EVALUATION AND MODELLING OF DIFFERENT GREENHOUSE MICROCLIMATES UNDER SOUTH AFRICAN AGRO-CLIMATIC CONDITIONS

E du Plessis

LITERATURE REVIEW

Submitted in partial fulfilment of the requirements
MScEng (Agriculture)
School of Engineering
University of KwaZulu-Natal
Pietermaritzburg
2014

Supervisor: Prof TS Workneh
Co-supervisor: Prof M Laing

PREFACE

I .... declare that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

(iv) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  (a) their words have been re-written, but the general information attributed to them has been referenced;

  (b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced.

(v) Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated, in detail, which part of the publication was actually written by myself alone and have fully referenced such publications.

(vi) This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed:

Supervisor:

Co-supervisor:

ABSTRACT

Greenhouse crop production has great potential for contributing towards poverty and food insecurity resolution in Southern Africa. Moreover, greenhouse food plant production technologies are expected to play a major role in reducing the effect of climate change of food production in Africa. Controlled environment agriculture are becoming more popular in South Africa. It is, however, often associated with high capital and operating costs. There is, however, not much empirical data available in literature. This literature review focuses on greenhouse climate parameters, climate control installations, greenhouse designs, greenhouse micro-climate modelling, agro-climatic conditions in South Africa, greenhouses in South Africa, different crops and their requirements and greenhouse installation costs. The literature shows that limited knowledge exists and very limited reviews have been done regarding the performance of different greenhouse structures and designs for local agro-climatic conditions in South Africa. Greenhouse cooling systems and the evaluation thereof, are especially relevant to the South African climate and for providing a solution to the problems experienced as a result of over-heating inside greenhouses. Several different cooling systems are locally available and installed throughout the country. Due to the lack of scientific knowledge, it is required to predict the performance of different greenhouse structures and cooling systems regarding internal micro-climate for different external agro-climatic conditions in South Africa, by generating and using experimental data and microclimate empirical models. Literature also shows that there is not much cost-benefit analysis data available for the different greenhouses. Thus, it is important that costs associated with each system should be evaluated and compared against the benefits and demand for different types of greenhouse and farming operations. Four different greenhouses, located in Pietermaritzburg, Kwa-Zulu Natal, will be used for microclimate data collection and to micro-climate and crop yield performance will be evaluated. Three mathematical equations are selected for fitting the experimental microclimate data and the coefficients of the three equations will be developed. In addition, four different varieties of lettuce crops will be planted in each greenhouse and their growth will be monitored.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS OR SYMBOLS, OR GLOSSARY OF TERMS

CO_2	carbon dioxide
˚C	degrees Celsius
ha	hectares
K	Kelvin
kPa	kilo Pascal
m	meter
µ	micro
ppm	parts per million
Pa	Pascal
S	seconds
W	Watt

1 INTRODUCTION

Greenhouse production can be traced back to the time of the Roman Empire, where cucumbers were grown under light frames and sheets of transparent stone and heated by fermenting animal manure (Jensen, 1999). There is little available literature on greenhouse production between these times and the thirteenth century (Venter, 2010). Only during the 1600's that was it proven that several techniques were used for heating horticultural crops against the cold. The first glass houses were built in the 1700's and were mostly used for the production of fruit crops and rarely for vegetable production. The greenhouse food production industry only started to grow when polyethylene was first used as a greenhouse cover in 1948 (Jensen, 1999).

Climate control systems, such as ventilation, cooling, humidification, heating and artificial lighting, have developed with the greenhouse and since the 1960's. Greenhouses have in some cases developed into more than a plant protector, and, can be seen as plant factories, where almost every aspect of the production system can be automated and optimized (Jensen, 1999).

Controlled environment agriculture is where the natural environment is modified or manipulated to optimize plant growth and leads to economic return. The main advantage of greenhouses is that it enables the all-year round production of fresh produce crops and is not influenced by adverse climatic conditions, which would be the case if they were grown in open fields (Venter, 2010).

Greenhouse production also ensures the efficient use of resources (water, fertilizers, pesticides and labour) (Pardossi *et al.*, 2004). It protects the crop from wind and hail damage, birds, weeds, rodents, insects, fungi, viruses and other diseases. It could also lead to higher yields per hectare, compared to open field cultivation, because of the optimal growing conditions and balanced plant nutrient (Jensen, 2002). In some instances, tomato yields can reach 500 – 600 tons per hectare per year in controlled greenhouses, in comparison to the 120 – 150 tons per ha per year of open field cultivation (Venter, 2010). Greenhouses are expensive and energy-intensive and should prove significantly cost-effective and competitive, compared to open field agriculture (Jensen, 2002), before the decision is made to invest.

Greenhouse production has grown significantly worldwide over the last 30 to 40 years. The estimated total area under greenhouse in major greenhouse production countries are as follows: China 2 760 000 ha; Korea 57 444 ha; Spain 52 170 ha; Japan 49 049 ha; Turkey 33 515 ha; Italy 26 500ha; Mexico 11 759 ha; the Netherlands 10 370 ha; France 9 620 ha; and the United States have 8 425 ha (WorldGreenhouseStats, 2012). China is an example of feeding one billion people (29% of the earth's population) with only 5% of the world's cultivated land, by using controlled environment agriculture (Jensen, 1999). It is estimated that there are currently 250-350 ha of protected flower cultivation in South Africa (de Visser and Dijkxhoorn, 2012). There is a total area of 136 000 ha of vegetable production in the country, with a very small percentage under protected cultivation (de Visser and Dijkxhoorn, 2012).

The world population is expected to grow by one more billion people within the next 13 years (Statistic Brain, 2012). South Africa has an estimated population growth rate of 1.7% per annum (du Toit, 2009). It is estimated that 35% of the South African population live with inadequate access to food. Conventional agricultural methods show obvious limitations and are not efficient enough to produce sufficient food for everyone. Land that is unsuitable for traditional farming contributes to shortages, as do urban conditions that prevent self-sufficiency (Venter, 2010). Africa is also thought to be extremely vulnerable to the impacts of climate change. A large proportion of Africa's crop production depends on rainfall, a factor that is expected to become a great uncertainty due to possible climate change (Challinar *et al.,* 2007). Although drought conditions and the lack of access to certain resources exist all over the world and are one of the most important causes of food insecurity in the continent, there is enough light and water to sustainably feed the earth's population over and over (Venter, 2010).

The development of small-scale and even large-scale greenhouses can have a significant impact on food security and malnutrition in South Africa. In terms of contributing to economic development in South Africa, there is a large domestic market and an increasing demand for a constant supply of good quality vegetables. The demand in Southern African countries is also increasing. If transports costs can be reduced, large markets can be accessed internationally. There are many opportunities in Southern Africa and Australia for exporting flowers from South Africa (de Visser and Dijkxhoorn, 2012).

Different types of greenhouse structures and climate control systems implemented in South Africa are described in the sections below. South Africa is a warm country with several different agro-climatic zones. In terms of internal greenhouse climate control, heating is generally not required in South African greenhouses (Venter, 2013) and more problems are generally experienced from overheating in greenhouses during the summer months. Cooling systems that are mostly used in South Africa include natural ventilation (with different vent configurations) and forced ventilation, using pad and fan, or only fans. Shading and misting are also often used to reduce internal temperatures. The running costs of forced ventilation systems are very high and are increasing, causing investors to move away from using these systems (Venter, 2013; Olsen, 2013; van Niekerk, 2013). Unlike places such as Europe, Israel and India, very little reliable information is available on the performance of the different types of greenhouses and cooling systems in different regions of South Africa. Even the success of existing greenhouses, in terms of cost-effectiveness and climate control, have not been documented properly and limited studies or experiments on crop production have been formally recorded. There are also limited locally-developed models that can be applied when it comes to designing new greenhouses for a specific area. In order to effectively increase the productivity of agricultural production under protected cultivation in South Africa, the existing local knowledge has to be scientifically expanded by obtaining empirical data on the microclimate of the existing greenhouses and modelling the changes in temperature, vapour pressure and relative humidity inside the greenhouses.

Research has shown that growers in the protected cultivation sector in South Africa do not show the willingness to cooperate and share knowledge and experience with other growers or emerging farmers (de Visser and Dijkxhoorn, 2012). In terms of greenhouse construction and design in this country, greenhouse suppliers (often international companies) regularly take the role of designing the complete greenhouse structure and environmental control systems for a specific investor. Specifically international suppliers rarely take into account local conditions at all (Venter, 2013). Suppliers use their own design techniques (based on models or experience) and have their own limited range of products, which may not result in the most desirable outcome for the investor. This makes research into the identified information gaps even more important.

Therefore, as heating is not often required in greenhouses in South Africa, this study will identify the applicable, most effective greenhouse designs and climate control systems with regards to cooling for the different climate regions in South Africa. The main aim of this study will be to compare the performance of four different greenhouses with regards to microclimate control and ultimately cost-effectiveness. Internal temperature, relative humidity, air exchange rate and input costs will be analysed. The climate parameters (temperature, vapour pressure and relative humidity) will also be modelled for further greenhouse applications under South African climate conditions and will be validated.

2 GREENHOUSE CLIMATE PARAMETERS

Plants require specific factors that enhances growth resulting from photosynthesis. Physiological fluxes should be optimized by limiting plant stress caused by unfavourable climate parameters. These parameters, namely, temperature, relative humidity, light and carbon dioxide, are described in the sections below.

2.1 Temperature

Temperature has a direct impact on the physiological development phases (flowering, germination, development) of the plant, controls the transpiration rate and, in turn, controls the plant water status through stomatal control during the photosynthesis. Temperature requirements in a greenhouse depend largely on the type of crop to be grown (Peet, 1999).

Each crop and its development process responds differently to temperature. High temperatures generally cause an escalation in plant growth rates, with an increase in leaf area. It then stimulates a greater transpiration rate in the plants, which try to cool itself down, and this can result in water loss and an imbalance of the distribution of photosynthates (Tognoni *et al.,* 1999). This can, in turn, cause physical disorders and restrict the reproductive development of plants (Peet, 1999).

The difference between day and night temperatures, as well as the average 24-hour temperatures can also affect plant growth. Low temperatures can have a significant effect on growth rates and can influence fruit and seed production (Peet, 1999). As further described in Section 6, South Africa is characterized by several different climatic conditions. Temperature in a climate area plays a large role in greenhouse design. When it comes to greenhouse production, South Africa generally has very high temperatures that can limit the success of all-year-round greenhouse crop production. This should be carefully considered when designing structures and control systems.

2.2 Relative Humidity

It is critical that the correct balance of temperature and humidity is kept in the greenhouse. Humidity control remains a challenge and high or low humidity levels affect plant development. Vapour pressure deficit (VPD) is the difference between the air's moisture content and the amount of moisture the air can hold when it is saturated. High VPD is usually caused by high temperatures and low humidity and affects plant growth by causing high stomatal resistance and plant water stress and the plant transpires more water than it can absorb. Low VPD, in turn, causes low plant transpiration and associated physical disorders (Körner *et al.*, 2003).

The main challenge with humidity control is the interaction with temperature. Many greenhouse operations are moving towards controlling the greenhouse according to VPD or moisture deficit, which measure the combined effect, rather than controlling only the relative air humidity (RH) (Peet, 1999). Areas specifically on the South African coastline have very high humidity and the effect of such external conditions can have detrimental implications on greenhouse crops. Designs and control systems have to thus be adjusted for these specific conditions. Moreover, the effectiveness of different greenhouse designs and control systems in terms of maintaining the optimum inside air relative humidity needs to be understood.

2.3 Light Intensity

The growth of plants is controlled by three light (photo) processes, namely photosynthesis, photomorphogenesis and photoperiodism (Venter, 2006). Every variation in light has a direct effect on these processes. Light is part of the photosynthesis process, by converting carbon dioxide into organic material and then releasing oxygen in the presence of light. Photomorphogenesis is the way plants develop under the influence of different types of light and photoperiodism is how the plant reacts to different day-lengths and whether it will seed or flower. The most important process is photosynthesis and light is the primary energy source to enable this process (Venter, 2006). In South Africa, light levels are generally sufficient for effective plant production and artificial lighting is only required for crops that require longer day lengths (de Visser and Dijkxhoorn, 2012).

2.4 Carbon Dioxide

Carbon dioxide (CO_2) is the primary substrate for the creation of photosynthates during photosynthesis (Tognoni *et al.*, 1999). It accelerates plant growth by increasing net photosynthesis in plants. A well-ventilated greenhouse in South Africa with healthy gas exchange rates and air circulation should ultimately have CO_2 levels of approximately 300 ppm. By increasing CO_2 levels from the natural level to a concentration of between 700 and 900 $\mu 11^{-1}$ increases plant growth (Panwar *et al.*, 2011). Recent studies have shown that plants do not really benefit much from dosing when CO_2 levels exceed 1000 $\mu 11^{-1}$. CO_2 is absorbed via stomata in the plant and effective absorption of CO_2 in a greenhouse is, therefore, strongly dependent on other climate factors affecting the stomata openings in the plant (Tognoni *et al.*, 1999).

3 CLIMATE CONTROL INSTALLATIONS

3.1 Cooling Systems

A big challenge of greenhouse growing and greenhouse production is cooling of the internal climate. High summer temperatures directly impact the success of year-round greenhouse crop production. Greenhouse designers should consider the economic viability of a cooling system that successfully controls the microclimate of the greenhouse in relation to external climatic conditions (Sethi and Sharma, 2007; Mutwiwa *et al.*, 2008; Kumar *et al*., 2009).

A brief description of the different technologies and challenges is provided in the sub-sections below.

3.1.1 Greenhouse ventilation systems

As presented in Section 4.2, the greenhouse structure should be specifically designed to incorporate the choice of ventilation and cooling. Net solar radiation in a greenhouse can reach values ranging between 500 and 600 $W.m^{-2}$. To maintain the inside temperatures of the greenhouse close to the outside temperatures, about 200-250 $W.m^{-2}$ of sensible heat should be removed (Kittas, 2004).

Ventilation should provide temperature control to prevent the extreme build-up of heat during the summer months, to control excessive humidity in the greenhouse and to ensure sufficient air exchanges occur inside the greenhouse (to manage carbon dioxide and oxygen levels in the greenhouse) (Venter, 2006).

Natural ventilation is the result of pressure differences created by wind and temperature gradients between the inside and outside of a greenhouse (Kumar *et al.*, 2009). It occurs through openings in the greenhouse structure. It controls humidity and temperature build-up within the greenhouse and can ensure sufficient air exchange. It requires less energy, in some cases no energy (fixed ventilation openings), and is, therefore, the cheapest method of cooling greenhouses. Natural ventilation works better than other cooling technologies for greenhouses, especially in humid, tropical and subtropical regions (Kumar *et al.*, 2009). Ventilation openings should be optimized in order to attempt to cool the greenhouse, even in low wind speed conditions. Ventilation areas should at least be 25-30% of the greenhouse floor area for most of our local South African regions (Venter, 2006). However, limited data is available in South Africa on which designs and ventilation systems are scientifically proven to be most effective, with specific outside conditions.

Forced ambient air ventilation can also be implemented by installing exhaust fans and blowers. Forced ventilation can reduce the internal air temperature of the greenhouse and improve greenhouse conditions (Kittas *et al.*, 2005). Certain experiments, however, have shown that forced ventilation without evaporative cooling pads might actually increase internal greenhouse temperatures with outside-conditions of low humidity and high temperatures (Willits, 2003).

In several instances in South Africa, closed greenhouses have been built, where forced ventilation is used, but because of rising electricity costs in the country, developers are moving away from this concept. The cost-effectiveness and performance of certain designs should, therefore, be evaluated in detail, prior to deciding on a system. Scientific empirical data and accurate modelling are required to properly evaluate this.

3.1.2 Shading

Direct solar radiation is the primary source of heat gain in greenhouses. This can be controlled by shading or reflection. Shading can be done using several different approaches, such as internal and external shade screens, paints and nets. Shading might negatively influence plant development and photosynthesis because of the reduction of light and the possible effect on ventilation rates/gas exchanging (Gonzalez-Real *et al.*, 2006). Hence, care should be taken, when deciding on the type of shading and associated control strategies. Partially reflected internal shade screens can be installed and have been proven to reduce the greenhouse air temperature by 6˚C, compared to ambient temperatures. The screens contain highly reflective aluminized materials, usually woven with plastic thread. The screens reflect the unwanted solar radiation from the greenhouse roof, while still allowing some light transmittance (Sethi and Sharma, 2007; Kumar *et al.*, 2009).

Many producers use paint/whitening on the roofs of the greenhouse for the cooling effect. It is an inexpensive method and has proven to effectively reduce the vapour pressure deficit, air temperature and canopy-to-air temperature and has a positive effect on the microclimate of the greenhouse (Sethi *et al.*, 2007; Kumar *et al.*, 2009). Whitening also transforms a large part of the direct radiation into diffused radiation, which has been proven to increase the absorbed radiation by the crop (Gonzalez-Real *et al.*, 2006). Another benefit of this cooling method is that it does not impact the ventilation rate of the greenhouse.

External mobile shade cloths are also used for shading and have been proven to reduce crop transpiration and internal VPD (Medrano *et al.*, 2004). They are preferable because it prevents the heat input in the greenhouse. External screens have to withstand all atmospheric conditions and are therefore expensive to install (Castilla, 2013). Internal shade screens are often used in South African greenhouses, but they also have a negative effect on light and ventilation rates, as described above (Venter, 2013).

3.1.3 Evaporative cooling

Evaporative cooling does not only decrease the air temperature in greenhouses, but also increases the absolute internal humidity and is therefore often more desirable in certain regions than the other cooling technologies (Abdel-Ghany *et al.*, 2006). Fan-pad systems, fogging systems and roof evaporative cooling systems are generally the most common and effective evaporative cooling installations for greenhouses. Its suitability is restricted to certain regions due to limited evaporation in most humid regions and it seldom suits tropical and subtropical climate regions (Kumar *et al.*, 2009). With evaporative cooling, water evaporates and absorbs the heat from the air and, in turn reduces the air temperature. It is seen as the most effective way to control temperature and humidity inside a greenhouse (Sethi *et al.*, 2007).

The fan-pad system consists of a fan on one gable end and a wet pad on the opposite end. A small stream of water is run over the pad continuously and air is drawn through the pad by the fans, absorbing heat and water vapour in the greenhouse (Arbel, 2002). It also increases the humidity of the internal air (Sethi *et al.*, 2007). This installation has shown a reduction in air temperature of up to 12˚C, even under very high ambient temperatures. The length of the greenhouse should be considered, as the efficiency might decrease and large temperature gradients can be expected across greenhouses of longer lengths (Sethi *et al.*, 2007). Other disadvantages are that it is an expensive installation with high operation costs, namely, fresh water supply, electricity and the maintenance costs (Vadiee *et al.*, 2012). However, there is no sufficient empirical data available for pad and fan systems under South African conditions.

Fogging installations are used to increase relative humidity and cooling inside a greenhouse. Water is pumped through high pressure nozzles and sprayed as extremely fine droplets into the air (Sethi *et al.*, 2007). The decrease in droplet size increases the surface area per unit mass of water, which increases the heat and mass exchange between water and air and, in turn, increases the evaporation rate (Linker *et al.*, 2011). The evaporation effect causes cooling, as well as humidification. Nozzles are usually installed just below gutter height and can be distributed throughout the greenhouse to ensure a uniform effect, which has proven more effective than the fan-pad system in terms of variations in temperature and humidity across the greenhouse (Linker *et al.*, 2011). Although some greenhouses that were designed and constructed in South Africa depend on fogging systems for cooling and humidification, there is not sufficient information on their performance in maintaining optimum temperature and humidity inside the structures.

Roof evaporative cooling includes spraying water onto the external surface of a roof and this creates a thin water layer on the surface. This decreases the solar radiation transmissivity to the greenhouse and increases the evaporation rate, which consequently decreases the water temperature and closely surrounding air (Sethi *et al.*, 2007). Again, this system will work most effectively in hot, dry climate regions. Literature shows that evaporative cooling (fogging, and pad and fan) has potential for controlled farming under the arid and semi-arid conditions of Africa, as well as South Africa.

3.1.4 Earth to air heat exchanger for cooling

The earth mass can be used for greenhouse cooling because the ground temperature remains between 26 and 28˚C. Earth-to-air heat exchanger systems (EAHES) have been developed to use this potential during hot summer months. Hot greenhouse air is circulated through buried pipes (2 – 4 m deep) and cooled by the underground soil (Sethi and Sharma, 2007). The disadvantages of this system are the initial cost involved, the life cycle of the pipes, and associated replacement costs due to corrosion (Kumar *et al.,* 2009).

The aquifer coupled cavity flow heat exchanger system (ACCFHES) utilizes deep underground aquifers, with an added evaporative cooling process to cool the greenhouse during summer months. It has also been implemented for the heating and cooling of greenhouses. The study by Sethi and Sharma (2007) has shown a difference of 6-7˚C internal air temperature compared to ambient temperature.

3.1.5 Solar radiation filtration

Global solar radiation enters a greenhouse as three different types of radiation, namely, ultraviolet radiation (UV), photosynthetic active radiation (PAR) and near infrared radiation (NIR). Most of the UV radiation is absorbed by the earth's atmosphere. The extreme exposure of plants to UV can result in the degradation of the photosynthetic process. PAR is absorbed by the plant and is important for photosynthesis and plant growth. NIR is less absorbed by the plant and more by the greenhouse structure and equipment, causing the increase in ambient temperature in the greenhouse (Hemming *et al.*, 2006). Cooling the greenhouse by modifying covering materials has been investigated and implemented for many years (Hemming *et al.,* 2006, Mutwiwa *et al.,* 2008). NIR-filtering is also done by using specific plastic films, glass for greenhouses, moveable screens or NIR filtering shading paint (Hemming *et al.*, 2006).

3.2 Internal Air Circulation System

Internal air velocities of a greenhouse are recommended to be between 0.5 to 0.7 m.s^{-1} for optimal plant growth, by facilitating gas exchange (CO_2 and water vapour) (Castilla, 2013). To ensure this, fans are often installed above the crop. The number of fans that have to be installed in the greenhouse are calculated to ensure 0.01m^3.s^{-1} per m^2 and have to be installed in the direction of the ridge. Distances between the fans should not exceed 30 times the diameter of the fans (Castilla, 2013).

3.3 Air Humidification

Other than using fogging installations for cooling and humidity control, the following systems are generally also used for humidification only:

a) Steam,
b) High pressure humidifiers, and
c) Pulsators.

Steam boilers are often used in colder countries to supply heat or for humidity control in greenhouses (Venter, 2010). Heaters can also be used to create saturated vapour that is then pumped into the greenhouse (Vadiee *et al.*, 2012).

For high pressure humidifiers, compressed air is used to split water into tiny droplets and then propelled through the greenhouse in an air stream. Pulsators are generally used for irrigation, but are often used for overhead irrigation and then also serve as humidification for the greenhouse (Venter, 2010). Pulsator drops are thus much larger than high pressure humidifiers, but can still be as successful and economical.

3.4 Carbon Dioxide Control

As previously described, carbon dioxide (CO_2) enrichment systems have shown positive effects on plant growth for many years. CO_2 enrichment is usually a source of fuel combustion. A brief description of some CO_2 enrichment systems that are available are given below (Kenig *et al.*, 2000):

- Liquid CO_2: Pure CO_2 is pumped from containers to the greenhouse and is the purest type of CO_2 enrichment. Like many other systems, it does not have, the greenhouse heating effect. The disadvantage of this system is the high cost of supplementing and transporting gas containers.
- Fuel combustion: Burning liquid kerosene, propane-butane gas or natural gas produces CO_2 as part of the gas emissions through the burners. Heat is also produced by this type of operation and is often the primary reason for the installation. The constraint of these systems is that CO_2 can only be dosed when

heat is also required in the greenhouse. The choice of the type of fuel is generally based on availability and cost per unit and the purity of the gas emissions.

Dosing should be specifically controlled according to light levels, temperature and ventilation in greenhouses, to ensure the efficiencies are optimized.

3.5 Artificial Lighting Systems

Artificial lighting can be used to ensure the optimum light levels as described in Section 2.3 are maintained for optimal plant growth. Different plants have different requirements the light source should be chosen based on this. Artificial lighting usually consists of different type of lamps installed at specific heights and geographical locations in a greenhouse (Venter, 2010).

4 GREENHOUSE DESIGNS

Not every system is cost-effective in every location. A large range of different requirements have to be incorporated when it comes to greenhouse design. The following list of items should be considered when designing and choosing greenhouses (Venter, 2010):

a) Sunlight utilization
b) Costs
c) Sufficient ventilation
d) Easily accessible
e) Low maintenance costs
f) Effective energy use
g) Adaptability for automation

The choice of crop also influences the type of greenhouse and climate required. A logical and model-based approach to greenhouse design can be described in Figure 4.1. A favourable economic outcome in the end determines the size of investment in the type of greenhouse design and control systems.

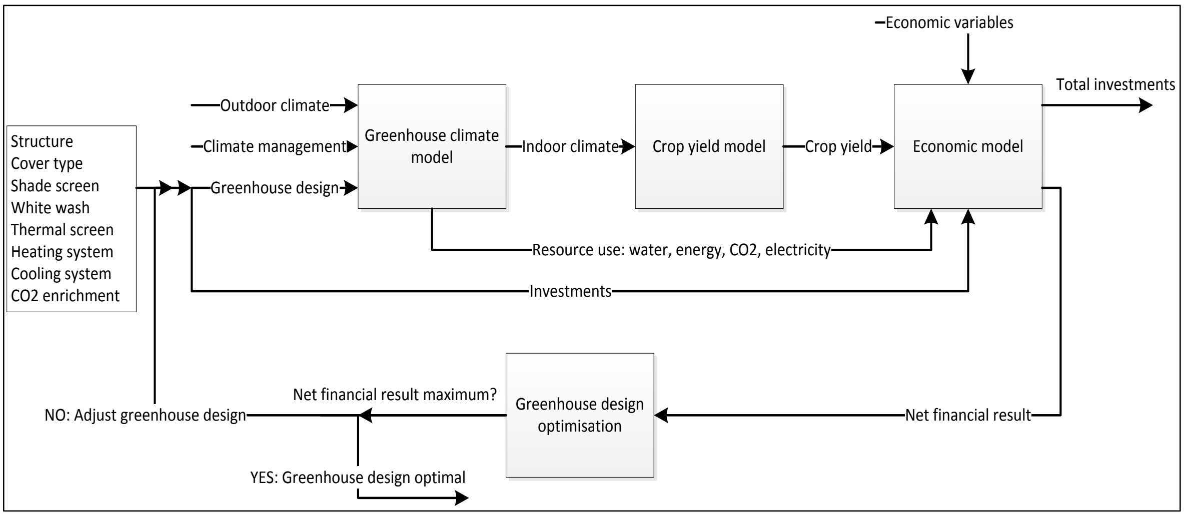


Figure 4.1 An overview of a model-based greenhouse design method (Vanthoor *et al.*, 2011)

4.1 Greenhouse Shapes and Sizes

Greenhouses can be categorized, based on shape and size, amongst other things. The different design form and typical application are listed and described below (Venter, 2010):

a) Span-roofed greenhouses: These greenhouses are mostly used for extensive commercial operations. They have vertical walls and pitched roofs and are generally used with cover materials like glass, glass fibre and polycarbonates.
b) Domestic greenhouses: Domestic greenhouses are generally the shape of span-roof greenhouses, but are usually 1.65 m-2.25 m high, between 1.8 and 3 m wide and 3-6 m long.
c) Mobile greenhouses: Mobile greenhouses were designed in Europe in order to be disassembled and moved around to different locations and to accommodate crops that have to be covered during the night and open during the day.
d) Curvilinear structure: These greenhouses are usually used in very cold countries and the structures are designed so that the different surfaces of the greenhouse can be faced more or less perpendicular to the sun for maximum absorption during certain times of the day.
e) Lean-to types of greenhouses: Lean-to greenhouses are built against another building and utilize the wall of the building as heat storage. They are generally used in colder countries and for small operations.
f) Plastic tunnels: These were only introduced towards the end of the twentieth century. They became popular because of their low cost and ease of construction and are used in large commercial operations. Different qualities and thickness of plastic are available. Tunnels are available in 6, 7, 8, 10 and 12 m widths and in 30 to 60 m lengths and they can be constructed as single span (standalone) or multi-span (joined) structures. The most common shapes of single span greenhouses studied by researchers are even-span, uneven-span, vinery, modified arch and quonset types (Sethi, 2008). Double plastic layer tunnels are also often used for better insulation. Air is pumped in between the two layers and serves as extra insulation.

g) Shade netting greenhouses: Crops can also be successfully grown commercially under shade netting, especially in warmer climates. Shade netting has a longer life-span than polyethylene, but is used in less expensive structures. Different colours (green, black, white) and densities of netting are available and various designs can be used (such as tunnels, multi-span)

h) Height: Recent focus has been on developing greenhouses with higher gutter heights. Glass greenhouses are constructed with a gutter height of 6 m and plastic covered greenhouses can go up to 3.5-4 m. This has been shown to significantly improve the growing environment for greenhouse crops (Connellan, 2002).

The structural design of the greenhouse also influences the energy efficiency of a system. A study done by Djevic and Dimitrijevic (2009) shows that the type of structure can influence energy input per kg of a product, energy efficiency and the productivity of a system.

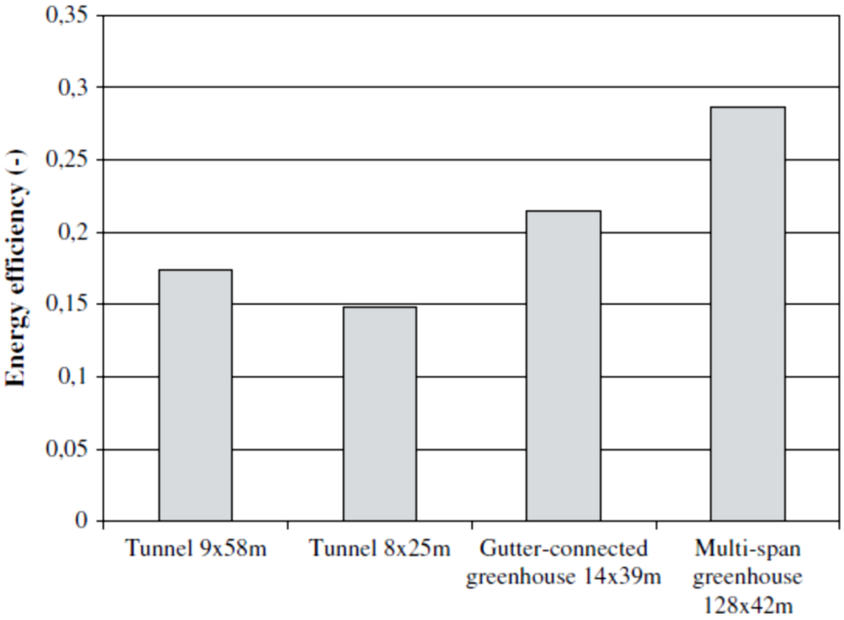


Figure 4.2 Impact of structural design of a greenhouse on energy efficiency (Djevic and Dimitrijevic, 2009)

4.2 Design for Greenhouse Cooling

Certain climate factors can influence the structural design of the greenhouse. These factors are normally the heating and cooling requirements of the greenhouse. Only greenhouses that are used in commercial operations will be studied.

Different shapes, orientation and vent configurations are used when designing for natural ventilation and these influence the ventilation rate and cooling effectiveness. Greenhouses are constructed in multi-span or single-span with continuous roof, side or roof and side ventilation (Figure 4.3, Figure 4.4 and Figure 4.5). Greenhouses are also designed with a natural ventilation system in combination with insect netting over the ventilation openings (Figure 4.5Figure 4.6).

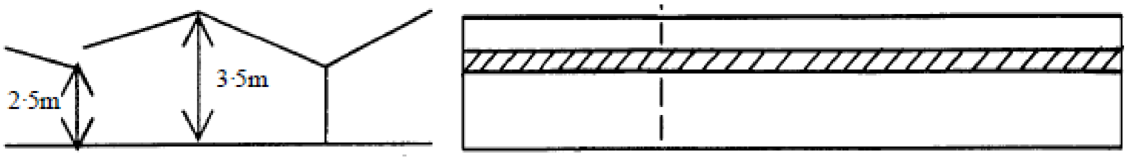


Figure 4.3 Continuous roof (one side) ventilation greenhouse (Boulard *et al*., 1997)

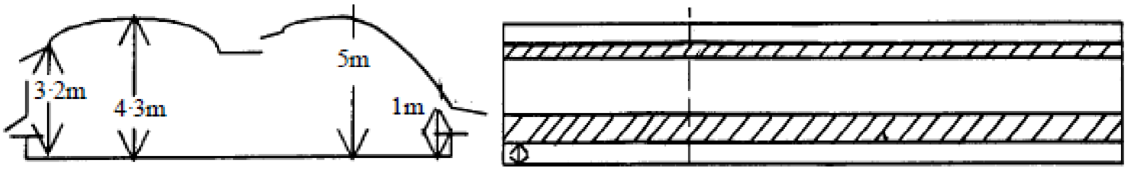


Figure 4.4 Continuous roof and side ventilation greenhouse (Boulard *et al*., 1997)

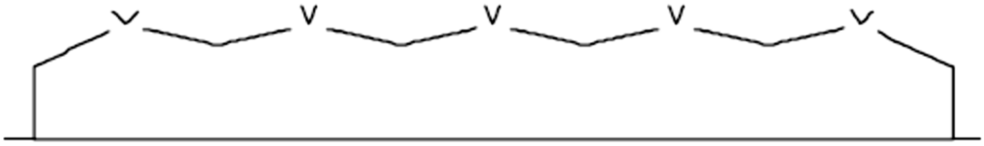


Figure 4.5 Continuous roof (double) roof ventilation greenhouse (Baeza *et al*., 2006)

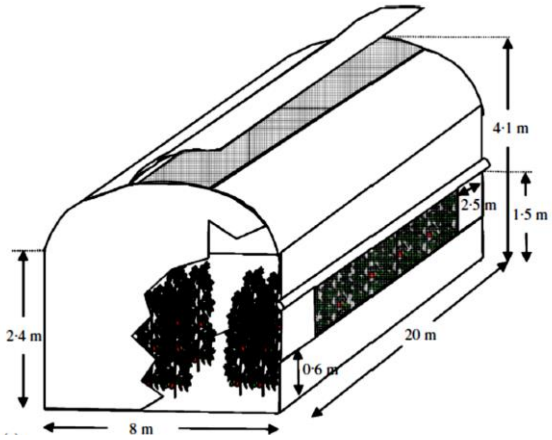


Figure 4.6 Naturally ventilated greenhouse with insect netting (Katsoulas *et al.*, 2006)

Greenhouses have to be specifically designed to apply forced ventilation and evaporative cooling. Greenhouses are constructed in multi-span or single-span, with exhaust fans and openings or with evaporative cooling pads and fans (Figure 4.7, Figure 4.8 and Figure 4.9).

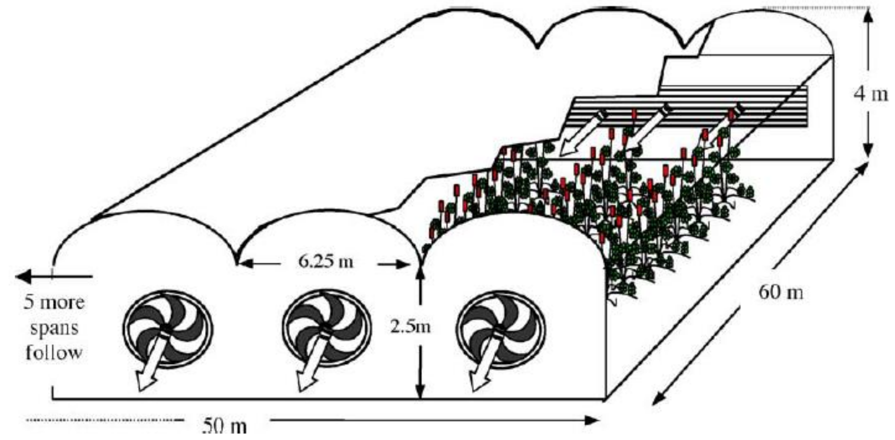


Figure 4.7 Greenhouse with exhaust fans and openings (Kittas *et al*., 2005)

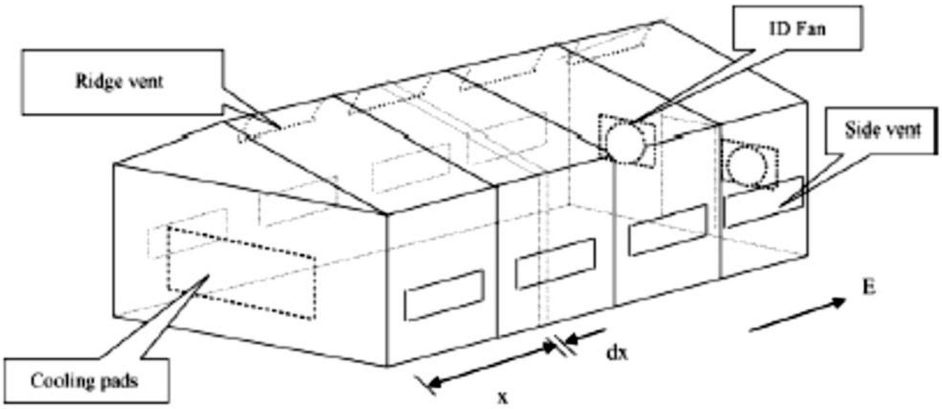


Figure 4.8 Greenhouse with forced and natural ventilated combination (Ganguly *et al.*, 2007)

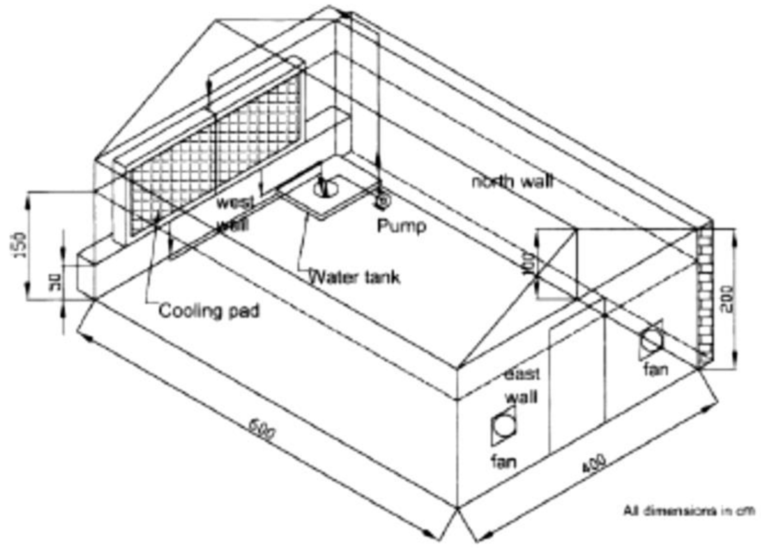


Figure 4.9 Pad and fan evaporative cooled greenhouse (Jain *et al.*, 2002)

5 GREENHOUSE MICRO-CLIMATE MODELLING

Several different greenhouse climate models have been developed over the years in order to ultimately evaluate or predict the performance of greenhouse designs. Predictions of micro-climatic conditions (temperature, vapour pressure and relative humidity) can be achieved by using experimental data or by simulations, using pure mathematical models (Abdel-Ghany and Kozai, 2006). Simulations and mathematical models are preferable because they are cheaper, quicker and more flexible (Wang and Boulard, 2000). Ideally, the coefficients of models should be calibrated with experimental work in order to use them in different conditions and situations (Baptista *et al.*, 2010). Certain developed models, based on energy and mass balance equations, can be classified as static, dynamic (Fitz-Rodriguez *et al.*, 2010) or homogeneous models (Abbes *et al*., 2010). Other, more complex, models are combined with crop requirements and include air state variables, which measure the system performance over time (Fitz-Rodriguez *et al.*, 2010), or heterogeneous models (Abbes *et al*., 2010) that are based on computational fluid dynamics (CFD) that can perform two- or three-dimensional numerical analysis of equations (Kittas and Bartzanas, 2007). Some models focus on specific phenomena, for instance, natural ventilation, forced ventilation, evaporative cooling, insect netting and heating. More recent studies on greenhouse climate control have focused on addressing optimizing energy usage, water consumption and CO_2 dosing (Fitz-Rodriguez *et al.*, 2010). Some of the different types of models are described in the following section.

5.1 Computational Fluid Dynamics

Computational fluid dynamics (CFD) are used more often now for heterogeneous modelling in many horticultural and agricultural applications (Reichrath and Davies, 2002). CFD is a simulation approach that evaluates the behaviour of different types of fluid flow, heat and mass transfer (Pontikakos *et al.*, 2005; de la Torre-Gea *et al.*, 2011; Lee *et al.*, 2013) or chemical reactions (Bartzanas *et al.*, 2013). The domain in which the simulation takes place (for example, the greenhouse and the environment) is divided into small cells and conservation equations are applied to each volume and variables are calculated from there (Pontikakos *et al.*, 2005). This type of modelling approach provides accurate simulations for a wide range of different geometrical and boundary conditions of greenhouses, enabling improvement in greenhouse designs and control for specific applications (Boulard *et al.*, 2002) and they can characterize non-steady ventilation rates, temperature and humidity inside the greenhouse.

The following equation describes the 3-D conservation equations for steady fluid flow characteristics (Kittas and Bartzanas, 2007, Ould Khaoua *et al.*, 2006):

$$\frac{\partial(U\phi)}{\partial x} + \frac{\partial(V\phi)}{\partial y} + \frac{\partial(W\phi)}{\partial z} = \Gamma\Lambda^2\phi + S_\phi \qquad (5.1)$$

Where: U, V, W = three components of the velocity vector; ϕ = the concentration of the transport quantity of components in either momentum, mass or energy equations; x, y, z = Cartesian space coordinates; Γ = diffusion coefficient; Λ = the velocity gradient; and S_ϕ = the source term.

CFD simulations for natural ventilation in greenhouses have been performed for different reasons. Ventilation rates and air movement have been studied for different roof vent configurations in greenhouses (Bartzanas *et al.*, 2004; Baeza *et al.*, 2006). Insect screens and the effect on greenhouse ventilation and air velocities have been predicted, using CFD modelling (Teitel 2009; Majdoubi *et al.*, 2009).

Franco *et al.* (2011) developed and validated a CFD model that optimizes pad and fan designs and the geometry of the pads, by evaluating different wind speeds and water flows on pressure drop over the pads. Humidifying and dehumidifying a greenhouse with fogging and refrigerative humidifiers and the humidity distribution in a single-span greenhouse were studied by Kim *et al.* (2008). Forced ventilation (Fidaros *et al.*, 2008) and the effect of solar radiation distribution and climatic behaviour in a greenhouse with a tomato crop have been numerically analysed, using CFD. Moreover, CFD simulations have also been used for describing climate control and buoyancy forces in greenhouses with pipe heating and electric air heaters (Bartzanas *et al.*, 2013).

CFD simulation reduces the cost and increases the quality of complex research involving fluid flows, heat and mass transfer and other reactions and is a well-proven tool (Lee *et al.*, 2013). Experimental data is important to validate the accuracy and reliability of CFD models, however, to date, a standard for validating any CFD model does not yet exist (Lee *et al.*, 2013) and the experimental results often do not correspond with the model. The inaccuracies may be because the greenhouse areas cannot always be assumed uniform (Teitel *et al.*, 2008, Bournet and Boulard, 2010). CFD modelling requires large computer memory and specific software that might limit the size and capacity of the use of the model (Lee *et al.*, 2013).

5.2 Static and Dynamic Micro-climate Models

Homogenous modelling (static and dynamic modelling) are based on energy and mass balance equations and they generally assume steady state conditions and uniform distribution inside a greenhouse.

5.2.1 Natural ventilation models

Different natural ventilation models have been developed and calibrated to predict the ventilation rate in a greenhouse. The effect on crop, vent-opening configuration, along with the two major forces (wind and stack forces), are all considered as the model parameters (Boulard *et al.*, 1997). A summary of natural ventilation models reviewed in this study is given in **Error! Reference source not found.** below.

Table 5.1 Natural ventilation models

Model	**Eq. No**	**For ventilation**	**Reference**
$G = \frac{S}{2} C_d \left[2g \left(\frac{\Delta T}{T} \right) \left(\frac{H}{2} \right) + C_w U^2 \right]^{0.5}$ Where: G= Volumetric flow rate ($m^3.s^{-1}$); S= Vent open area (m^2); C_d= Discharge coefficient (dimensionless);	5.2	Roof or side	Boulard *et al.* (1997)

Model	Eq. No	For ventilation	Reference
g= Gravity constant; T= Air Temperature (K); ΔT = temperature difference between inside and outside (K); H = Vertical distance separating the openings for air inflow and outflow (m); C_w= Wind effect coefficient (dimensionless); and U = wind speed (m.s^{-1})			
$G = \frac{S_T}{2} C_d \left[2g \in^2 \left(\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right) + C_w U^2 \right]^{0.5}$ Where: G, C_d, g, T, ΔT, H, C_w and U is the same as above, and: S_T = Total roof and side ventilation area $\varepsilon = 2\sqrt{2b}/(1+b)(1+b^2)^{0.5}$; b= $\frac{S_R}{S_S}$;	5.3	Roof and side	Boulard *et al.* (1997)
$G = \frac{S}{2} C_d {C_w}^{0.5} u_w$ Where: G, C_d, S, C_w is the same as above; and U_w = wind speed across openings m.s^{-1}	5.4	Roof or side	Kittas *et al.* (1996)
$N = \left(\frac{3600}{V}\right) C_d \left[\left(\frac{A_r A_s}{\sqrt{{A_r}^2 + {A_s}^2}}^2 \right) 2gx \left(\frac{T_i - T_e}{T_i}\right) + \left(\frac{A_r + A_s}{2}\right)^2 C_w {u_e}^2 \right]^{0.5}$ Where: N= air renewal rate (h^{-1}); V= Volume of the greenhouse (m^3) T_i, T_e = internal and external temperature (K) x=height (m)	5.5	Roof and side	Fatnassi *et al.* (2003), Kittas *et al.* (1997); Mashonjowa *et al*. (2013)

Model	Eq. No	For ventilation	Reference
S_R or A_R= roof vents area(m^2), S_s or A_S= Side vents area (m^2); and U_e = wind speed (m.s^{-1})			

C_d and C_w (discharge and wind effect coefficient) are descriptive values of each type of greenhouse and can be calculated by using experimental data and fitting it into the models. These equations have been widely used to evaluate the effect of different vent configurations on ventilation and air exchange in a greenhouse (Ganguly and Ghosh, 2009; Mashonjowa *et al.*, 2013). However, these equations and models do not take into account physiological fluxes and solar radiation and cannot predict internal relative humidity, all of which are critical factors for successful greenhouse design and crop production.

5.2.2 Other models for temperature and humidity prediction

Table 5.2 below describes more models that were developed to predict air temperature and relative humidity, with basic descriptions of the types of control systems applied to a greenhouse.

Table 5.2 Summary of temperature and humidity models

Model	Eq. No	EP	Control system applied	Reference
$m_g C_p \frac{dT_g}{dt} = Q_{available} - UA_{covering}(T_g - T_a) - \dot{m}_v C_p (T_g - T_a)$ Where: m_g = greenhouse air mass; T_g= temperature of the greenhouse air (K); T_a= ambient /outdoor temperature (K); Q = total heat flow rate (W); $\dot{m}_v$= air mass flow rate caused by natural ventilation; and C_p = specific heat of air in J.kg^{-1} K^{-1}	5.6	T_g	Natural ventilation, shading	(Ganguly and Ghosh, 2009)
$P_c - h_{csky,LWR}(T_c - T_{sky}) = h_{cg,CON}(T_c - T_g) - \lambda E_{cg}$	5.7	T_c	Natural ventilation, insect screens	(Impron *et al.*, 2007)
$h_{ga,CON}(T_g - T_a) + h_{ga,VEN}(T_g - T_{out}) = P_g - h_{cg,CON}(T_c - T_g)$	5.8	T_g		(Impron *et al.*, 2007)
$h_{ga,LAT}(e_g - e_a) = \lambda E_{cg}(S, T_g, T_c, e_g)$	5.9	VP		(Impron *et al.*, 2007)
Where: P_c= solar radiation absorbed by greenhouse cover; P_g= solar radiation flux to the greenhouse air; T_c and T_{sky}= temperatures of the crop canopy and the sky (K); E_{cg}= crop transpiration (kg.m^{-2}.s^{-1}); λ=latent heat (J.kg^{-1}) $h_{csky,LWR}$= the thermal conductance between greenhouse cover and the sky (W.m^{-2}.K^{-1}); $h_{cg,CON}$= thermal conductance between the crop and greenhouse in W.m^{-2}.K^{-1}, $h_{ga,CON}$ = overall sensible thermal conductance between the greenhouse and outdoor via the plastic cover W.m^{-2}.K^{-1}, $h_{ga,VEN}$= sensible thermal conductance between greenhouse and outdoor air by ventilation in W.m^{-2}.K^{-1}, $h_{ga,LAT}$ = thermal conductance by ventilation in W.m^{-2}.Pa^{-1}, e_g= outdoor air water vapour pressure in Pa; e_a= indoor air water vapour pressure in Pa; and S= outdoor radiation (global) in W.m^{-2}				
$(K_s + K_c)\Delta T + K_L \Delta e = \mu S - Q_m$	5.10	T_g VP	Natural ventilation, shading	(Kumar *et al.*, 2010)

Model	**Eq. No**	**EP**	**Control system applied**	**Reference**
$\left(\delta\,(T_g) - (T_a)\right)\Delta T + \left[\frac{\gamma(r_s+r_a)}{\rho C_p I_{LA}} K_L + 1\right]\Delta e - \delta(T_g)\Delta T_{fo} = D_o$	5.11	T_c		(Kumar *et al.*, 2010)
$\frac{\rho C_p I_{LA}}{r_a}\Delta T - K_L \Delta e - \frac{\rho C_p I_{LA}}{r_a}\Delta T_{fo} = -R_n$	5.12			(Kumar *et al.*, 2010)

Where:
K_s= sensible heat transfer coefficient in (W.m^{-2}.K^{-1});
K_c= overall heat transfer coefficient (W.m^{-2}.K^{-1});
K_L= latent heat transfer coefficient (W.m^{-2}.K^{-1}).
ΔT= the internal-external difference in temperature in Kelvin;
D_o= vapor pressure deficit of the external air;
ΔT_{fo} = the temperature difference between the crop canopy and external air
Δe = vapor pressure difference (VPD) between the greenhouse and outside (Pa);
μ= solar heating efficiency (dimensionless);
Q_m= heat transfer rate of the soil in W.m^{-2};
δ= saturation air water vapour pressure gradient in Pa.K^{-1};
γ = psychometric constant in Pa.K^{-1};
r_s = stomatal resistance in s.m^{-1};
r_a = aerodynamic resistance in s.m^{-1};
ρ= air density in kg.m^{-3};
C_p = specific heat capacity of the air J.kg^{-1}.K^{-1};
I_{LA} = is the leaf area index (dimensionless); and
R_n = net solar radiation inside (W.m^{-2})

Model	Eq. No	EP	Control system applied	Reference
$\lambda E_{cg} = \frac{(K_1 K_s + K_2 \delta)\Delta T + K_2 D_o}{1 - K_1 + \frac{K_2}{K_L}}$, where $K_1 = \frac{\delta}{\delta + \gamma(1 + \frac{r_s}{r_a})}$ and $K_2 = \frac{2 I_{LA} \rho \frac{C_p}{r_a}}{\delta + \gamma(1 + \frac{r_s}{r_a})}$ Where the parameters are defined in the previous section (Kumar *et al.*2010) and K_1 and K_2 are constants	5.13 5.14 5.15	E_{cg}	Natural ventilation, heating and cooling	(Boulard and Wang 2000)
$A_c(SC + RC) - Q_{c-am} - Q_{c-a} - 2QE_c = (mC_p)_c \frac{dT_c}{dt}$	5.16	T_g, T_c, T_p, ω_a	Natural ventilation, fogging	Abdel-Ghany and Kozai (2006)
$Q_{f-a} + Q_{c-a} + Q_{p-a} + Q_{pot-a} - Q_{vs} - \kappa(\beta \dot{m}_w) = (mCp)_a \frac{dT_g}{dt}$	5.17			
$\dot{m}_{ven} = \frac{A_f(G_s \tau_{sc}) - UA_c(T_g - T_a) - A_f D}{I_a - I_{am}}$	5.18			

ω_a = absolute humidity of the internal greenhouse air (kg of vapour);
T_p = plant temperature ;
A_c= greenhouse area (in m^2);
SC, RC = solar and thermal radiation respectively absorbed by the cover (W.m^{-2})
Q_{c-am}= convective heat transfer between cover and ambient;
Q_{c-a}= convective heat transfer between cover and internal air
Q_{f-a}= convective heat transfer between the floor and internal air;
Q_{p-a}= convective heat transfer between plants and internal air;
Q_{pot-a}= convective heat transfer between the pot soil surface to the internal air;
Q_{vs}= sensible heat associated with ventilated air during the natural ventilation process;
QE_c= emission from the cover surface;
κ = latent heat due to vaporization of water (J.kg^{-1})
β = fraction of the evaporated fog;
$\dot{m}_w$ = water flow rate of fogging water;
$\dot{m}_{ven}$ = natural ventilation rate of moist air in kg.s^{-1};
A_c= surface area of the greenhouse cover (m^2);
A_f = surface area of the greenhouse floor (m^2);
G_s = solar radiation flux (W.m^{-2});
τ_{sc}= dimensionless transmittance of cover to solar radiation;
U = overall heat transmission coefficient;
D = soil heat flux; and
I_a , I_{am}= enthalpy of moist air inside and outside the greenhouse respectively

<table>
<tr><th>Model</th><th>Eq. No</th><th>EP</th><th>Control system applied</th><th>Reference</th></tr>
<tr><td>$\rho_a c_a v_a \frac{\partial T_g}{\partial t} = \alpha_a S + Q_{loss} + Q_{s-a} + Q_{p-a} + Q_{ven} + Q_{heat}$</td><td>5.19</td><td>$T_g$</td><td>Hot water heating</td><td>(Du *et al.*, 2012)</td></tr>
<tr><td colspan="5">S = net solar radiation entering the greenhouse;
Q_{loss}= heat loss rate from the greenhouse;
Q_{s-a} = heat flux between the soil and greenhouse air;
Q_{p-a}= heat flux between the plants and greenhouse air;
Q_{ven} = heat flux caused by greenhouse ventilation;
Q_{heat} = heat supply rate by the heating system;
T_g, ρ_a, c_a, v_a = air temperature, specific heat, greenhouse air density and air volume respectively; and
α_a = net solar radiation absorption coefficient by air in the greenhouse</td></tr>
<tr><td>$a\alpha\tau G_0 + b\delta(T_0)\Delta T - (b + K_1)\Delta e + bD_0 + \lambda W = 0$
$a\alpha\tau G_0 + (b + \beta)\delta(T_0)\Delta T - (b + \beta + K_1)\Delta e + (\beta + b)D_0 = 0$</td><td>5.20
5.21</td><td>Energy balance</td><td rowspan="5">Natural ventilation and fogging</td><td rowspan="5">(Boulard and Baille 1993)</td></tr>
<tr><td>$\Delta T = \frac{\left[\left(\frac{b+K_1}{K_1}\eta G_0\right) - bD_0 - a\alpha\tau G_0 - F\right]}{\left[b\delta(T_0) + \frac{(b+K_1)(K_S+K_C)}{K_1}\right]}$</td><td>5.22</td><td>$\Delta T$</td></tr>
<tr><td>$\Delta e = \frac{[\eta G_0 - \Delta T(K_S+K_C)]}{K_1}$</td><td>5.23</td><td>VP</td></tr>
<tr><td>$\lambda E_t = K_1 \Delta \mathrm{e} - \mathrm{F}$</td><td>5.24</td><td>$E_t$</td></tr>
<tr><td>$K_c = A + BV$
$K_s = \frac{\rho C_p V_g N}{3600 S_g}$
$K_1 = \frac{\gamma\rho\lambda V_g N}{3600 S_g}$
$N = \left[\varsigma\left(\frac{S_o}{2}\right) C^{0.5} V\right]\left(\frac{3600 S_g}{V_g}\right)$</td><td>5.25
5.26
5.27
5.28</td><td></td></tr>
<tr><td colspan="5">K_S= sensible heat transfer coefficient in (W.m^{-2}.K^{-1});
K_C= overall heat transfer coefficient (W.m^{-2}.K^{-1});
K_1= latent heat transfer coefficient (W.m^{-2}.K^{-1});
A and B = coefficients;
F = latent heat of misted water;
ρ= air density in kg.m$^{-3;}$
C_p= specific heat capacity of the air J.kg^{-1}.K^{-1};
V = Wind speed (m.s^{-2});
γ= conversion factor between air and vapour content;
λ= latent heat of vaporization;
ζ= discharge coefficient;</td></tr>
</table>

<table>
<tr><th>Model</th><th>Eq. No</th><th>EP</th><th>Control system applied</th><th>Reference</th></tr>
<tr><td colspan="5">V_g=greenhouse volume (m^3);
N=Greenhouse ventilation rate;
S_g= ground area (m^2);
ΔT= the internal-external difference in temperature in Kelvin;
T_o= outside temperature in Kelvin;
D_o= vapor pressure deficit of the external air (kPa);
Δe = vapor pressure difference (VPD) between the greenhouse and outside (Pa);
η= solar heating efficiency (dimensionless);
b and a= functions of the canopy resistances (s.m^{-1});
α= canopy absorption coefficient for solar radiation (dimensionless);
τ= greenhouse global transmission;
δ= saturation air water vapour pressure gradient in Pa.K^{-1};
G_o= Global outside radiation (W.m^{-2}); and
F= latent heat of vaporization of sprayed water (W.m^{-2})</td></tr>
</table>

Eq. No = Equation number, EP = estimated parameter, VP = Vapour Pressure

The models developed and validated by Impron (2007) are to determine crop canopy temperature, air temperature and air water vapour pressure. The models are designed to optimize cover properties and ventilation rates of a greenhouse with side and roof ventilation openings, as well as insect netting (Table 5.2, Eq. 5.7 - 5.9).

Kumar's (2010) models were also developed to specifically predict air vapour pressure, internal air temperature and crop canopy temperature on three different greenhouses with roof and side ventilation. The model takes into account solar radiation absorbed and transferred by the crop canopy and greenhouse cover and ignores heat transfer of the soil. These models were validated with experimental data and found to be reliable and accurate (Table 5.2, Eq.5.10 - 5.11).

Boulard and Wang (2000) developed a dynamic model that determines greenhouse crop transpiration. The parameters are discussed and different greenhouse types and crops are taken into consideration (A summary of natural ventilation models reviewed in this study is given in **Error! Reference source not found.** below.

Table 5.2, Eq. 5.13).

The dynamic model (Eq. 5.16) developed by Abdel-Ghany and Kozai (2006) determines the air, crop, greenhouse cover and floor temperatures, as well as relative humidity in a fog-cooled and naturally-ventilated greenhouse (Table 5.2). On the other hand, Jun Du *et al.* (2012) developed and validated a simulation model (Eq. 5.19) for greenhouse heating, using heat-pipe system with a thermal storage tank. Air and soil temperatures were predicted (Table 5.2). Another simplified model (Eq. 5.22) to predict inside RH, temperature and crop transpiration and temperature in a greenhouse with natural ventilation fogging was developed by Boulard and Baille (1993) (Table 5.2).

5.2.3 Forced ventilation models

The relationship between greenhouse ventilation and greenhouse temperature (V and T) has also been examined within a closed multi-span greenhouse with forced ventilation. The effect of ventilation rate caused by the fans, external wind speed, external air temperature, solar radiation and the transmissivity of the cover material on greenhouse air temperature, has been modelled and validated. The following relation was derived from a greenhouse energy balance equation (Kittas *et al.*, 2005):

$$T_i = T_o + \frac{R_{s,o}\tau(1-\alpha)}{\left(\frac{A_c}{A_g}\right)(K_1+K_2u)+\rho C_p V_a} \qquad (5.29)$$

Where T_i/T_o = inside and outside temperatures, respectively (˚C); $R_{s,o}$= outside solar radiation (in Wm^{-2}); τ = greenhouse transmissivity to solar radiation; α = latent heat transfer rate to radiation ratio; A_c is the greenhouse cover surface area (m^2); A_g= greenhouse ground surface area (m^2); $K_1$and K_2 are constants; μ= outside air speed ($m.s^{-1}$); ρ = air density (kg air per m^3 air); C_p = specific heat of air at a constant pressure (Jkg^{-1}˚C^{-1});$V_a = \frac{Q}{A_g}$ is the greenhouse ventilation rate for the floor area (m^3.s-1.m^{-2}); Q = ventilation flow rate (m^3[air].s^{-1}). The model assumes a regularly transpiring crop. Relative humidity in the greenhouse is not predicted by this model, which is a critical factor to consider.

Ganguly and Gosh (2007) developed and validated a model (Tx= Ta+ AB+ $\left(T_{pad} - T_a - \frac{A}{B}\right) e^{-Bx}$

$$T_x = \left(T_a + \frac{A}{B}\right) + \left(T_{pad} - T_a - \frac{A}{B}\right) e^{-Bx}$$

(5.30) predicting the internal temperature for cooling and ventilation through a pad and fan greenhouse under steady-state conditions. Shading was also applied and the effect of plant heat absorption is taken into account. The Ganguly and Gosh (2007) model is presented as follows:

$$T_x = \left(T_a + \frac{A}{B}\right) + \left(T_{pad} - T_a - \frac{A}{B}\right) e^{-Bx} \qquad (5.30)$$

where:

$$A = \frac{(1 - C\alpha)(S_c(I_{tc.N} + I_{tc.S})P + S_{sw} I_d 2H)}{V\rho C_p} \qquad (5.31)$$

and

$$B = \frac{2U(P + H)}{V\rho C_p} \qquad (5.32)$$

Where:
T_x = the internal greenhouse temperature, distance x (in meter) from the cooling pad in Kelvin; T_a = ambient temperature in (K); T_{pad} = air temperature through the cooling pad (K); A = greenhouse solar heat load coefficient; B = heat loss coefficient through greenhouse cover; C = fraction of surface area covered by crop; α = plant absorptivity; S_c and S_{sw} are shading factors for the canopy and the side walls, respectively (1 for zero shading and 0 for full shading); $I_{tc.N}$ and $I_{tc.S}$ = total radiation heat transfer rate of the north and south canopy respectively in W.m^{-2}; I_d= dispersed radiation heat transfer rate in W.m^{-2}; H= greenhouse height in m; V = ventilation rate of the fan in m^{3}.s^{-1}; ρ= air density in kg.m^{-3}; C_p= specific heat capacity of the air; U = the overall heat loss coefficient of the greenhouse in W.m^{-2}.K^{-1} ; P = is the half perimeter distance of the cover in m. The model assumes that the relative humidity remains constant and does not predict it.

Kittas *et al.* (2003) also developed and validated another model (Eq.$T_{in}(x) = T_o + \left[-\eta\left(T_o - T_{o,w}\right) - A_1\right]e^{-A_2 x} + A_1$ (5.33) that predicts the internal air temperature profiles in a greenhouse fitted with evaporative cooling pads, fans and shading in the greenhouse.

$$T_{in}(x) = T_o + \left[-\eta\left(T_o - T_{o,w}\right) - A_1\right]e^{-A_2 x} + A_1 \qquad (5.33)$$

where

$$A_1 = \frac{[\tau(1-\alpha)R_g]L}{V_p C_p} \tag{5.34}$$

and

$$A_2 = \frac{K_c L}{V_p C_p} \tag{5.35}$$

and

$$\eta = \frac{T_o - T_{pad}}{T_o - T_{o,w}} \tag{5.36}$$

Where:

$T_{in}(x)$ = internal temperature (in ˚C) at a distance x in the length of the greenhouse in meter; T_o = the outside air temperature in ˚C; η = the cooling efficiency of the system; $T_{o,w}$= outside wet bulb temperature in ˚C; T_{pad}= dry bulb air temperature leaving the pads in ˚C; $A_1$and A_2= coefficients; R_g= the outside global solar radiation in W.m^{-2}; L = the greenhouse width in meter; V = Ventilation rate in m^3.s^{-1}; C_p= specific air heat in J.kg^{-1}.˚C^{-1}; K_c= the heat loss coefficient of the greenhouse cover; α = coefficient that represents the influence of solar radiation/energy on the plant transpiration.

The coefficients that are critical for accurate prediction in this model are K_c and α and are determined by optimizing experimental data. Soil heat transfer and evaporation are neglected in this model. The response of plant physiology to local physical conditions is not incorporated in this model.

Fuchs *et al.* (2006) developed and validated another model (Eq. $T_i = T_p + \frac{r_X(R_n - E)}{\rho C_p}$ (5.37) that predicts average greenhouse temperature, crop transpiration and water vapour pressure in an evaporative cooled greenhouse.

$$T_i = T_p + \frac{r_X(R_n - E)}{\rho C_p} \tag{5.37}$$

where

$$E = \frac{\rho C_p e(T_c) - e_p}{\gamma\ (r_a + r_s)} \tag{5.38}$$

and

$$e_i = e_p + \frac{\gamma r_X E}{\rho C_p} \tag{5.39}$$

Where:

T_i = internal greenhouse temperature in ˚C; T_p = the temperature of air leaving the cooling pads in ˚C; T_c= temperature at crop canopy in ˚C; r_X = ventilation resistance in s.m^{-1}; R_n= the net radiation of the foliage in W.m^{-2}; E = heat transfer rate of the crop in W.m^{-2} ; ρ = the outside air density in kg.m^{-3}; $e(T_c)$ = saturated water vapour pressure at the crop in kPa; γ= psychrometric constant ≈ 0.0667 kPa.K^{-1}; r_a and r_s = the total convective resistance and crop foliage resistance to water vapour diffusion respectively, in s.m^{-1}; e_i= internal greenhouse vapour pressure in KPa ; e_p= air vapour pressure of the air leaving the cooling pad in kPa.

These models were not developed for conditions of South Africa. To use these models, the coefficients need to be optimized, using experimental data obtained under South African conditions.

6 AGRO CLIMATIC CONDITIONS IN SOUTH AFRICA

As mentioned in the previous sections, the type of greenhouse design depends largely on the location and the associated agro-climatic conditions. The different regions of South Africa can be seen in Figure 6.1 (FOA, 2005). Climate conditions range from Mediterranean in the south-west side, moderate in the central plateau and subtropical towards the north-east side of the country. There are four main climatic zones, including the desert (hyper-arid and arid zones), the semi-arid zone, the subtropical wet (humid) zone and the Mediterranean (dry sub-humid) winter rainfall region (Benhin, 2006).

The desert (arid region) generally borders the Northern Cape Province and north-eastern parts of the Western Cape Province. The average temperatures during the winter and summer in these areas are 10.2˚C and 23.8˚C, respectively, with minimum and maximum temperatures of 10.2˚C and 23.8˚C, respectively (Benhin, 2006).

The semi-arid zone is comprised of Limpopo, Mpumalanga, the North-West, Free State, the western parts of KwaZulu-Natal (KZN) and the Eastern Cape and the northern parts of the Western Cape. The average long term temperatures during winter and summer in these areas range between 9.5 - 15.4˚C and 18.4 - 22.8˚C, respectively, with minimum and maximum temperatures of 8.9 and 22.8˚C (Benhin, 2006). Within the same category, extremely cold temperatures are experienced in certain areas in the Free State, with temperatures dropping to 1˚C in winter, where places in Limpopo have warmer winters and extremely warm summers (they can reach up to 45˚C).

The coastal strip of KZN and the Eastern Cape are classified as sub-tropical wet zones. Average 24-hour temperatures during winter and summer in these areas are 12.3˚C and 19.1˚C, respectively, with minimum and maximum temperatures of 9.1˚C and 21.3˚C, respectively (Benhin, 2006). Durban’s daily temperatures in summer average at 32.0˚C.

The winter rainfall Mediterranean regions is comprised of the southern coastal strip of the Western Cape. The average temperatures for these areas range between 20.8˚C in summer and 10.8˚C in winter, with minimum temperatures of 9.5˚C in winter and 19.4˚C in summer.

Maximum temperatures during summer for these areas are 21.3˚C (Benhin, 2006). Coastal winters can drop to 7.0˚C where inland temperatures drop to 5.0˚C.

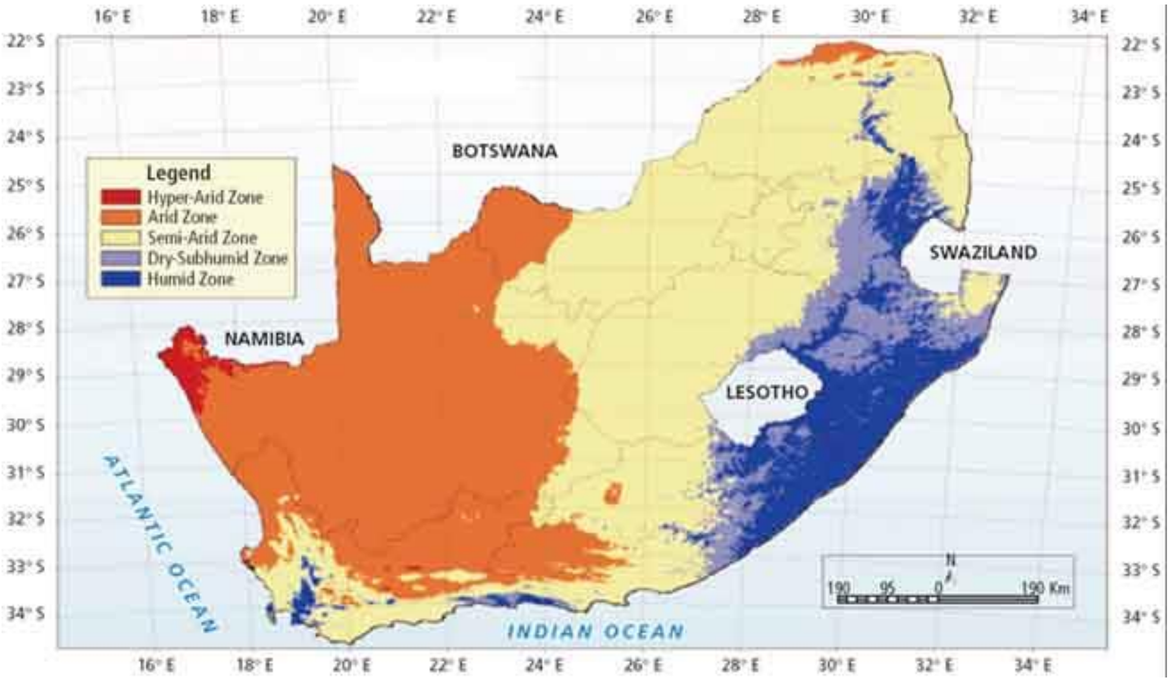


Figure 6.1 Agro-climatic areas of South Africa (FOA, 2005)

South Africa generally has ideal growing conditions and greenhouses were initially only used in South Africa for crop protection against excessive rains and hail. Another big stumbling block for growers in South Africa is the availability of water and crop cover, therefore hydroponic crop production is implemented to improve the efficiency of water-use (Sydow, 2010). Greenhouse production is also implemented, due to the significant fluctuations in temperature throughout the different regions and it therefore improves the indoor climate and optimizes production (Visser, 2012). Greenhouse designs and choice of crop are related to the differences in climate with respect to temperature, humidity and radiation. South Africa generally has high temperatures and the management of supra-optimal temperatures in the greenhouses remains one of the biggest challenges in the engineering of greenhouse systems. Johannesburg, Durban and Cape Town are the main production areas in South Africa (Sydow, 2010).

7 GREENHOUSES IN SOUTH AFRICA

The first vegetable production in South Africa was started by the Dutch in 1653. The flower industry in South Africa began between the 1920's and 1930's (de Visser and Dijkxhoorn, 2012). The first flower crops were cultivated under protection in South Africa during the 1960's, with vegetables following in the 1970's and 80's.

Farmers in South Africa are, generally, categorized as follows (de Visser and Dijkxhoorn., 2012):

a) Commercial farmers,
b) Emerging (small scale) farmers, and
c) Subsistence farmers – focusing on only supplying food only for their own consumption.

Table 7.1 below also describes the general classification of these types of farmers in relation to the type of greenhouse technology and production systems that are being used. It is also compared to the standard quality grown in the United States of America (USA). Each of these types of farmers might at some stage have the opportunity to make a transition towards improved crop productivity. Choosing the applicable technology for a region then becomes critical.

Table 7.1 Approximate classification of South African protected horticulture (de Visser and Dijkxhoorn, 2012)

	Technology type		
	Low	**Medium**	**High**
Typical size	1-10 ha	2-50 ha	3-20 ha
Cover type	Shadow net	Plastic roof, net walls	Plastic, glass
Production process	Soil	Hydroponics	Hydroponics, climate control
Cooling system	Natural ventilation	Natural ventilation	Pad&Fan
US 1 Quality of produce	40%	60-70%	90%
Farmer	Subsistence Emerging Farmers	Emerging Commercial Farmers	Commercial Farmers

Some of the major greenhouse construction companies in the country were consulted and information was gathered regarding existing greenhouse installations in South Africa (Venter, 2013; Olsen, 2013, van Niekerk, 2013). In hyper-arid areas of South Africa, greenhouses are generally structures of 4 m high and equipped with a combination of natural ventilation, fogging, pad and fan cooling and energy saving screens. Heating is often also installed, based on the type of crop planted, to control the cold nights in these areas. In semi-arid areas, greenhouses are generally constructed 4.5-5 m high and equipped with a combination of natural ventilation (in some places forced ventilation and pad and fan cooling), hot water heating, air circulation fans and screening (shading and thermal screens).

In the subtropical, humid areas of South Africa, greenhouses are generally higher (5-6 m gutter height), to improve ventilation and humidity control. Ventilation is maximized by having side and roof ventilation and shade screens and fans are often installed to control temperature and humidity. Heating is not often installed. In the dryer sub-tropical (Mediterranean) areas, greenhouses are also constructed at a 5 m height, with natural ventilation. Closed greenhouses are often used in these areas equipped with pad and fan.

In most cases, it is found that problems with pad and fan cooling are often experienced in terms of the rising cost associated with electricity consumption, as well as the fact that it is the only method of ventilation, even during cold periods, and has negative effects on plants. Problems have also been experienced regarding ventilation, and the fact that natural ventilation is often not sufficient. It is also found that many installations are designed and specified by international companies and are often not optimally utilized in certain areas.

8 DIFFERENT CROPS AND THEIR REQUIREMENTS

The main crops that are grown in greenhouses in South Africa are tomatoes, cucumbers, sweet peppers, lettuce, aubergine, herbs, strawberries, melons, gem squash, baby marrows and beans (Venter, 2013). Some of the crops and their climate requirements are provided in Table 8.1 below.

Table 8.1 Different crop temperature requirements

Crop	**Temperature**	**Reference**	
	Optimum night (˚C)	**Optimum day (˚C)**	**Reference**
Tomato	14	18 (no fruit set above 25˚C daily mean)	Peet (1999)
Cucumber	20	30	Hui *et al.*, (2003)
Eggplant	18	30	Hui *et al.*, (2003)
Sweet pepper	16	21 (maximum 32 ˚C for fruit set)	(Manrique (1993)
Lettuce and herbs	12	24	Manrique (1993);Peet (1999)
Spinach	15	20	Peet (1999); Hui *et al.*, (2003)
Cabbage	2	15-16	Peet (1999)
Strawberries	12 12	18 (optimum growth for roots and fruits) 25 (growth of the whole plant)	Manrique (1993); Wang and Camp (2000)
Baby marrows	18	30	Hui *et al.*, (2003)
Melons (musk melon)	15	32	Nonneke (1989)

9 GREENHOUSE INSTALLATION COSTS

Economical and bankable feasibility is critical for any type of investor, regardless of the classification (low, medium or high technology) and purpose of the greenhouse. Examples of costs for different greenhouse types and components are given in Table 9.1 below:

Table 9.1: Greenhouse installation costs

Multi-span 1 ha greenhouse	
Component	Cost/m^2 (ZAR)
Structure with continuous double sided ridge ventilation	150-200
Screens for shading	60-80
Drip irrigation with fertigation system	40-50
Fogging	30-50
Hot water heating	150-180
Hot air heating	40-50
Computer climate control system (controlling only critical aspects)	15-30
Ground cover (plants grown on ground)	5-10
Gutter growing system	40-50
Pad and fan	40-50
Shade net greenhouse (low cost) – multi-span 1ha structure	
Structure and cover	50-60
Irrigation	40-50
Ground cover	5-10

The costs are generally based on a 1ha multi-span greenhouse. Costs per m^2 will increase, if the size of the greenhouse is reduced, and decrease for larger sizes.

10 DISCUSSION AND CONCLUSION

Greenhouses have been designed by suppliers in South Africa, who often provide specific technologies and greenhouse designs (van Niekerk, Venter, 2013). Particular climatic conditions are rarely taken into account when designs are prepared and could lead to high operating and maintenance costs, as well as sub-optimal performance of greenhouses with regards to climate control (Venter, 2013). There is also limited expertise in the field of greenhouse technologies and design requirements in Africa, including South Africa and not many investors consult others for input into design/technology selection.

Microclimate conditions that have to be controlled to optimize crop growth include temperature, RH, solar radiation, CO_2 and internal air velocity. Light intensity (solar radiation) and CO_2 are the primary factors that enhance photosynthesis and plant growth. Temperature and RH are the critical factors to control (Bournet and Boulard, 2010), to optimize plant photosynthesis under optimal light and CO_2 conditions, but also the most difficult factors to successfully control in greenhouses, especially in South Africa, where extremely high temperatures are experienced at certain times of the year and therefore greenhouse cooling remains challenge (Kumar *et al.*, 2009).

Greenhouse structures are designed to control and optimize the internal micro-climate inside the structure. Types of greenhouse structures and the performance in terms of internal temperature and ventilation rates have been evaluated by some (Boulard *et al.*, 2007; Sethi, 2008). Different shapes, sizes, orientations and greenhouse covers are used in combination with cooling systems, to attempt the optimal control of the internal climate. Various cooling systems across the globe and their performance in controlling these factors have been reviewed and compared by several researchers (Kumar *et al.*, 2009; Sethi and Sharma, 2007). Experimental and numerical studies have been done, as described in the literature, on the performance of different cooling systems under specific conditions. Natural ventilation, pad-fan evaporative cooling, screening and fogging systems are commonly-used cooling systems in South Africa. Each system will perform differently, depending on the area. Limited literature is available for cooling system performance for the variable agro-climatic conditions in Southern Africa. However, Maboko *et al*. (2010) have indicated that evaporative cooling systems like the use of a wet pad and fan are not often used in South

Africa, because of high operating and maintenance costs. Researchers have also stated that natural ventilation might not effectively manage the extreme high temperatures experienced inside greenhouses (Maboko *et al.,* 2010; Mashonjowa *et al.,* 2010). System performance in similar agro-climatic conditions, other than South Africa, has been researched and shows that for tropical and subtropical regions, greenhouses should be fitted with a ventilation area of 15-30% of the floor area. Fogging systems and pad and fan systems during summer seasons, with shading for areas with lower average humidity, are also often used (Kumar *et al.,* 2009). In Mediterranean regions, natural ventilation with cover whitening and shading was proven to be the preferred option (Castilla, 2008; Gonzalez and Baille, 2006). Evaporative cooling and forced ventilation systems are proven to be more effective in dry (arid) areas (Jensen, 2002). The lowest cost greenhouse is, however, shade-net greenhouse.

To predict the performance of different greenhouse structures and climate control (cooling) systems under certain conditions, several models are being developed (Boulard *et al.,* 1997; Fatnassi *et al.,* 2003; Abdel-Ghany and Kozai, 2006). More complex or heterogeneous models are used to characterize the non-uniform situation of the internal climate of a greenhouse. Recently, Computational Fluid Dynamics (CFD) modelling has been used for these purposes. Homogenous (static or dynamic) models assume steady-state conditions in a greenhouse and are based on the energy balance of the internal system. It also assumes a uniform distribution. Homogenous models that can predict greenhouse temperature and humidity are more complex, and have more input parameters and can only predict the overall averages of the climate parameters. Models for predicting the ventilation rate and greenhouse temperatures for different structures and vent configurations have been developed extensively, but do not have the capability to predict RH (Ganguly and Ghosh, 2009; Mashonjowa *et al*., 2013).

In conclusion, there is a large knowledge gap in data and literature availability, to sufficiently assist local South African investors/farmers to select the optimum greenhouse design and the associated systems. There is limited peer-reviewed literature available in South Africa that compares the performance of different natural and evaporative cooling systems. To be able to develop models for predicting this performance for different designs and climatic conditions, the calibration and optimization of models are required. The selection of greenhouses cannot be done without taking into account capital expenditure and operating and maintenance costs. This research project will, thus, also look at these aspects for the greenhouse selection process.

11 RESEARCH PROJECT PROPOSAL

The world population is expected to grow by one more billion people within the next 13 years (Statistic Brain Research Institute, 2013). South Africa has an estimated population growth rate of 1.7% per annum (du Toit, 2009). It is estimated that 35% of the South African population live with inadequate access to food. Conventional agricultural methods show obvious limitations and are not efficient enough to produce sufficient food for everyone. Land that is unsuitable for traditional farming contributes to shortages, as do urban conditions that prevent self-sufficiency (Venter, 2010). Drought conditions and the lack of access to certain resources exist all over the world and are the most important cause of food insecurity on the continent. There is, however, enough sun light and water to sustainably feed the world population (Venter, 2010).

Poverty and food insecurity are closely linked (du Toit, 2009). There is, therefore, also a need to empower people financially through providing appropriate and sustainable agro-technologies that are proven to be useful, to increase agricultural productivity. Recent research work done on boosting smallholder production for food security indicated that food insecurity is linked to strong institutional support and a favourable external environment and that certain policies and strategies, developed to increase agricultural productivity, can have a substantial contribution towards reducing the general food insecurity status of the country (du Toit, 2009). One of the proven agricultural technologies for growing produce under controlled conditions is use of greenhouses. Due to the aridity of the land, water scarcity and declining soil health in South Africa, the popularity of greenhouse crop production is expected to increase (de Visser and Dijkxhoorn, 2012). Greenhouse production can contribute in achieving the strategic objectives of the plan for South African agriculture related to:

- An increased creation of wealth in agriculture and rural areas,
- increased sustainable employment,
- increased incomes and increased foreign exchange earnings,
- reduced poverty and inequalities in land and enterprise ownership,
- improved farming efficiency,
- improved national and household food security, and

- stable and safe rural communities, reduced levels of crime and violence and sustained rural development.

Development of small-scale and even large-scale greenhouses all over South African can have a significant impact on food security, malnutrition and economic development in South Africa. Local municipalities and the national government of South Africa are in support of projects like these and it is critical to ensure that the outcome is successful and sustainable. Several different types of greenhouse structures are available in South Africa. However, there is limited sufficient scientific information available on the performance of different types of greenhouses, cooling systems, heating systems and climate control installations. Since the typical climate of South Africa generally causes supra-optimum temperatures in greenhouses, the focus of studies should be on comparing the performance of different cooling systems in the country. Similarly, there are no comprehensive studies aimed at screening and analysing the low-cost greenhouses with regards to the sustainability of producing food crops, with less intensive climate control. Typical cooling systems installed in South Africa include evaporative cooling (fogging, pad and fan) and natural ventilation (roof/side or roof and side ventilation or the use of shade netting). Based on the above analysis, a study on the engineering of sustainable and appropriate greenhouse technologies in South Africa needs to be undertaken, in order to identify or develop the best greenhouse technologies that can be best-fitted to the different agro-climatic conditions in the country.

11.1 Aims and Objectives

The aim of the project is to generate data and information on four different greenhouse designs, with different air ventilation and cooling systems, and to identify easily applicable greenhouse designs, specifically for the cooling of the micro-environment in a greenhouse, for use in the different agro-climatic conditions of the different regions in South Africa.

The specific objectives of the project are:

- to compare the internal temperature and relative humidity of the air inside the four different greenhouse designs and cooling systems,
- to evaluate the effect of different microclimates in four greenhouses on growth performance of selected sample lettuce,

- develop models using experimental data obtained and to predict the performance of the identified greenhouses in terms of microclimate temperature and control systems for various external climates,
- to compare major cost factors for each greenhouse (capital, maintenance and running costs), and
- to develop a computational fluid dynamics model for the microclimate and heat and mass balances of four greenhouses.

11.2 Materials and Methods

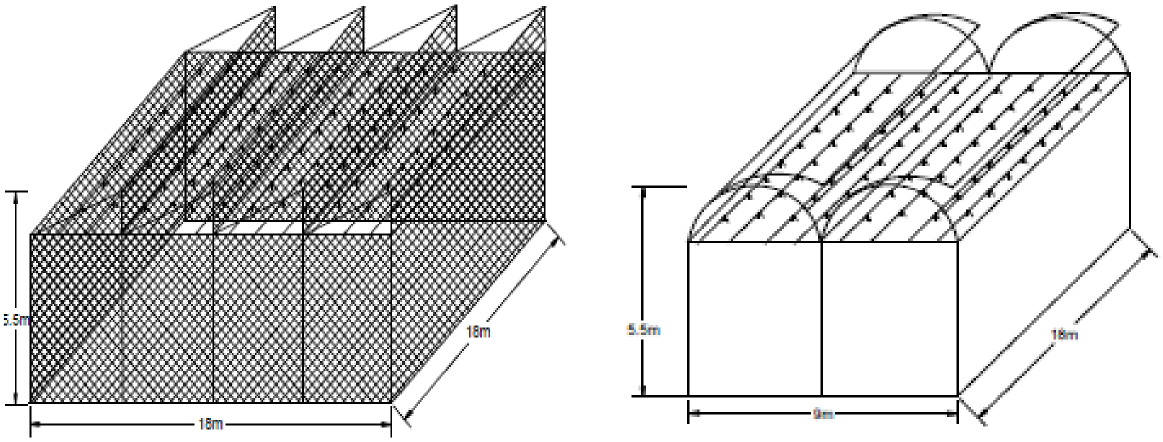
The following sections describe the research site, different greenhouses and materials and procedures that will be used.

11.2.1 Experimental site

The research will be conducted at the University of KwaZulu-Natal’s College of Agriculture, Engineering and Science campus, Pietermaritzburg, South Africa (29°37’39.72’’S, 30°24’09’’E). The average maximum air temperatures vary between 20.6 and 27.8˚C and the average minimum temperatures vary between 6 and 16.4˚C. Solar radiation varies between 15.1-27.8 $MJ.m^{-2}.day^{-1}$ and the daily average RH ranges between 61.1-75.3% (Schulze, 1997).

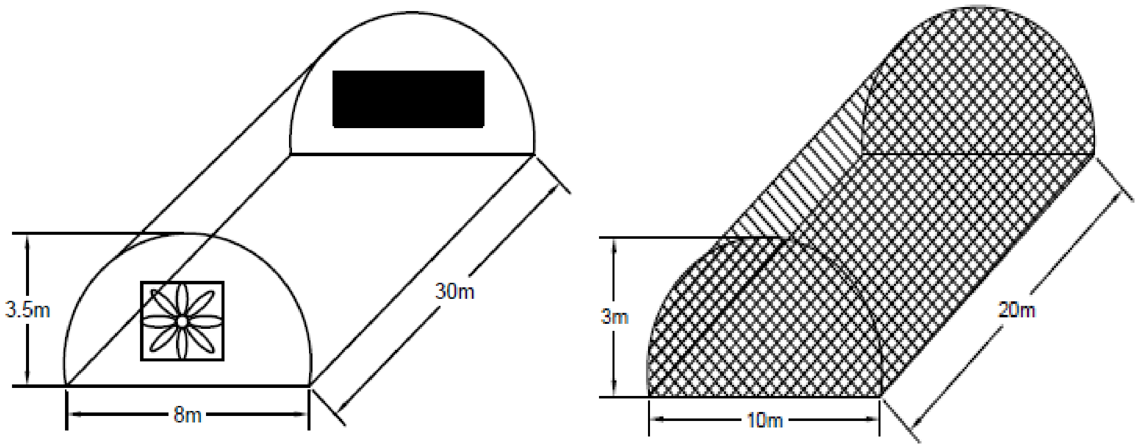
11.2.2 Greenhouses

Four greenhouses will be used in this study as presented in Figure 11.1 below. Greenhouse (a) and (b) are the same size (18 m in length and width and 5.5 m high), one with side-ventilation with nets (Greenhouse (a)), equipped with fogging and covered with polycarbonate, and one with roof ventilation (Greenhouse (b)) fitted with fogging and covered with polyvinyl. Overhead irrigation is fitted over 50% of the area of Greenhouse (a). The pad and fan greenhouse is 30 m long, 8 m wide and 3.5 m high and covered with polycarbonate (Greenhouse (c)). The shade net (Greenhouse (d)) greenhouse is 20 m long, 10 m wide and 3.5 m high.



a) Side ventilation and fogging

b) Roof ventilation and fogging



c) Pad and fan greenhouse

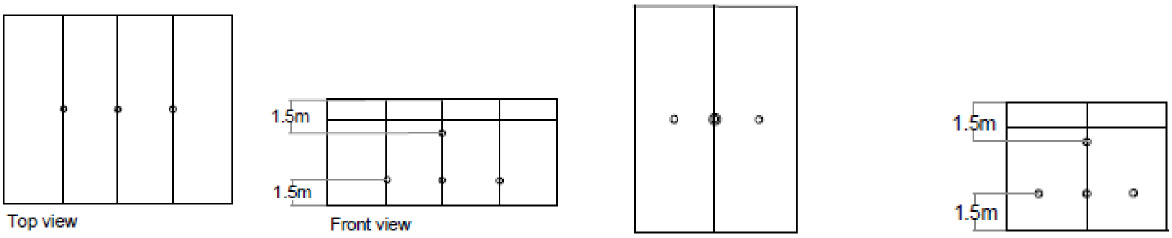
d) Shade net tunnel

Figure 11.1 Schematic diagrams of the different greenhouses used for research study

11.2.3 Experimental design

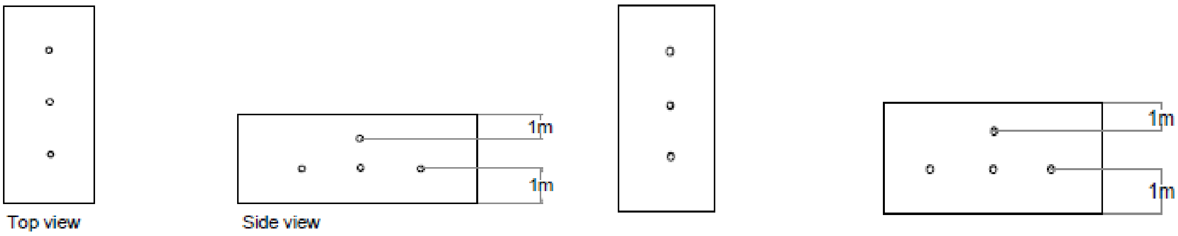
The experiment consists of four greenhouses. The measurements of temperature and relative humidity will be done in all greenhouses. Internal temperature and relative humidity will be measured using hobo data loggers (further described in Section 11.2.4). For Greenhouse (a) (Figure 11.1
Figure 11.2), four data loggers will be used for each greenhouse. Three will be placed 4.5 m apart and 1.5 m above the greenhouse floor and one will be placed in the middle of the greenhouse at 1.5 m below the ridge height. Sensors in Greenhouse (b) will be placed 1.5 m apart in the middle of the greenhouse, 1.5 m above the greenhouse floor and the one in the middle, 1.5 m below the ridge height. For Greenhouse (c) (Figure 11.2

Figure 11.2), four data loggers will be used. Three sensors will be placed along the centre of the greenhouse every 10 m, at a height of 1 m above floor level, and one sensor will be placed exactly in the middle of the greenhouse, 1 m below ridge height. For Greenhouse (d) (Figure 11.2), four data loggers will be used. Three sensors will be placed in the middle of the greenhouse every 6 m, at a height of 1 m above floor level, and one sensor will be placed exactly in the middle of the greenhouse, 1 m below ridge height.



a) Side ventilation and fogging

b) Roof ventilation and fogging



c) Pad and fan

d) Shade net greenhouse

Figure 11.2 Experimental sensor setup

The arrangement of the loggers should ensure that the distribution of temperature and relative humidity is more accurately observed. A sensor will also be placed at a central area outside the greenhouses to measure ambient temperature and relative humidity. Global outside solar radiation and wind speed will also be measured (described in detail in Section 11.2.4 below).

To ensure that the effect of the crop transpiration is taken into account, lettuce plants of the same size will be placed in each greenhouse. The plants will be irrigated, using drip irrigation.

11.2.4 Measurements of climate parameters

Digital data loggers (Hobo Pro v2 optic data loggers) will be used to record the inside temperature and relative humidity. The RH sensor will have a measuring range of 0-100% with a ± 2.5% accuracy and the temperature sensors have a measurement capacity of temperature ranging between -40˚C and 70˚C, with accuracy of ± 0.2%. The data will be recorded at 10-minute interval for four weeks and then averaged hourly. The external climate parameters, including global solar radiation and wind speed will be obtained from a local meteorological weather station located on the site (http://agromet.ukzn.ac.za:5355).

11.2.5 Crop agronomic parameters and growth data collection

Lettuce crops will be grown simultaneously in each of the greenhouses. Twenty-eight plants of the same age will be planted in each greenhouse. Four different Salanova® cultivars will be used in each, namely, Erasmus RZ; Gaugin RZ; Xerafin RZ and Cook RZ. Salanova®. The effect of the climate in each greenhouse on the lettuce crop will be monitored by capturing the number of new leaves developed, leaf area, dry mass and fresh weight yield (Ogbodo *et al.*, 2010, Urbonaviciute *et al.*, 2007). Drip irrigation will be used to supply water and nutrients to the plants. In the pad and fan greenhouse, plants will be irrigated using a nutrient flow technique (NFT). The number of leaves will simply be counted and the leave area will be determined by measuring the width and length of the leaves with a ruler and averaging the areas of the sample taken (Ogbodo *et al.*, 2010). Dry mass will be determined, using the oven-drying method. Fresh weight per plant will be measured in grams using a digital scale and averaged per sample. Soil will be washed from the plants and then weighed. Measurements will be taken at the beginning and end of the experimental period.

11.2.6 Greenhouse climate modelling

The following section describes the procedures that will be followed in the process of modelling climate conditions. The model described in Table 5.2 (Boulard and Baille, 1993) will be used for modelling and predicting temperature and water vapour pressure (humidity). The coefficients a and b in Eq. 5.22 will be optimized by fitting experimental data to the models. All other parameters required for the optimization of the selected models will be obtained from the existing literature, since the values are within a narrow range (Boulard and Baille, 1993).

The following factors were considered when the specific model was selected:

- Simplicity and ease of use,
- It can be applied to different cooling systems, and
- Low computational requirements and thus smaller computer memory needed.

The models and equations are summarized below (Boulard and Baille, 1993).

The water vapour balance:

$$a\alpha\tau G_0 + b\delta(T_0)\Delta T - (b + K_1)\Delta e + bD_0 + \lambda W = 0 \tag{5.23}$$

$$a\alpha\tau G_0 + (b + \beta)\delta(T_0)\Delta T - (b + \beta + K_1)\Delta e + (\beta + b)D_0 = 0 \tag{5.24}$$

The water vapour and energy balance combination (Boulard and Baille, 1993):

$$\Delta T = \frac{\left[\left(\frac{b+K_1}{K_1}\eta G_0\right) - bD_0 - a\alpha\tau G_0 - F\right]}{\left[b\delta(T_0) + \frac{(b+K_1)(K_S+K_C)}{K_1}\right]} \tag{5.10}$$

Where:

$$K_c = A + BV \tag{5.25}$$

$$K_s = \frac{\rho C_p V_g N}{3600 S_g} \tag{5.26}$$

$$K_1 = \frac{\gamma\rho\lambda V_g N}{3600 S_g} \tag{5.27}$$

Table 11.1 Summary of parameters to be used

	Description	**References**
To be measured	Inside/outside temperature (T_0, T_i) Global solar radiation (G_0) Wind speed (V) Relative humidity	Boulard and Baille, 1993
To be calculated	Ventilation rate (N) Sensible heat, latent heat and heat transfer and coefficient of the cover (K_s $K_1 K_c$) Outside vapour pressure deficit (D_0) Latent heat of vaporization (F)	Boulard and Baille, 1993

To be determined from literature	Coefficient A, B, a and b Solar efficiency (η) Discharge coefficient (δ) Conversion factor (γ) Greenhouse global transmission (τ) Canopy absorption coefficient (α)	Boulard and Baille, 1993
To be recorded	Water application rate (W) Ventilation openings (S_g/S_o)	Boulard and Baille, 1993

11.3 Measure cost benefit analysis

A simple economic model will be developed to analyse the costs against the benefits for each greenhouse (Canakci and Akinci, 2006). The benefits in terms of optimal climate control will be measured against the cost of installation, operation and maintenance. The operational cost will primarily include water and energy costs. The latter will be derived from the design specifications and installation and maintenance costs will be retrieved from the installer of the systems.

11.4 Data Analysis

The statistical analysis of the microclimate data, lettuce crop growth parameters and yield component will be analysed, using a Statistical Analysis System (SAS) and other relevant statistical computer packages.

11.5 Resource Planning

Funds for the research have been privately secured. The following resources will be required for the study: computer, plants, irrigation, data loggers, fertilizers and pesticides, automated controllers (fogging and pad and fan), fertigation equipment, software and protective clothing.

11.6 Health, Safety, Environmental and Ethical Considerations

The research is not expected to contravene any health, safety or environmental laws. Protective clothing in the form of masks, gloves and overalls will be required when handling fertilizers and pesticides.

11.7 Research Project Schedule

Table 11.2 Research project schedule proposal

Research Project deliverables (2013-2015)	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Literature Review and Research Proposal	■	■	■	■	■	■	■	■	■									
Data collection										■	■	░	░	░	░	░		
Data analysis											■	■	■	■				
Thesis Write-up	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Draft submission															■			
Corrections																■	■	■
Final submission																		■

12 REFERENCES

Abbes, M, Farhat, A, Mami, A, and Dauphin-Tanguy, G. 2010. Pseudo bond graph model of coupled heat and mass transfers in a plastic tunnel greenhouse. *Simulation Modelling Practice and Theory* 18:1327-1341.

Abdel-Ghany, AM, and Kozai, T. 2006. Cooling efficiency of fogging systems for greenhouses. *Biosystems Engineering* 94(1):97-109.

Abdel-Ghany, AM and Kozai, T. 2006. Dynamic modelling of the environment in a natural ventilated, fog-cooled greenhouse. *Renewable Energy* 31(10):1521-1539.

Alkilani, MM, Sopian, K, Alghoul, MA, Sohif, M, and Ruslan, MH. 2011. Review of solar air collectors with thermal storage units. *Renewable And Sustainable Energy Reviews* 15:1476-1490.

Arbel, A, Barak, M, and Shklyar, A. 2003. Combination of Forced Ventilation and Fogging Systems for Cooling Greenhouses. *Biosystems Engineering* 84:45-55.

Baeza, EJ, Perez-Parra, JJ, and Lopez, JC. 2006. CFD Study of the Natural Ventilation Performance of a Parral Type Greenhouse with Different Numbers of Spans and Roof Vent Configurations. Proceedings from International Symposium on Greenhouse Cooling. *Acta Hort* 719:333-340.

Baeza, EJ, Perez-Parra, JJ, and Lopez, JC. 2006. CFD Study of the Natural Ventilation Performance of a Parral Type Greenhouse with Different Numbers of Spans and Roof Vent Configurations. Proceedings of International Symposium on Greenhouse Cooling, *Acta Hort* 719:333-340.

Baptista, FJ, Bailey, BJ, Meneses, JF, and Navas, LM. 2010. Greenhouse climate modelling. Tests, adaptation and validation of a dynamic climate model. *Spanish Journal of Agricultural Research* 8(2):285-298.

Bartzanas, T, Boulard, T, and Kittas, C. 2002. Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. *Computers and Electronics in Agriculture* 34(1-3):207-221.

Bartzanas, T, Boulard, T, and Kittas, C. 2004. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. *Biosystems Engineering* 88(4):479-490.

Bartzanas, T, Kacira, M, Zhu, H, Karmakar, S, Tamimi, E, Katsoulas, N, Bok Lee, I, and Kittas, C. 2013. Computational fluid dynamics applications to improve crop production systems. *Computers and Electronics in Agriculture* 93:151-167.

Benhin, JKA. 2006. Climate change and South African Agriculture: Impacts and adaption options. CEEPA Discussion Paper No.21, Special series on Climate Change and Agriculture in Africa ISBN 1-920160-01-09: ISBN 1-920160-21-3.

Boulard, T and Baille, A. 1993. A simple greenhouse climate control model incorporating effects of ventilation and evaporative cooling. *Agricultural and Forest Meteorology* 65:145-157.

Boulard, T and Wang, S. 2000. Greenhouse crop transpiration simulation from external climate conditions. *Agricultural and Forest Meteorology* 100:25-34.

Boulard, T, Feuilloley, P, and Kittas, C. 1997. Natural Ventilation Performance of Six Greenhouse and Tunnel Types. *Journal of Agricultural Engineering Research* 67:249-266.

Bournet, P and Boulard, T. 2010. Effect of vent configuration on the distributed climate of greenhouse: a review of experimental and CFD studies. *Computers and Electronics in Agriculture* 74(2):195-217.

Broos, J. 2013. Personal communication. Anima Trading. Monster, the Netherlands. 23/09/2013.

Canakci, M and Akinci, I. 2006. Energy use pattern analyses of greenhouse vegetable production. *Energy* 31(8-9):1243-1256.

Castilla, N. 2013. Greenhouse Technology and Management, CABI, Oxfordshire, United Kingdom.

Challinor, A, Wheeler, T, Garforth, C, Craufurd, P, and Kassam, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climate Change* 83:381-399.

Connellan, GJ. 2002. Selection of Greenhouse Design and Technology Options for High Temperature Regions. Proceedings on the International Symposium on Tropical and Subtropical Greenhouses. 2002. *Acta Hort* 578:113-117.

Dannehl, D, Schuch, I, and Schmidt, U. 2013. Plant production in solar collector greenhouses – Influence on yield, energy use efficiency and reduction in CO2 emissions. *Journal of Agricultural Science* 5 (10):1916-9752.

Davies, PA. 2005. A solar cooling system for greenhouse food production in hot climates. *Solar Energy* 79:661-668.

De Visser, P, and Dijkxhoorn, Y. 2012. Business opportunities for protected horticulture in South Africa. Wageningen UR Greenhouse Horticulture Rapport GTB-1164.

Djevic, M and Dimitrijevic, A. 2009. Energy consumption for different greenhouse constructions. *Energy* 34:1325-1331.

Du Toit, DC, Ramonyai, MD, Lubbe, PA and Ntushelo, V. 2011. Food security. Report for Agriculture, forestry and fisheries Republic of South Africa. By Directorate Economic Services, Production Economics unit. Pretoria, South Africa. Available from http://www.nda.agric.za/docs/GenReports/FoodSecurity.pdf.

Du, J, Bansal, P and Huang, B. 2012. Simulation model of a greenhouse with a heat-pipe heating system. *Applied Energy* 93:268-276.

FAO. 2005. Fertilizer use by crop in South Africa. [Internet]. FAO, Rome, Italy. Available from http://www.fao.org/docrep/008/y5998e/y5998e06.htm [Accessed January 2014].

Fatnassi, H, Boulard, T and Bouirden, L. 2003. Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens. *Agricultural and Forest Meteorology* 188:97-111.

Franco, A, Valera, DL, Pena, A and Perez, AM. 2011. Aerodynamic analysis and CFD simulation of several cellulose evaporative cooling pads used in Mediterranean greenhouse. *Computers and Electronics in Agriculture* 76(2):218-230.

Fuchs, M, Dayan, E and Presnov, E. 2006. Evaporative cooling of a ventilated greenhouse rose crop. *Agricultural and Forest Meteorology* 138:203-215.

Ganguly, A and Ghosh, S. 2007. Modelling and analysis of a fan-pad ventilated floricultural greenhouse. *Energy and Buildings* 39:1092-1097.

Ganguly, A and Ghosh, S. 2009. Model development and experimental validation of a floriculture greenhouse under natural ventilation. *Energy and Buildings* 41:521-527.

Gonzalez-Real, MM and Baille, A. 2006. Plant response to greenhouse cooling. *Acta Hort.* 719:427-437.

De la Torre-Gea, G, Soto-Zarazúa, GM, López-Crúz I, Torres-Pacheco, I and Rico-García, E. 2011. Computational fluid dynamics in greenhouses: A review. *African Journal of Biotechnology* 10(77):17651-17662.

Hare, JG, Norton, B and Probert, SD. 1984. Design of ‘Greenhouses’: Thermal Aspects. *Applied Energy* 84: 0306-2619.

Harreguy, X. 2013. Personal communication. Ulma. Onati, Spain 23/09/2013.

Hemming, S, Kempkes, F, van der Braak, N, Dueck, T and Marissen, N. 2006. Greenhouse cooling by NIR-reflection. Proceedings from International Symposium on Greenhouse Cooling. *Acta Hort* 719:97-106.

Henning, D. 2013. Personal communication. Dynatrade, Gauteng, South Africa. 22/11/2013.

Hui YH, Ghazala Sue, Graham, M Dee, Murrel, KD and Nip WK. 2003. Handbook of Vegetable Preservation and Processing. Technology and Engineering. CRC Press, Florida, United States.

Impron, I, Hemming, S and Bot, GPA. 2007. Simple greenhouse model as a design tool for greenhouses in tropical lowland. *Biosystems Engineering* 98:79-89.

Jain, D and Tiwari, GN 2002. Modeling and optimal design of evaporative cooling system in controlled environment greenhouse. *Energy Conversion and Management* 43:2235-2250.

Jensen, H. 1999. Hydroponics Worldwide. Proceedings of International Symposium on Growing Media and Hydroponics. *Acta Hort*. 481:719-730.

Jensen, H. 2002. Controlled Environment Agriculture in Deserts, Tropics and Temperate Regions – A World Review. Proceedings of International Symposium on Tropical and Subtropical Greenhouses. *Acta Hort* 578:19-25.

Katsoulas, N, Bartzanas, T, Boulard, T, Mermier, M and Kittas, C. 2006. Effect of vent openings and Insect Screens on Greenhouse Ventilation. *Biosystems Engineering* 93(4):427-436.

Kavga A., Alexopoulos G., Bontozoglou V., Pantelakis, S. and Panidis, Th., 2012. Experimental Investigation of the Energy Needs for a Conventionally and an Infrared-Heated Greenhouse. *ISHS Acta Horticulturae* 893:461-468.

Kenig, A. 2000. CO2 enrichment in greenhouse production: Practice and bottlenecks. Workshop on greenhouse technology towards 3 Mill. *Acta Hort* 534:221-230.

Kim, K, Yoon, J, Kwon, H, Han, J, Son, J, Nam, S, Giacomelli, GA and Lee, I. 2008. 3-D CFD analysis of relative humidity distribution in greenhouse with a fog cooling system and refrigerative humidifiers. *Biosystems Engineering* 100(2):245-255.

Kittas, C, Bartzanas, T, Jaffrin, A. 2003. Temperature Gradients in a Partially Shaded Large Greenhouse equipped with Evaporative Cooling Pads. *Biosystems Engineering* 85:87-94.

Kittas, C, Boulard, T, Mermier, M, and Papadakis, G. 1996. Wind Induced air exchange rates in a greenhouse tunnel with continuous side openings. *Journal of Agricultural Engineering Research* 65:37-49.

Kittas, C, Boulard, T and Papadakis, G. 1997. Natural ventilation of a greenhouse with ridge and side openings; sensitivity to temperature and wind effects. *Transaction of the American Society of Agricultural Engineers* 40(2):415-425.

Kittas, C, Karamanis, M, and Katsoulas, N. 2005. Air temperature regime in a forced ventilated greenhouse with rose crop. *Energy and Buildings* 37:807-812.

Körner, O and Challa, H. 2003. Process-based humidity control regime for greenhouse crops. *Computers and Electronics in Agriculture* 39:173-192.

Kumar, KS, Madan KJha, Tiwari, KN and Singh, A. 2010. Modeling and evaluation of greenhouse for floriculture in subtropics. *Energy and Buildings* 42:1075-1083.

Kumar, KS, Tiwari, KN, Madan, KJha. 2009. Design and technology for greenhouse cooling in tropical and subtropical regions. *A Review Energy and Buildings* 41:1269-1275.

Lee I, Bitog JPP, Hong S, Seo I, Kwon K, Bartzanas T and Kacira M. 2013. The past, present and future of CFD for agro-environmental applications. *Computers and electronics in Agriculture* 93:168-183.

Linker, R, Kacira, M, Arbel, A. 2011. Robust climate control of a greenhouse equipped with variable speed fans and variable pressure fogging system. *Biosystems Engineering* 110:153-167.

Manrique, L.A., 1993. Greenhouse Crops: A Review. *Journal of Plant Nutrition* 16(12):2411-2477.

Mashonjowa, E, Ronsse, F, Milford, JR, Pieters, JG. 2013. Modelling the thermal performance of a naturally ventilated greenhouse in Zimbabwe using a dynamic greenhouse climate model. *Solar Energy* 91:381-393.

Medrano, E, Lorenzo, P, Sánchez-Guerrero, MC, García, ML, Caparrós, I and Giménez, M. 2004. Influence of an external greenhouse mobile shading on tomato crop transpiration. *Acta Horticulturae* 659:195-199.

Nonnecke, Libner, Ib.1989. Vegetable production. Van Nostrand Reinhold, USA.

Olsen, G. 2013. Personal communication. Rhino Agrivantage. Port Elisabeth, South Africa, 01/11/2013.

Ogbodo, EN, Okorie PO and Utobo EB. 2010. Growth and yield of lettuce at Abakaliki Agro-Ecological Zone of Southeastern Nigeria. *World Journal of Agricultural Sciences* 6(2):141-148.

Ozgener, O, Hepbasli, A. 2005. Performance analysis of a solar-assisted ground-source heat pump system for greenhouse heating: an experimental study. *Building and Environment* 40:1040-1050.

Ozgener, O, Hepbasli, A. 2005. Performance analysis of a solar-assisted ground-source heat pump system for greenhouse heating: and experimental study. *Building and Environment* 40:1040-1050.

Panwar, NL, Kaushik, SC, Kothari, S. 2011. Solar greenhouse an option for renewable and sustainable farming. *Renewable and sustainable energy reviews* 15:3934-3945.

Pardossi, A, Tognoni, F, Incrocci, L. 2004. Mediterranean Greenhouse Technology, ISHS ACTA *Horticulturae* 797:25-36.

Peet, MM. 1999. Greenhouse crop stress management. Proceedings of Internaltional Symposium on Growing Media and Hydroponics. *Acta Hort* 481:643-654.

Pontikakos, C, Ferentinos, K and Tsiligiridis, T. 2005. Web-based estimation model of natural ventilation efficiency in greenhouses using 3D computational fluid dynamics. Informatics laboratory, Agricultural University of Athens, Greece.

Rennie, D. 2007. Brief History of the Greenhouse Vegetable Industry in SA. Intensive Agriculture South Africa, 20 Mar 2010.

Rojano, A, Salazar, R. 2011. Temperature and humidity as physical limiting factors for controlled Agriculture. Proceedings of International Symposium on High Technology for Greenhouse Systems, *Acta Hort* 893:503-507.

Savage, MJ. Agrometeorology Discipline, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Schulze, RE. 1997. *South African Atlas of Agrohydrology and Climatology.* Report No Tt82/96. Water Research Commission, Pretoria, South Africa.

Sethi, VP. 2008. On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. *Solar Energy* 83: 21-38.

Sethi, VP, Sharma, SK. 2007 Survey of cooling technologies for worldwide agricultural greenhouse applications. *Solar Energy* 81:1447-1459.

Sethi, VP, Sharma SK. 2008. Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications Solar Energy 82:832–859.

Sonneveld, PJ, Swinkels, GLAM, Kempkes, F, Campen, JB, Bot, GPA. 2006. Greenhouse with an Integrated NIR Filter and a Solar Cooling System. Proceedings from International Symposium on Greenhouse Cooling. *Acta Hort* 719:123-130.

World Hunger Statistics – Statistic brain, 2013. Statistic Brain Research Institute [Internet]. Available from http://www.statisticbrain.com/world-hunger-statistics/ [Accessed July 2013].

Teitel, M, Ziskind, G, Liran, O, Dubovsky, V, Letan, R. 2008. Effect of wind direction on greenhouse ventilation rate, airflow patterns and temperature distributions. *Biosystems Engineering* 101(3):351-369.

Tognoni, F, Pardossi, A, Serra, G. 1999. Strategies to match greenhouses to crop production. Proceedings of Internaltional Symposium on Growing Media and Hydroponics. *ISHS Acta Hort*. 481:451-462.

Urbonaviciute, A, Pinho, P, Samuoliene, G, Duchovskis, P, Vitta, P, Stonkus, A, Tamaluaitis, G, Zukauskas, A, Halonen, L. 2007. Effect of short-wave length light on lettuce growth and nutritional quality. *Scientific works of the Lithuanian Institute of Horticulture and Lithuanian University of Agriculture* 26(1):157-165.

Vadiee, A and Martin, V. 2012. Energy management in horticultural applications through the closed greenhouse concept, state of the art. *Renewable and sustainable energy reviews* 16:5087-5100.

Vanthoor, BHE, de Visser, PHB, Stanghellini, C, van Henten, EJ. 2011. A methodology for model-based greenhouse design: Part2, description and validation of a tomato yield model. *Biosystems Engineering* 110:378-395.

Vanthoor, BHE, Stanghellini, C, van Henten, EJ, de Visser, PHB. 2011. A broad range of designs and climates. *Biosystems Engineering* 110 (2011) 363-377.

Van Niekerk, B. 2013. Personal communication. Rhino Plastics, Port Elizabeth, South Africa, 25/09/2013.

Venter, G. 2010. Successful Hydroponics: 21st Century Technology for Commercial and Home Applications: a Comprehensive Practical Guide to Scientifically Based Hydroponic Crop Production, Xlibris Corporation, United States.

Venter, G. 2013. Personal communication. International consultant: Hydroponics and greenhouses, Cape Town, South Africa, 26/11/2013.

Venter, G. 2006. Climate control in greenhouses (Part 1): Ventilation can lead to higher yields. *The SA Journal of Hydroponics and Greenhouses* 1(3):41-47.

Venter, G. 2006. Light – how it affects plant growth. *The SA Journal of Hydroponics and Greenhouses* 1(2):8-19.

Wang, SY, Camp, M., 2000. Temperatures after bloom affect plant growth and fruit quality of strawberry. *Scientia Horticulturae* 85(3):183-199.

Willits, DH. 2003. Cooling Fan-ventilated Greenhouses: a Modelling Study. *Biosystems Engineering* 84(3):315-329.

Yildiz, A, Ozgener, O, Ozgener, L. 2011. Exergetic performance assessment of solar photovoltaic cell (PV) assisted earth to air heat exchanger (EAHE) system for solar greenhouse cooling. *Energy and Buildings* 43:3154-3160.