipulated so that condensation occurred, and in the control compartment (Fig 4.10), where conditions were kept such that condensation did not develop. The results were measured continuously at 10 minutes averages from the 26th to 27th of February 2007, at the Biological Science Department, University of Zimbabwe. The 10 minutes time period at which the logger was averaging the results was too large and this resulted in loss of important data, especially on leaf wetness, which shows a step change of moisture from 0 % to 42 %. The averaging time was reduced to 1 minute when the winter observations for the winter results were made (Fig 4.16).

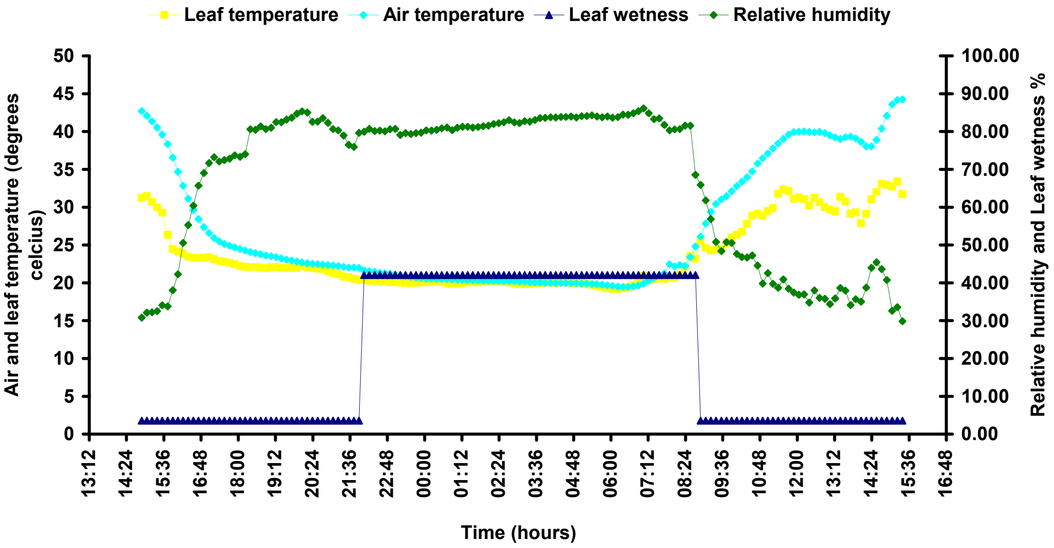

Figure 4. 9: Greenhouse relative humidity, air and plant temperature conditions in the test compartment of the experimental greenhouse at the Biological Science Department, University of Zimbabwe from 26th to 27th of February 2007.

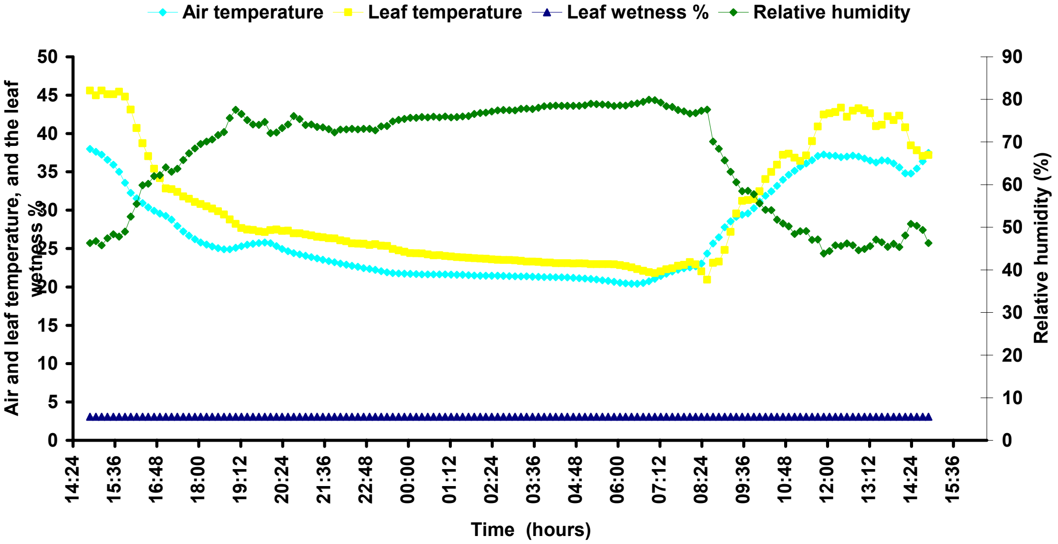

Figure 4. 10: Greenhouse relative humidity, air and plant temperature conditions in the control compartment of the experimental greenhouse at the Biological Science department, University of Zimbabwe from the 26th to 27th of February 2007,.

In Figure 4.9, early morning (00:00hrs-0800hrs) relative humidity observed for the period was always above 80 % (Fig 4.10), with the highest measured values (89 %) being recorded at sunrise. It was observed that the leaves were also wet whenever the relative humidity was above 80 %. Maximum wetness percentages (>40 %) were observed during the night until early morning (2100 to 08:30). Highest leaf wetness duration of 11 hours was recorded on a clear day. No condensation developed on plant leaves during the night periods when the relative humidity was below 80 % (Fig 4.10). The plant temperature was always above the greenhouse air temperature during the night.

4.4.1.1 Effect of relative humidity and vapour pressure deficit (Δ*e*) on leaf wetness development at 22 – 25 °C

Fig 4.11 and Fig 4.12 show the effect of vapour pressure deficit and relative humidity, respectively on dew development in a greenhouse, when the greenhouse air temperature was kept at a constant range of 22 °C to 25 °C, but varying the relative humidity from 70 % to 100 %, corresponding to Δ*e* of 0.1 kPa to 1.2 kPa. The results were recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe.

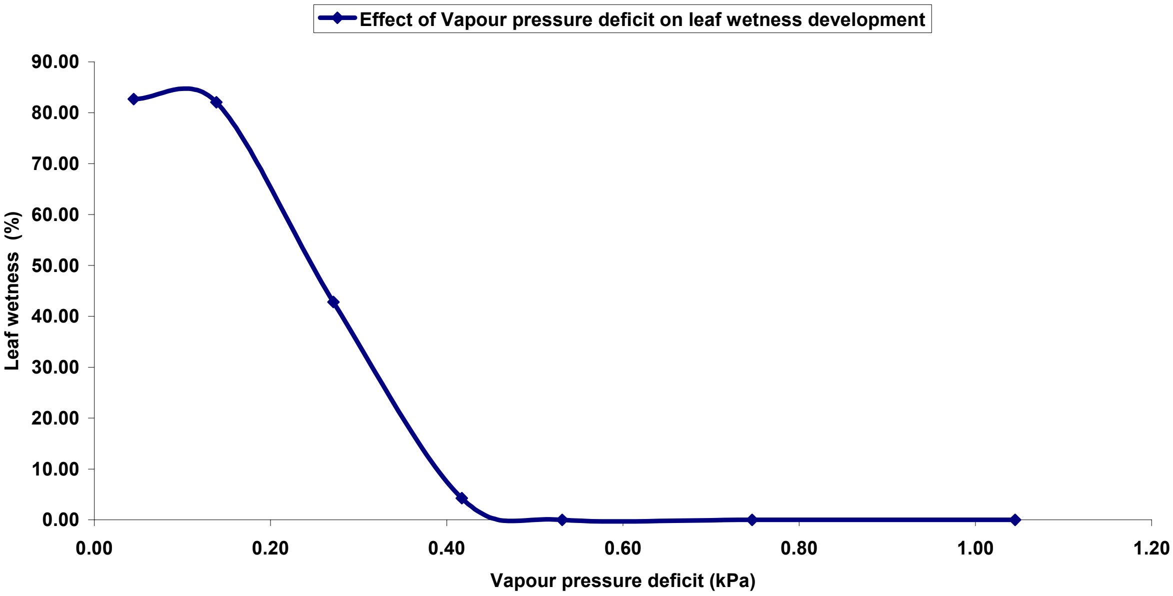

Figure 4.11: Effect of vapour pressure deficit on dew development in a greenhouse when the greenhouse air temperature was kept at a constant range of 22 °C – 25 °C, recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe.

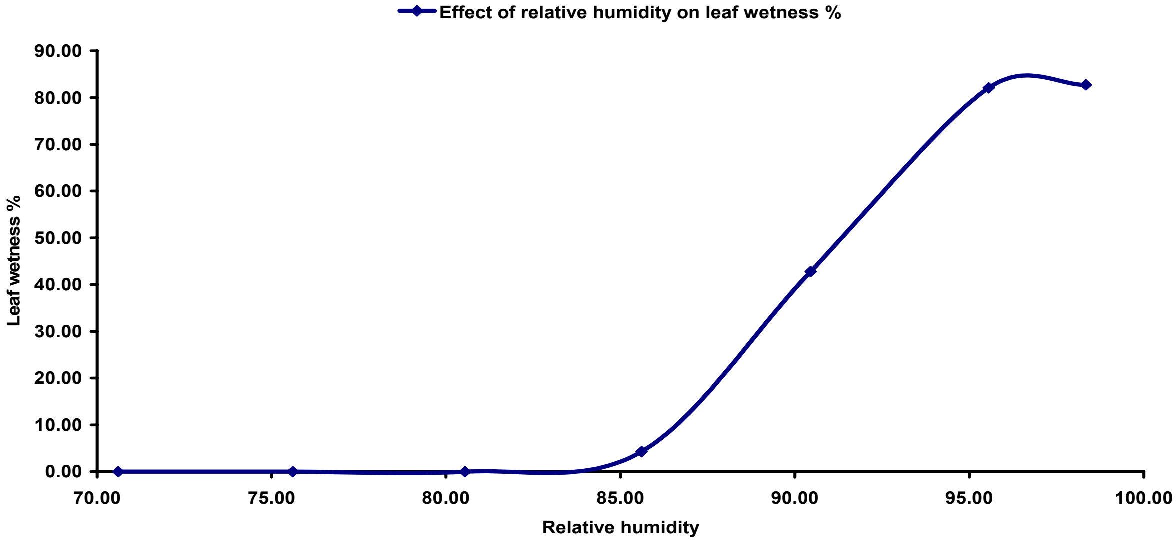

Figure 4.12: Effect of relative humidity on dew development in a greenhouse when the greenhouse air temperature was maintained at a constant range of 22 °C - 25 °C. Recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe

The leaf wetness percentage was observed to initially develop on plant leaves when the Δe was at a threshold of 0.45 kPa. Condensation process on plant leaves was found to increase with a fall in Δe, up to a maximum wetness value of 82.72 %, which was received when the Δe was at 0.2 kPa. No wetness was observed on plant leaves when the vapour pressure deficit was high (>0.45 kPa). Therefore, condensation occurred on plant leaves when the Δe range was (0.2 kPa- 0.45kPa).

A threshold relative humidity ($RH_{th)}$ of 84 % was observed Figure (4.12). Prenger, and Ling, (2000), developed relative humidity and Δe thresholds for disease prevention, corresponding to Δe of 0.20 kPa to 0.463 kPa, when the temperature and humidity was varied from 10 °C to 30 °C and 83 % to 95 %, respectively. These results compare well with the findings of Prenger and Ling's studies, where the Δe thresholds for disease prevention, were found to correspond to Δe ranging from 0.2 kPa to 0.45kPa.

4.4.1.2 The effect of vapour pressure deficit and relative humidity, on dew development in a greenhouse, during summer nights under natural conditions.

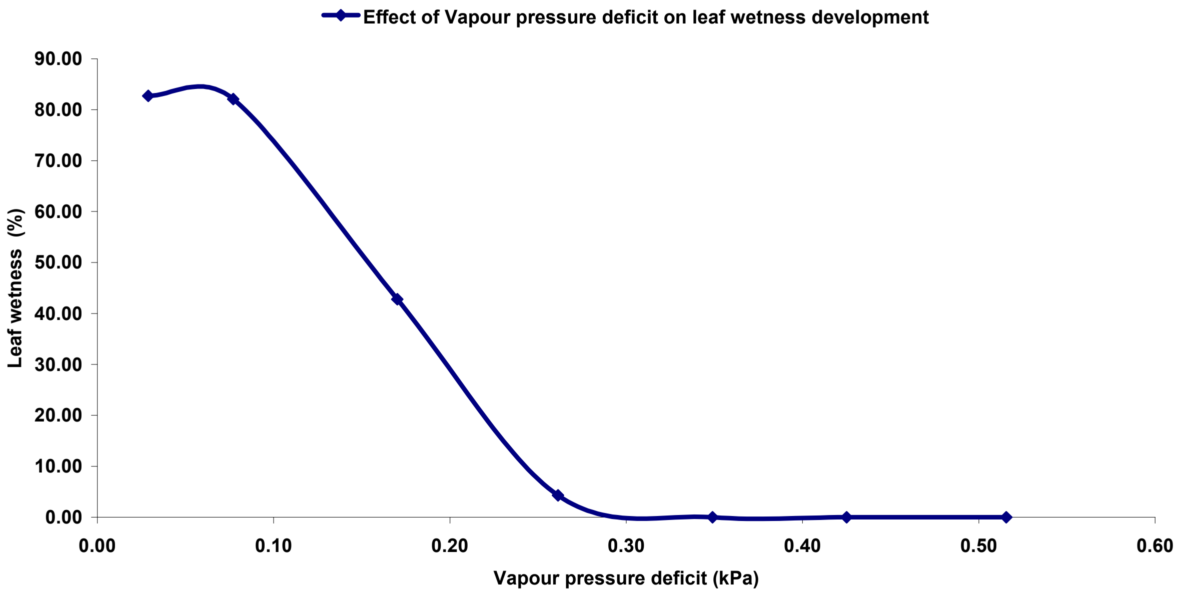

Figure 4.13: Effect of vapour pressure deficit on dew development in a greenhouse under uncontrolled night summer temperatures. Recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe.

Fig 4.13 shows the effect of vapour pressure deficit on dew development in a greenhouse, during the nights when the greenhouse air temperature was not controlled. The results were recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe 2007.

The leaf wetness percentage was observed to initially develop on plant leaves when the Δe was at a threshold of 0.3 kPa. Condensation process on plant leaves was found to increase with a fall in Δe, up to a maximum wetness value of 82.72%, which was received when the Δe was at 0.1 kPa. The summer nights temperatures were observed to range from 15°C to 17°C.

No wetness was observed on plant leaves when the vapour pressure deficit was high (>0.3 kPa). Therefore, condensation occurred on plant leaves when the Δe range was (0.1 kPa-0.3kPa).

In Fig 4.14, the greenhouse relative humidity which was also recorded during the same experiment was found to have a threshold relative humidity (Rh_{th}) of 87 %.

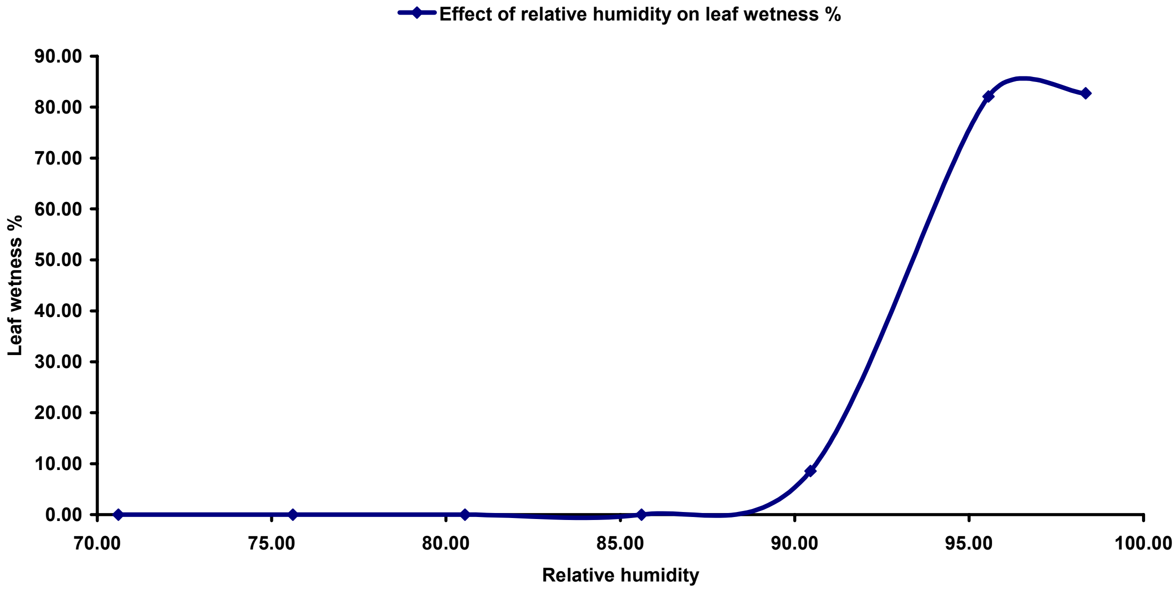

Figure 4.14: of vapour pressure deficit on dew development in a greenhouse under uncontrolled night summer temperatures. Recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe.

Fig 4.15 shows the effect of vapour pressure deficit on dew development in a greenhouse, recorded and measured continuously at 10 minutes averages from on 26th and 27th of May 2007 at the Biological Sciences Department, University of Zimbabwe. Dew development on plant leaves was initially recorded at around 2200 hrs, when the Δe was around 0.25 kPa. A step change of leaf moisture from a value of 0 to 42 % was noticed, when the Δe was 0.25 kPa at 2200 hrs. Condensation is expected to have started earlier before 2200 hrs when the Δe was lower than 0.25 kPa.

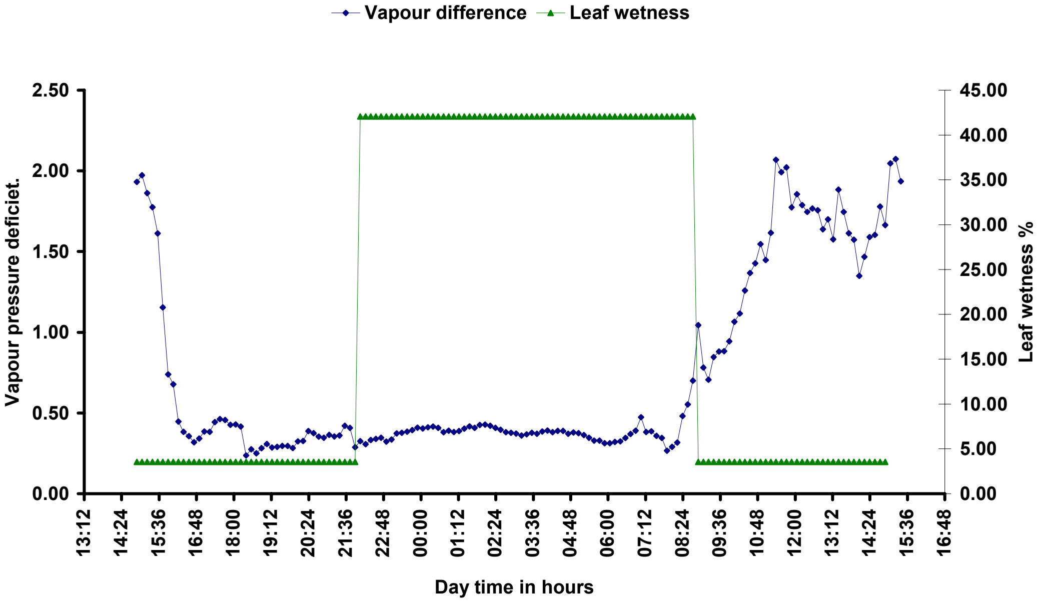

Figure 4.15: Effect of vapour pressure deficit on dew development in a greenhouse, measured continuously at 5minutes averages from the 26th to the 27th of May 2007 at the Biological science department, University of Zimbabwe.

After the initial development of dew, the Δe remained at an approximately constant range of 0.25 kPa to 0.3 kPa, until 0750hrs when it rose sharply to a Δe of 1.04 kPa during the morning (0830 hrs), when moisture disappeared completely on plant leaves. The leaf wetness on plant leaves was observed to remain uniform for the whole period. The vapour pressure deficit had been at lower values as early as 16:48 before leaf wetness was observed at around 22:00. This is not normal. Under normal conditions, condensation is expected to develop on plant leaves when the Δe approaches zero or when ever it is negative. Such a theory is supported by the fact that, when Δe approaches zero or is negative, moisture tends to move from the air towards a cooler leaf surface in response to a vapour pressure gradient (Montheith and Unsworth, 1990).

4.4.2 Observed relative humidity, air and leaf temperature conditions when leaf wetness developed inside the greenhouse during winter season

Fig 4.16 shows the greenhouse relative humidity, air and plant temperature conditions which prevailed in the test compartment, where the conditions were such that condensation occurred. The results were measured continuously at 1 minute averages (unlike 10 minutes averages in Fig 4.9) from 11th to 12th May 2007, at the Biological Science Department, University of Zimbabwe.

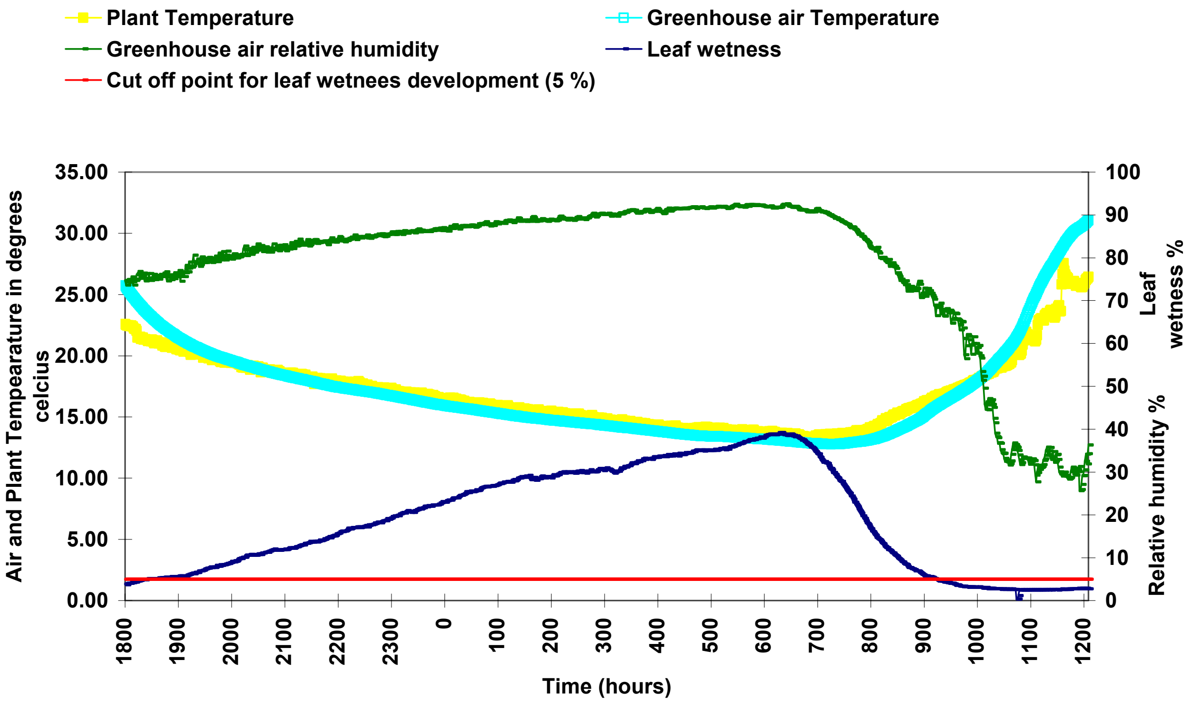

Figure 4.16: Greenhouse relative humidity, leaf wetness, plant temperature and the air temperature measured continuously at 5minutes averages 11th to 12th May 2007, at the University of Zimbabwe 2007.

In Figure 4.16, during the night period to early morning time (19:30hrs-08:00hrs) relative humidity observed for the whole period was always above 80 %, with the highest values (92%) being recorded towards sunrise. Leaf wetness was observed whenever the relative humidity was above 80% (i.e. from 19:00 to 9:00 in the following day). Maximum wetness percentages (>40 %) were observed towards sunrise (06:10). High leaf wetness duration of 15 hours was recorded. These results, together with data from the literature (Hanan, 1998), permit a relationship between dew development inside the greenhouse and the inside air temperature, relative humidity and the plant leaf temperature to be calculated.

Condensation occurred during the periods when the greenhouse air temperature was close to or below the plant temperature at night (Fig 4.16). Condensation is expected to develop on plant leaves when the relative humidity is high (> 80 %) plant temperature falls below the air temperature (Montheith and Unsworth, 1990). Theoretically, when dew has formed on the leaf surface, the leaf surface is assumed to be perfectly wet and covered by a thin film of dew. In this case, the boundary layer resistance of the leaf surface will be equal to zero, and the latent cooling will be maximal for the leaf boundary layer, thereby reducing the leaf temperature to fall below the air temperature, (Montheith and Unsworth, 1990, Jones, 1992). However, the suspicious leaf temperature measurements may have been subjected to poor contact with the leaf surface, so this may have led to errors that compromised this observation.

No leaf wetness was recorded on plant leaves during the night periods when the relative humidity was below 80 %. The greenhouse air temperature was always above the plant temperature during the night. Such conditions occurred under cloudy sky days.

Fig 4.17, shows the effect of vapour pressure deficit on dew development in a greenhouse, when the greenhouse air temperature was kept at a constant range of 9^{o}C to 12^{o}C, but varying the Δe from 0.1 kPa to 1.2 kPa. The results were recorded during the 11th to 30th May 2007, using data from the Biological science department greenhouse.

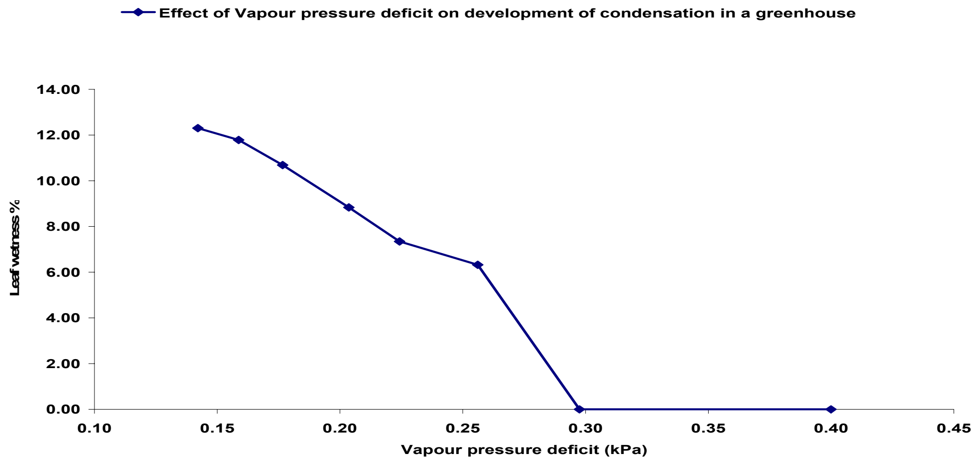

Figure 4. 17: Effect of vapour pressure deficit on dew development in a greenhouse when the greenhouse air temperature was kept at a constant range of 9 °C-12 °C, recorded between January 2007 and March 2007, at the Biological science department, University of Zimbabwe.

The leaf wetness percentage was observed to initially develop on plant leaves when the Δe was at a threshold of 0.3 kPa. Condensation process on plant leaves was found to increase with a fall in Δe, up to a maximum wetness value of 12 %, which was received when the Δe was had fallen to 0.15 kPa. No wetness was observed on plant leaves when the vapour pressure deficit was high (>0.3 kPa). Therefore, condensation occurred on plant leaves when the Δe range was (0.15 kPa- 0.3kPa).

When the same air temperature range of 9°C to 12°C was maintained, while the relative humidity varied from 70% to 100 %, a threshold relative humidity (rh_{th}) of 75 % was observed (Figure 4.18). These results also compares well with the findings made by Prenger, and Ling, (2000), where the Δe thresholds for disease prevention, were found to correspond to 0.2kPa and 0.5kPa.

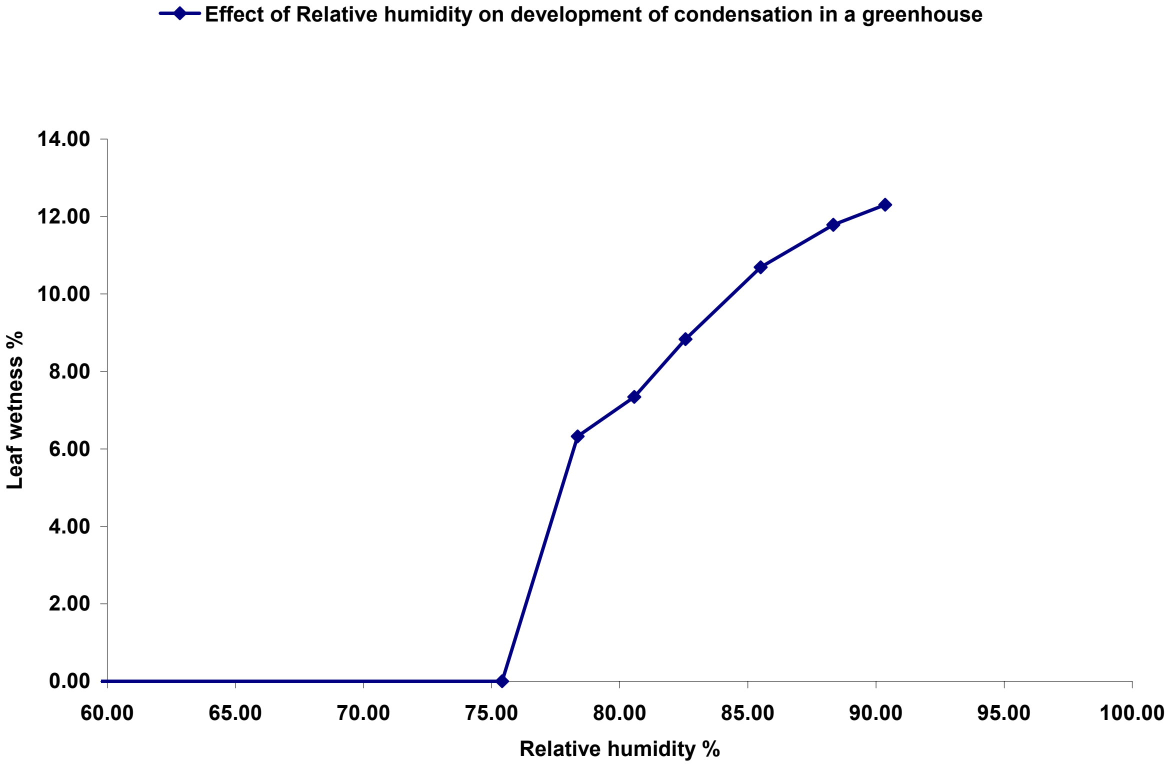

Figure4. 18: Effect of relative humidity on dew development in a greenhouse when the greenhouse air temperature was kept at a constant range of 9°C-12°C. Recorded between 11th and 24th of May 2007, at the Biological Science Department, University of Zimbabwe

In a an experiment (Fig 4.19) to investigate the effect of vapour pressure deficit on dew development in a greenhouse, recorded and measured continuously at 1 minute averages from

11th and 12th May 2007 at the Biological Sciences department, University of Zimbabwe 2007, dew development on plant leaves was initially recorded at 1830 hrs, when the Δe was around 1.15 kPa.

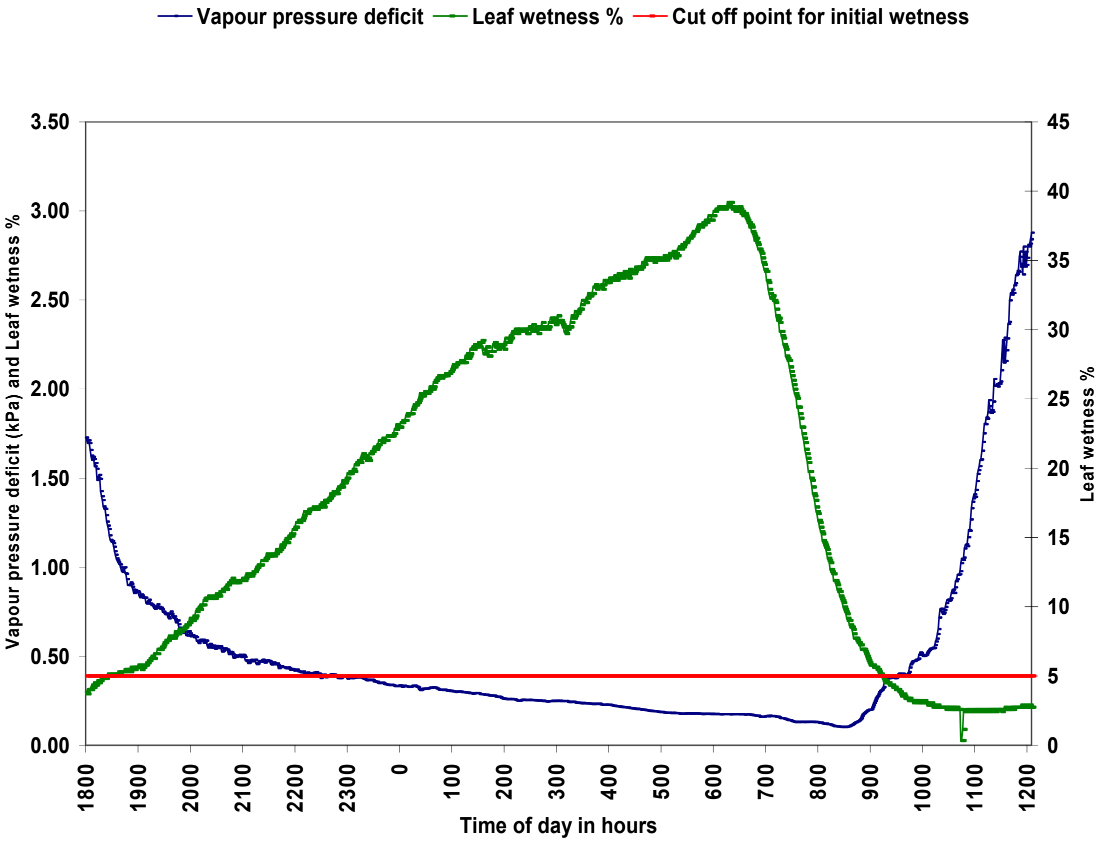

Figure 4. 19: Effect of vapour pressure deficit on dew development in a greenhouse, measured continuously at 1 minute averages from 11th to 12th of May 2007, at the Biological science department, University of Zimbabwe 2007.

The Δe fall sharply, until 1900hrs when it began to fall slowly through the whole night to the lowest value of 0.17kPa during the morning (0:830).

The leaf wetness on plant leaves was observed to increase at a steady rate, in uniform with the falling Δe, until it reached a maximum wetness value of 39 %. The time (0:610) at which the maximum wetness percentage on plant leaves occurred did not coincide with the time at which lowest value of Δe was observed. Leaf wetness began to fall at a period when the Δe was still on a downward trend. Such a condition is against theory, where maximum leaf wetness should have occurred a few minutes after the lowest vapour pressure deficit was observed (Prenger and Ling, 2000).

4.5 Model Results

The GDGCM was run using the recorded outside weather data at Floraline (Pvt.) Ltd weather station, for the period of 14th to 24th of May.

4.5.1 Outside and inside air temperature

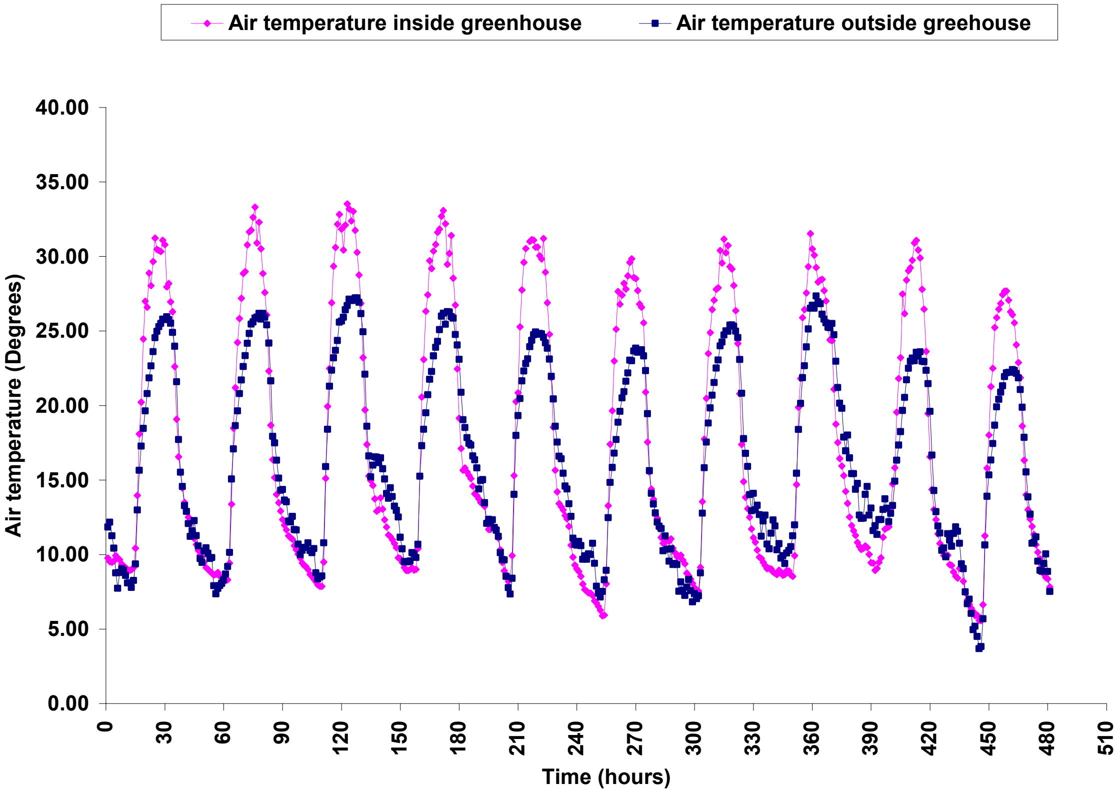

Figure4. 20: Outside and inside air temperature measured continuously at 30 minutes averages from 14th to 24th of May 2007 at Floraline (Pvt.) Ltd weather station.

Fig 4.20 depicts the outside and inside air temperatures, measured continuously on cloudless days at 30 minutes averages from 14th to 24th of May 2007, at Floraline (Pvt.) Ltd weather station. The air temperature inside the greenhouse was always higher than the outside air temperature during the day, and was mostly close to and slightly below the outside air temperature during the night. Maximum temperature (33 °C) was experienced in the greenhouse during the day, when the maximum temperature outside the greenhouse was around 27 °C. Lowest temperatures (3 °C) were observed outside the greenhouse, whilst the lowest temperature in the greenhouse was 5 °C.

4.5.2 Outside and inside air relative humidity recorded during the winter season at Floraline (Pvt.) Ltd

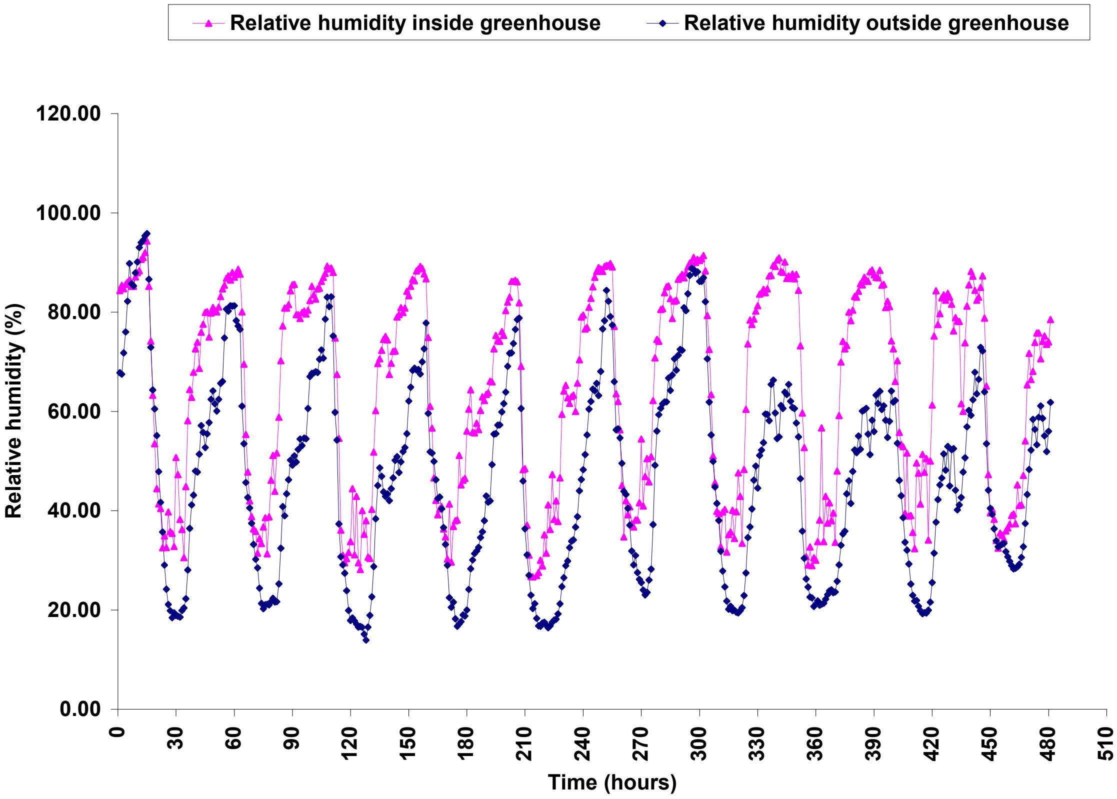

Figure 4. 21: Outside and inside air relative humidity measured continuously at 30 minutes averages from 14th of May 2007 to 24th of May 2007 at Floraline (Pvt.) Ltd weather station.

Figure 4.21 depicts outside and inside air relative humidity that was measured continuously at 30 minutes averages from 14th of May 2007 to 24th of May 2007 at Floraline (Pvt.) Ltd weather station. The relative humidity inside the greenhouse was always higher than the outside relative humidity during both the day and night periods, with the highest values (94 %) being recorded towards sunrise. Early morning time (04:00hrs-0800hrs) relative humidity at outside and inside the greenhouse was always above 80 %. Lowest relative humidity levels (13 %) were observed outside the greenhouse during the day time hours, when the relative humidity inside the greenhouse stayed above 26%.

4.6 Simulated results

The model produced simulated results which include air temperature, relative humidity, plant temperature, stomatal resistance, canopy surface wetness and global radiation. However, since one of the main objectives of this study is to validate and calibrate a condensation sub-model, only simulated results of air temperature, relative humidity, plant temperature and canopy surface wetness were discussed and then compared with measured results.

4.6.1 Comparison of temperature measured in the greenhouse and the temperatures simulated by the model

Fig 4.22 depicts the simulated and measured air temperature observed inside the greenhouse. The data was recoded at 30 minutes averages from 14th to 24th May 2007; at Floraline (Pvt.) Ltd weather station.

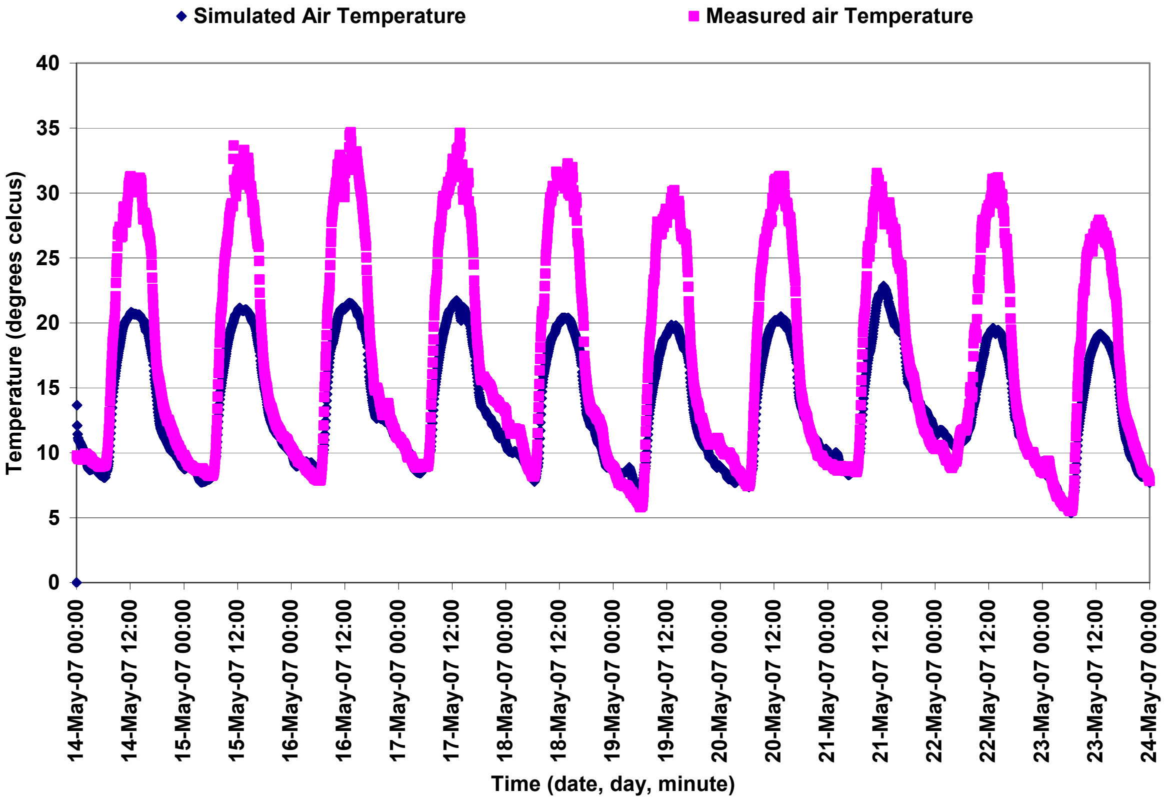

Figure 4. 22: Measured air temperature, and the model simulated air temperature, measured continuously at 30 minutes averages from 14th to 24th of May 2007 at Floraline (Pvt.) Ltd weather station.

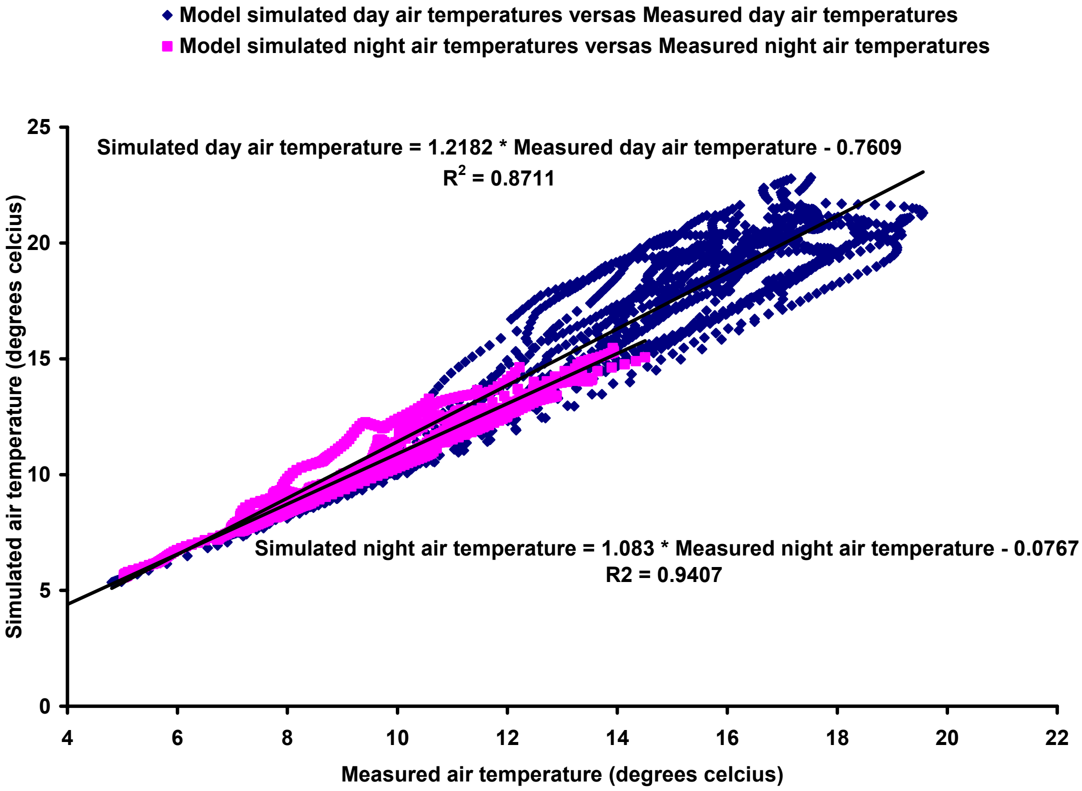

Figure4. 23: Measured air temperature, and the model simulated air temperature, measured continuously at 30 minutes averages from 14th to 24th of May 2007 at Floraline (Pvt.) Ltd weather station

The model was good in simulating lower temperatures, which occurred during night periods (Fig 4.22). A comparison of the model results and the measured results showed good predictions, with a regression co-efficient of 0.9407 during the night (Fig 4.23). Limited precision of the model simulations were observed during the day (R^2=0.8711), and this occurred when the temperatures were high. The measured day time temperatures were always higher than the model results, with an underestimation close to 50%. Although the temperature underestimation of the model is clear in Fig 4.22, the regression analysis (R^2=0.8711) failed to show this scenario. Calculation of the RSME was 2.23 °C. Surprisingly, the model gave daytime temperatures inside the greenhouse which are less than the external temperatures. Unsatisfactory simulated results at high temperatures during the day may not affect the model‘s calculation of condensation, since condensation occurs at night when temperatures are relatively low. Therefore, the main objective of the study, which is to determine the conditions when condensation develops on the leaves, may not be affected.

4.6.2 Comparison of relative humidity measured in the greenhouse and the relative humidity simulated by the model

Fig 4.24 shows the observed relative humidity measured inside the greenhouse and the relative humidity that was simulated by the model. The results were recoded at 30 minutes averages from 14th to 24th May 2007, at an automatic weather station at Floraline (Pvt.) Ltd.

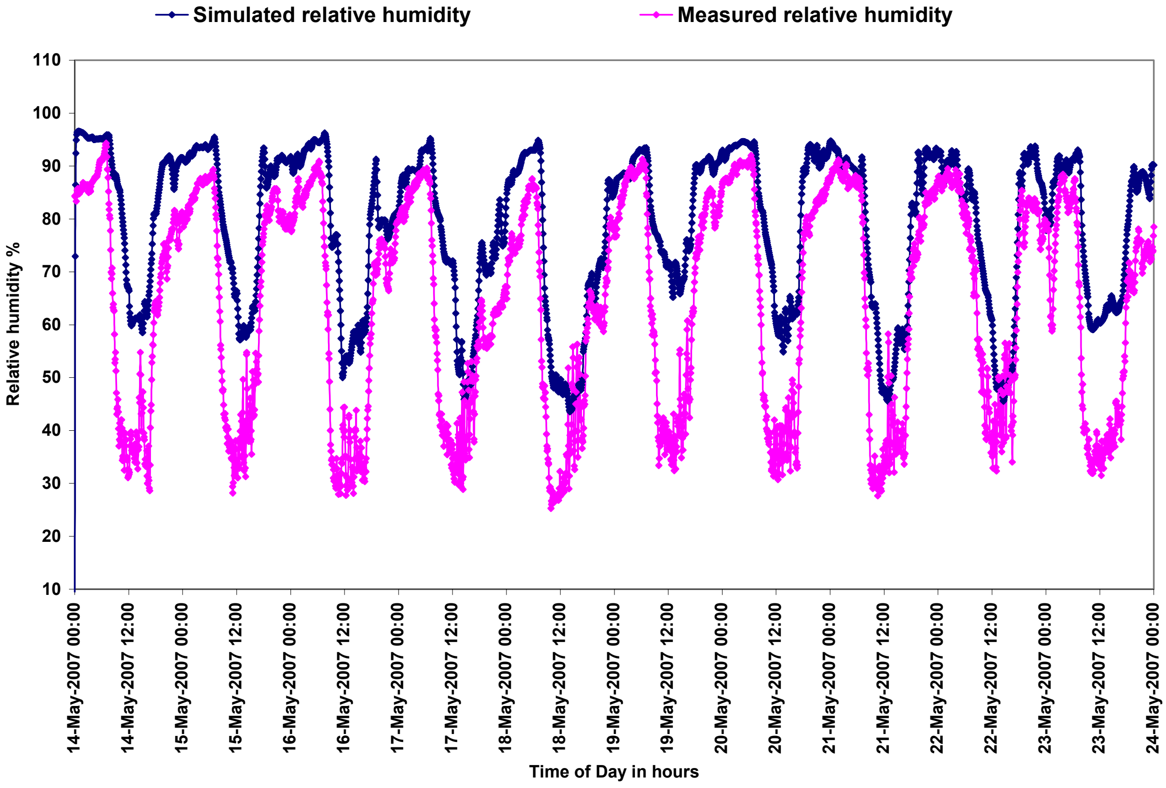

Figure 4.24: Relative humidity, measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station.

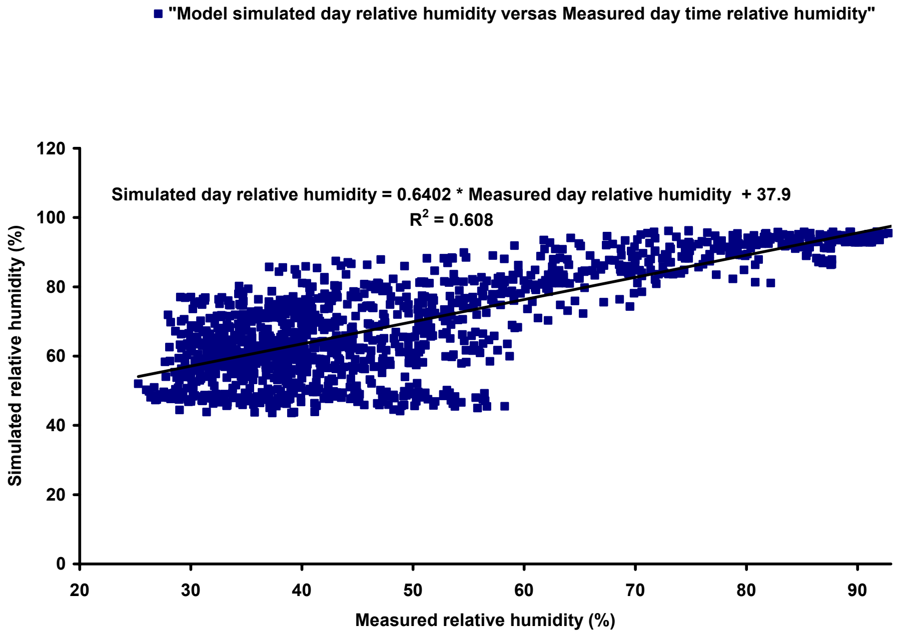

Figure 4. 25: Relative humidity, measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station.

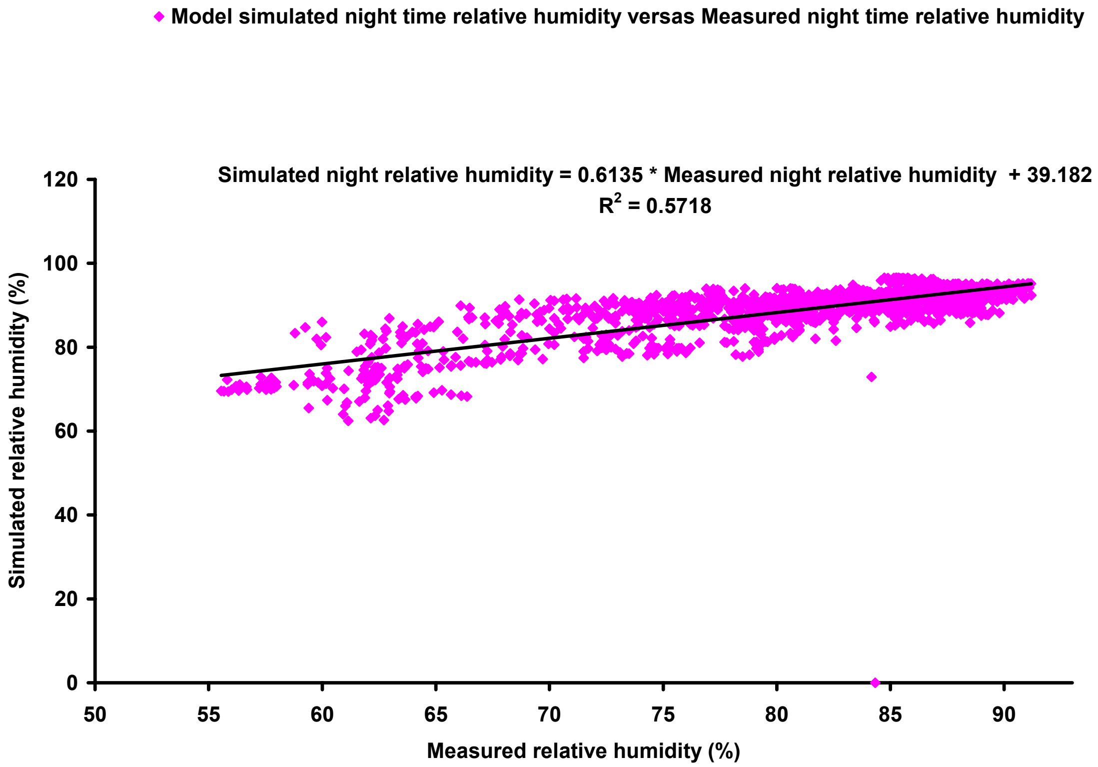

Figure 4. 26: Relative humidity, measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station

The model was also good in simulating relative humidity during the night periods when the measured relative humidity was always above 50% (Fig 4.24). Underestimated relative humidity simulated results were observed during the day when the relative humidity was below 50%. A regression analysis (Fig 4.25) comparing the model results to the measured results showed an average relationship (R^2=0.6402) during the day, and (R^2=0.5718) during the night periods. The calculated RSME was 22.14 % The unsatisfactory simulated results at low relative humidity levels during the day may not affect the model‘s calculation of condensation, since condensation occurs at night when temperatures are relatively low.

4.6.3 Comparison of the plant leaf temperatures measured in the greenhouse and the simulated plant leaf temperatures from the model

Fig 4.26 shows the plant leaf temperatures measured inside the greenhouse and the simulated plant leaf temperatures that were predicted by the model. The plant temperatures were measured using fine thermocouples and recoded at 5 minutes averages from 14th May 2007 to 24th May 2007, inside the commercial greenhouse at Floraline (Pvt.) Ltd.

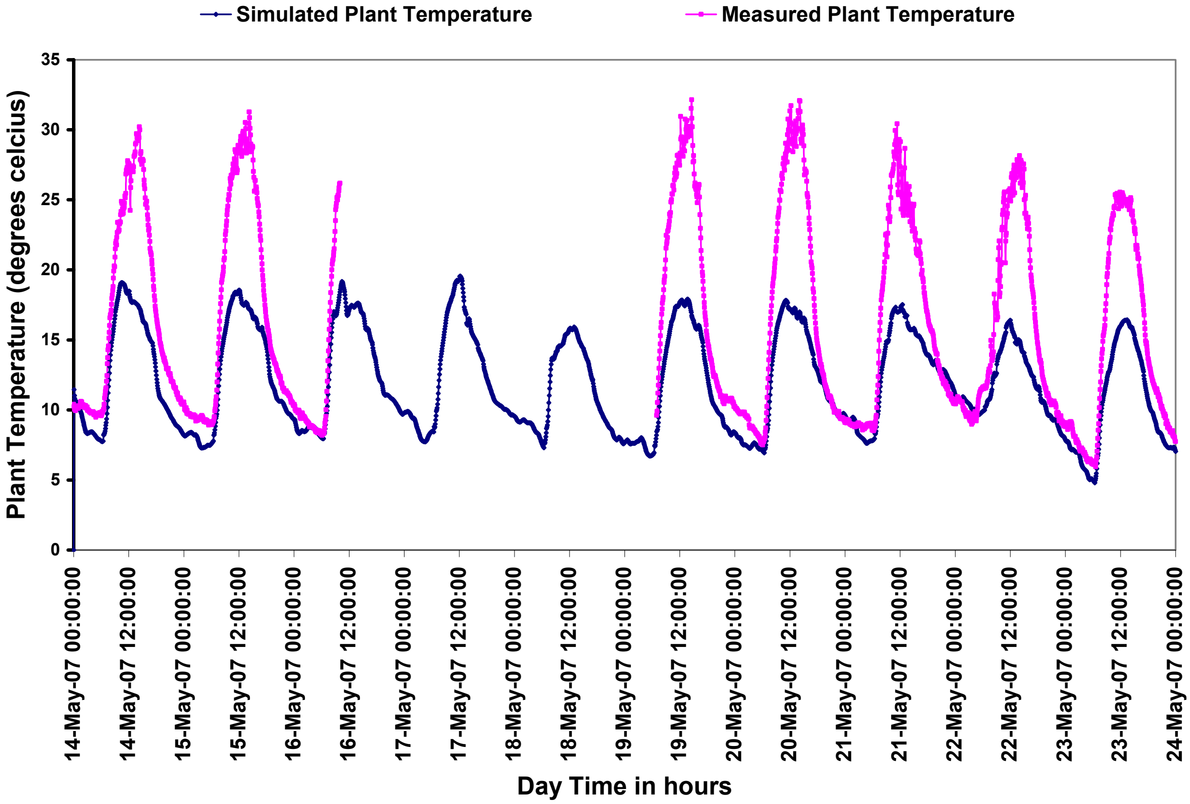

Figure 4. 27: Plant leaf temperature measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station.

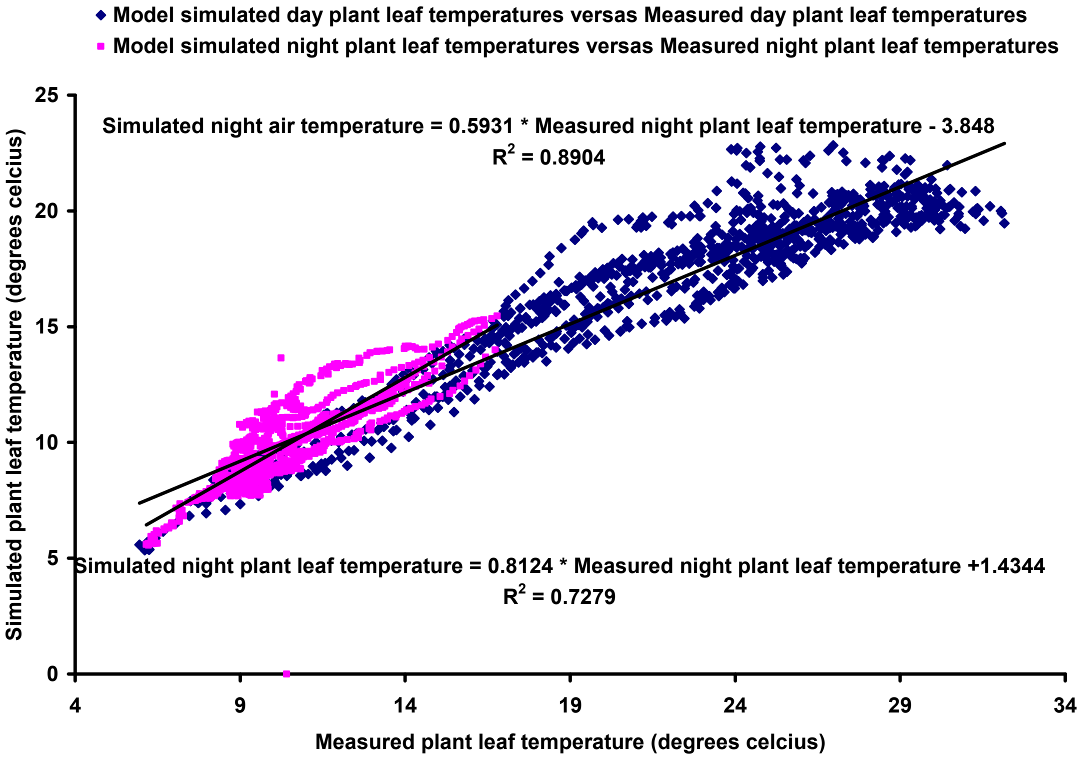

Figure 4. 28: Plant leaf temperature measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station.

The measured leaf temperatures were always higher than the simulated plant leaf temperatures during the day, and close to or equal to the air temperature during the night periods (Fig 4.26). In general, night leaf temperatures calculated by the model (Fig 4.27), reproduces quite satisfactorily the measured temperatures especially during the night (R^2=0.8904, RSME=10.50 °C). During the day period, the model underestimated temperatures by close to 12°C. Variation of such a magnitude renders the model unreliable to predict day temperatures of a greenhouse for disease control scenarios. However, the model simulations during the night and at lower temperatures below 20 °C may offer a possibility of managing the monitoring and control of low plant temperatures in the greenhouse for the control of fungal disease such as botrytis.

4.6.4 Comparison of the canopy surface wetness measured in the greenhouse and the canopy surface wetness calculated by the model

Fig 4.28 shows the canopy surface wetness measured inside the greenhouse and the simulated leaf canopy surface wetness that was developed by the model. The results were recorded at 5 minutes averages from 14th of May 2007 to 24th 0f May 2007, at Floraline (Pvt.) Ltd weather station.

.

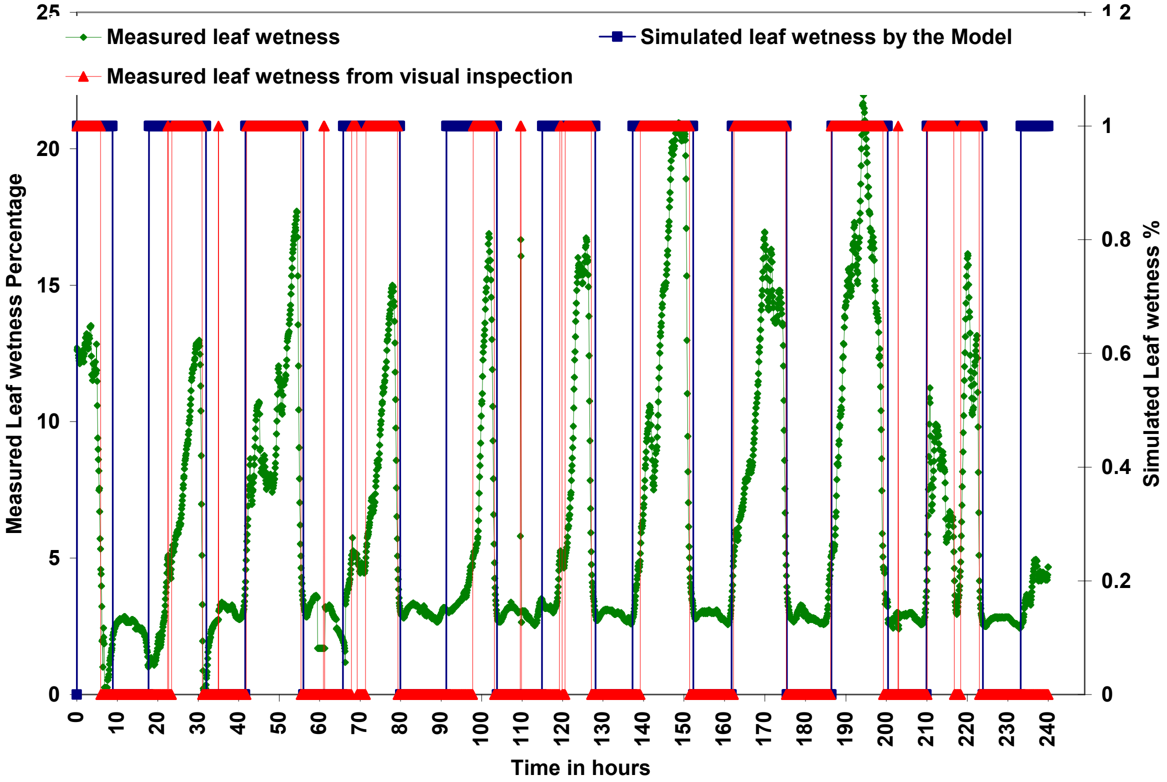

Figure 4. 29: Simulated plant leaf wetness and plant leaf wetness measured continuously at 30 minutes averages from 14th to the 24th of May 2007, at Floraline (Pvt.) Ltd weather station.

The model identified presence and absence of leaf wetness in most of the occasions (82%). Just like most models that have been developed before (Kim *et al*., 2004), the error rate of estimating the presence and absence of wetness was high towards sunrise and sunset. The model tends to over estimate the presence of moisture towards sunset and sunrise. Sunset and sunrise are transitional events in energy exchanges on a surface in terms of shortwave radiation (Kim *et al*., 2004). Therefore simulation errors are likely to occur during such period of the day. In separate experiments carried out by Sentelhas, *et al*. (2006), and (Kim *et al*. (2004), problems of underestimations and overestimations of the wetness durations, especially at sunset was also observed. However, the comparison of the simulated results, together with measurements shows that the model allows prediction of condensation to within 82 %.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main aim of this study was to experimentally determine and forecast the conditions when dew forms on leaf surfaces from measured ambient conditions. Condensation on the leaf surfaces was observed whenever the relative humidity was high (80%) and the foliage of plants in the greenhouse was close to as well as slightly above the surrounding air temperature. Because of its incorporation of both temperature and humidity in its calculation, vapour pressure deficit (Δe) was found to be a convenient indicator of the condensation potential. Condensation process inside the greenhouse was observed to occur at different Δe thresholds (Δe_{th}) depending on the season and nature of the night temperatures. During the night summer days, Δe_{th} range of 0.1 kPa to 0.27 kPa and corresponding to relative humidity threshold of 83% to 87% was observed. The Δe threshold range during winter nights was 0.15 kPa to 0.3 kPa and was corresponding to relative humidity threshold of 75% to 80%. When temperature was maintained constant at a range of 22°C -25°C, the Δe threshold (Δe_{th}) range of (0.2 kPa to 0.45 kPa), corresponding to relative humidity threshold of 84% to 90% was observed. Therefore, environmental management of a greenhouse in Zimbabwe must be practiced in such a way that the set limits of vapour pressure deficit and relative humidity established in this study are prevented from taking place using heaters, fans, and vents so as to culturally control fungal and bacterial diseases.

It was found that night-time relative humidity in the greenhouse was always above 80% for the whole study period. Average night-time temperatures of 15°C were experienced during the summer period. Plant temperature was mostly close to or below air temperature during the day and mostly close to or equal to the air temperature just before sunrise.

Comparison of measured and calculated temperatures and saturation deficits in the plant canopy showed a good agreement for night measurements, but the measurements during the day period were unsatisfactory.

In general, the night plant temperatures below 20ºC, calculated by the model, compares quite satisfactorily with the measured temperatures. The simulated leaf wetness comparison with measurements shows that the model allows prediction of condensation to within 82% of the sampled occasions. The fact that the mean temperature of the plant differs from that of the air and thus produces a quite different saturation deficit has important implications for the disease incidence. The model gives Δe values, which can be used to predict disease-causing climate conditions, while taking into account different temperature levels.

In prediction of leaf wetness on plant leaves, the model programming was upgraded from a vapour pressure deficit threshold of 0.3kPa to use a threshold of 0.45kPa. Therefore, a vegetative condensation model that offers the possibility to verify whether condensation is present on the leaves was adapted and validated. Therefore, the Gembloux Greenhouse Climate model may be relied upon to predict plant leaf wetness, plant and air temperatures, relative humidity and hence the vapour pressure deficit inside the greenhouse. However more work still needs to be done so that prediction of both air plant temperatures are satisfactorily simulated to allow environmental management of the greenhouse for disease control. This research project was able to answer all the questions set by the objectives of the study, and also to come up with ways of improving environmental management in Zimbabwean greenhouses.

5.2 Recommendations

- The set vapour pressure deficit threshold limits in the study are recommended for use to farmers in a greenhouse for environmental management in the production of rose. Farmers are advised to employ the normal environmental control instruments such as heaters, funs, and humidifiers when controlling the greenhouse vapour pressure deficit, so that the set threshold limits obtained in the study are not exceeded.
- Condensation process in roses and other crops is a function of the leaf area index and age of the plant. The age parameter is not fully accounted for in the model. Further research is therefore recommended in modeling plant age as a function of condensation process into the model.
- To increase accuracy and reliability, it is recommended that the study should be re-done across different climatic regions and bi-seasonal conditions at the same period of time so as to investigate the reliability of the model in decision making for the whole country.

References

Alderman, S.C., Lacy, M. L., and Everts, K. L. 1985. Influence of interruptions of dew periods on numbers of lesions produced on onion by *Botrytis squamosa*. Phytopathology 75:808-810.

Anderson, M.C., Bland, W.L, Norman, J.M., Diak, G.D., 2001. Canopy wetness and humidity prediction using satellite and synoptic-scale meteorological observations. Plant Dis. 85, 1018-1026

Anon, K., 1998. International Code Of Conduct for the Production of cut-flowers: August 1998.

Baier, W., 1966. Studies on dew formation under semi-arid conditions. Agric. Meteorol. 3: 103-112

Baille, A., Kittas, C., Giaglaras, P., 1994. The plastic film and the plant canopy. . Agric. Meteorol. 9: 374-385.

Bakker, J. C., Bot, G. P. A., Challa, H., and Van de Braak, N. J., 1995. Greenhouse Climate Control, an integrated approach. Wageningen Press. 135-155.

Blad, B.L, Steadman, J.R, and Weiss, A., 1978. Canopy structure and and irrigation influence on white mold disease and microclimate of dry edible beans. Ecology Epiemiol 68:1431-1437.

Blakeman, J. P., 1980. Behavior of copnidia on aerial plant surfaces. Pages 115-151: The Biology opf Botrytis. Coley-Smith. J. R, Verhoeff K. and Jarvis W. R., eds. Academic Press, London.

Boulard, C., Draoui, M., 1995. Air Velocity in a Naturally Ventilated Greenhouse. Jounal of Zhejiang University Science.

Burrage, S.W., 1972. Dew on Wheat. Agric. Meteorol 10: 3-12.

Carre, D. D., and Coyier, D. L., 1984. Influence of atmospheric humidity and free water on germ tube growth of *Botrytis cinerea*. (Abstract) Phytopathology 74:1136.

Davies, R., 2000. The Impact of Globalization on local Communities: A case study of the cut-flower industry in Zimbabwe. ILO/SAMAT Discussion paper No 13.

Elad, Y., and Shtienberg, D., 1995. *Botrytis cinerea* in greenhouse vegetables; Chemical, cultural, physiological and biological controls and their integration. Integr. Pest Manage. Rev. 1:15-29.

Epton, H. A. S., and Richmond, D. V., 1980. Formation, structure and germination of conidia. Pages 41-83 in: The Biology of Botrytis. Coley- Smith J. R,. Verhoeff K, and Jarvis W. R, eds. Academic Press, London.

Fitter A.H and Hay R.K.M., 1989. Environmental Physiology of Plants 2nd Ed. Published by Academic Press Limited. Pg 188- 190.

Hanan J.J., 1998. Greenhouses. Advanced Technology for Protected Horticulture. CRC Press Pg 1, 286, 349, 352.

Huber, L., and Gillespie, T.J., 1992. Modelling leaf wetness in relation to plant-disease epidemiology. Ann. Rev. Phytopathol. 30: 553-577.

Javis, W. R.,1989. Managing disease in greenhouse crops. Plant. Dis. 73:190-194.

Jewett T.J and Jarvis W.R 2001. Management of the greenhouse microclimate in relation to disease control: a review Agronomie 21: page 351-366

Kim, K. S., Taylor, S. E., Gleason, M. L. and Koehler, K. J., 2002. Model to Enhance Site-Specific Estimation of Leaf Wetness Duration. Iowa State University, Ames 50011. Plant Disease/ February 2002, 86, 179-185. Downloaded from the address (www.apsnet.org/pdfs/2001/1217-02s.pdf)

Kim, K.S., Taylor, S.E., Gleason, M.L., 2004. Estimation of Leaf Wetness Duration Using Empirical Models in Northwestern Cost Rica, Fifth Conference of Agriculture and Forest Meteorology pp 54-57.

Kittas, C., Baille, A., Giaglaras, P., 1999. Influence of covering Meterial and Shading on the Spectral Distribution of light in Greenhouse. . Agric. Meteorol. 6: 263-274.

Linde, M. and Shishkoff, N., 2003. quoted in Encyclopedia Of Rose Science. Edited by Roberts A. V., Debenter T and Gudin S. Volume one. ElSEVIER academic press.

Liemt, G., 1998. The world cut flower industry: Trends amd Prospects. ILO Geneva.

Lomas, J., 1965. Note on dew duration recorders under semiarid conditions. Agric. Meteorol. 2: 351-359.

Luo, W., Goudriaan, J., 1990. Analysis of leaf wetness in the rice crop caused by dew formation-a simulation study. In: Proceedings of symposium on Practical Applications of Agrometeorology in plant protection. Firenze, Italy, pp. 551-560.

Luo, W., Goudriaan, J., 1999. Effects of altering water temperature on leaf wetness in paddy rice crops. Agric. Meteorol. 97: 33-42.

Luo, W., Goudriaan, J., 2000. Dew formation on rice under varying durations of nocturnal radiative loss. Agric. Meteorol. 104: 303-313.

Magarey R.D., Weiss, A., Gillespie, T.J., Huber, L., Seem R.C., 2005. Estimating Surface wetness on plnts. In: Hatfield, J.L., Baker, J.M., Oudemans, P.V., 2001. Site-specific weather information without on-site sensors. Plant Dis. 86: 4-13.

Magarey R.D., Russo J.M., Seem R.C, and Gadoury D.M., 2004. Surface wetness duration under controlled environmental conditions. Agric. For. Meteorol. 128, 111-122.

Magarey, R.D., Seem, R.C, Russo J.M., 2006.Grape canopy surface wetness simulation versus visualization and measurement. Agric. For. Meteorol. 139, 373-381.

Mashonjowa, E., 2001. The effect of Covering Material on Plant Microclimate. Msc thesis. Agricultural Meteorology, University of Zimbabwe.

Marois, J. J., Redmond, J. C., and MacDonald, J. D., 1988. Quantification of the impact of environment on the susceptibility of Rosa hybryda flowers to *Botrytis cinerea*. J. Am. Soc. Hortic. Sci. 113: 842-845.

Monteith, J.L and Unsworth, M., 1990. Principles of Environmental Physics. Second edition, Athenaeum Press.

Monteith, J.L., Butler, D.R., 1979. Dew and thermal lag: a model for cocao pods. QJR Meteorol. Soc. 105, 207-215.

Morgan, W. M., 1984. The effect of night temperature and glasshouse ventilation on the incidence of *Botrytis cinerea* in a late planted tomato crop. Crop Prot. 3: 243-251.

Noffsinger, T.L., 1965. Survey of techniques for measuring dew. Humidity and Moisture (A. Wexler, ed.), Meas. Contr. Sci. Ind. 2 : 523-531.

O'Neill, T. M, Shtienberg, D, and Elad, Y., 1997. Effects of some Host and Microclimate Factors on Infection of Tomato Stems by *Botrytis cinerea*. Plant Dis. 81:36-40.

Papastamati K., McCartney H.A., Van den Bosch F., 2003. Modelling leaf wetness duration during the rosette stage of oilseed rape. Agricultural and Forestry Meteorology 123, 2004: 69-78.

Pasipanodya, T. T., 2005. Modelling of Greenhouse Microclimate for Rose Production in Zimbabwe. MSc thesis, University of Zimbabwe.

Pedro Jr., M.J., Gillespie, T.J., 1982a. Estimating dew duration. I. Utilizing micrometeorological data. Agric. Meteorol. 27: 285-296.

Pedro Jr., M.J., Gillespie, T.J., 1982b. Estimating dew duration. II. Utilizing standard weather station data. Agric. Meteorol. 25, 297-310.

Pieters, J.G 2002., Greenhouse climate modelling. From fundamental thermodynamics to detailed climate mechanism.

Pieters J. G. and Deltour J. M. 1997. Performances of greenhouses with the presence of condensation on cladding. J. Agric. Engng. Research. 68, 125-137.

Pollet, I.V., 2002. Radiation transmission through dry and condensate covered greenhouse cladding materials. PhD Thesis. Facultiet Landbouwkundige en Toegepaste, Biologische Werenschappen, Universitiet Gent.

Prenger, J.J. and P.P. Ling., 2000. "Greenhouse Condensation Control.": Understanding and using vapor Pressure Deficit (Δ*e*) *Fact Sheet (Series) AEX-800.* Ohio State University Extension, Columbus, OH (**AEX-804-01)**

Rao, P.S., Gillespie, T.J., Schaafsma, A.W., 1998. Estimating wetness duration on maize ears from meteorological data. Agric. Meteorol. 25, 283-296.

Rosenberg, N.J., Blad, B.L, and Verma, S.B., 1983. Microclimate the biological environment 2nd Edition. Published by John Wiley and Sons.

Salmas, J., Glandorf, D. C. M., Picavet, E. D., and Verhoeff, K., 1989. Effects of temperature, relative humidity and age of conidia on the incidedence of spotting on gerbera flowers caused by Botrytis cinerea. Plant Pathology. 95:51-64.

Schuh, W., 1993. Influence of interrupted dew periods, relative humidity, and light on disease severity and latent infections caused by *Cerospora Kikuchii* on Soyabean. Phytopathology 83:109-113.

Schwinn, F. J., 1992. Significance of fungal pathogens in crop production. Pestic. Outlook 3:18-28.

Semboja, H.H., Mbelwa, R., 1999. Community and Economic Impact of Export Diversification: The cut-flower Industry in Tanzania. ILO, Geneva, mimeo.

Sentelhas, P.C., Gillespie, T.J., Gleason M.L., Monteiro, J. B. M., Pezzopane, J. R. M and Pedro. M. J., 2006. Evaluation of a Penman-Monteith approach to provide "reference" and crop canopy leaf wetness duration estimates. Agric. For. Meteorol. 141, 105-117.

Sentelhas, P.C., Gillespie, T.J., Gleason M.L., Gleason, M.L, Monteiro, J.E.B.A., Helland, S.T., 2004. Operational exposure of leaf wetness sensors. Agric. For. Meteorol. 126, 59-72.

Shtienberg, D., and Elad, Y., 1996. Icorporation of Weather Forecasting in Integrated, Biological- Chemical Management of *Botrytis cinerea*

Stenghellini, C., 1987. Measurements and Estimation of Transpiration of a soiless Rose crop in a Greenhouse. For. Meteorol. 131, 49-58.

Uchida Frausto, H.; Pieters, J.G.; Deltour, J.M., 2003. Modelling Greenhouse Temperature by means of Auto Regressive Models. *Biosystems Engineering* 84, 2: 147-157.

Wallin, J.R., 1967. Agrometeorological aspects of dew. Agricultural and Forestry Meteorology. 4: 85-102.

Wang, S. and Boulard, T., 2000. Predicting the microclimate in a naturally ventilated plastic house in a Mediterranean climate. Journal of Agricultural Engineering Research, 75, 27-38.

Webster 1913., Quoted in an internet address www.online dictionary. Datasegment. Com/word/china+rose.

Weiss, A., L.E Hipps, B.L. Blad, and Steadman, J.R.., 1980. Comparison of within canopy microlimate and white mold disease *(sclerotina sclerotiorum)* development in dry edible beans as influenced by canopy structure and irrigation. Agric Metorol 22:11-21.

Wilks, D.S., Shen, K.W., 1991. Threshold Relative-Humidity Duration Forecasts for Plant-Disease Prediction. J Apply. Meteorol. 30, 463-477.

Xu, X. and Pettitt, T., 2003. quoted in Encyclopedia Of Rose Science. Edited by Roberts A. V., Debenter T and Gudin S. Volume one. El Sevier Academic Press.

Yang, X., 1995. Greenhouse micrometeorology and estimation of heat and water vapour fluxes. University of Connecticut. Storrs, CT06269, USA. J. Agric Engng Res 61, 227-238.

Yunis, H., Shteinberg, D., Elad, Y., and Mahrer, Y., 1994. Quantitative approach for modeling outbreaks of gray mold epidemies in non- heated cucumber greenhouses. Crop. Prot. 13:99-104.