Environmental Modelling and Expert Fuzzy Control of Climate in a Miniature Cropping House

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For Grandad The Quiet Man

Thanks to all those who advised and supported the author during this work   You know who you are

Special thanks to my supervisor, Richard Hayes

I hereby Certify that this material which I now submit for assessment on the programme of study leading to the award of MSc is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed Damien Barry ID No ____________________

Date 28th July 1996

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Project Abstract

This work describes the development of an inexpensive control system for a miniature cropping house which uses the method of crop production

The control system was first developed in the Matlab-Simulink environment where it controlled a simulated model of the plant The model was composed of four differential equations describing, air temperature in the cropping house, water temperature, CO_2 concentration and inside humidity The controller comprises a fuzzy "expert" controller which accepts inputs of light intensity and air temperature and returns fan speed and water temperature set-point as outputs The latter was applied as a set-point for digital PID controller which controls water temperature in the cropping house

Expert advice, as well as knowledge of the plant gained from observation of the plant and the model, were used to develop fuzzy sets and a fuzzy rule-base The controller was implemented in Matlab simulation language and tested on the model of the plant

Finally, the controller was implemented in "C" source and assembly for a standalone Motorola 68HC11 microprocessor based digital controller Development of software for the micro-controller was conducted using the Motorola's Evaluation Tool-kit PCBUG The controller circuits included two temperature sensing circuits, a light input and power control circuitry for both a DC fan and a set of aquarium heaters

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Chapter 1 Introduction

1.1 Background to the Development of the Control System for the Cropping House

The world population is increasing at a rate of 320,000 per day One of the principal problems created by this increase in world population is the difficulty in feeding everyone From 1950 to 1984, global food production tripled Since then, loss of usable farmland has resulted in a levelling off in production (World Book 1993) This has resulted in a search for alternative and more resource-efficient methods of growing food, such as hydroponics Hydroponics is a means of growing plants using a solution of nutrients in the place of soil The advantage of this technique is that the nutrient can be designed to meet each plants nutritional needs exactly, thus reducing the amount of minerals and nitrates which are released into the surrounding environment In addition, because the plants receive an ideal mix of nutrient, they grow faster than those grown using conventional techniques Of course there is a price to pay for this extra productivity Hydroponics growth systems require energy to heat the nutrient solutions to a certain optimum temperature Consequently it is necessary to control the environment inside such cropping houses to conserve energy while keeping crop productivity high

The principal aim of this work, is to develop a control system for a miniature hydroponic cropping house The control system will be expandable to allow additional controlled variables to be added at a later date if so required It will also to be inexpensive to produce and need the minimum of attention by the grower Any aids to the growth of plants within the growing house will be automated where possible

This work will also present a deterministic mathematical model of a miniature hydroponics-based growing house. This model is to be used in the development of an environmental controller for the real system. The control system will be an expert system which uses existing growers' knowledge to make decisions about ventilation and heating requirements of the growing house.

1.2 The Mathematical Model of the Climate Within the Cropping House

Modern research into new products often involves the use of some form of model either physical or mathematical, to assist understanding of the system being designed and to aid development work. A mathematical model of the miniature cropping house was developed to fulfil these roles. The model was developed from consideration of the physics of the system. Since the model was developed from physical principles, the parameters affecting each variable in the model are transparent to the user. This allows these parameters to be changed easily, to test new designs involving different construction materials, cropping house dimensions or new control devices or control strategies.

1.3 Using a Computer to Control the Environment within a Greenhouse

The advantage of using a computer-based or ***digital*** controller for climate control in a greenhouse is that, in addition to performing all of those functions performed by a standard hard-wired analogue climate controller, a digital controller can make decisions based on stage in cropping cycle, time of day or time of year. The configuration of digital controllers is easily altered and this makes them very flexible. Vendors of such controllers may easily have the software altered to suit changing control environments and to follow advances in control theory. For instance, many manufacturers of commercial control systems have added modules which implement fuzzy logic control (Mitsubishi, Motorola) The hardware for these controllers is very similar if not identical to that required for conventional control techniques (Motorola 1993)

Growers rely to a large extent on their own experience when making decisions which affect the crop and the environment inside growing houses Their reactions to changing environmental conditions inside and outside the growing house can be easily encapsulated in the rule-base of a computer-based fuzzy logic controller (McDowell 1994, MacSioman 1994)

The computer-based environmental controller will accept as inputs, air temperature water temperature and light intensity It will control nutrient temperature by regulating the power to an electric water heater and will affect the aerial environment within the cropping house by controlling the power to a small d c fan

1 4 Summary of the Contents of this Thesis

This **first chapter** has given a brief introduction to the project and its various components

Chapter two will discuss the problems and control constraints associated with the development of a hydroponic crop production system The information contained in this chapter is the expert knowledge which is used in the design of the expert fuzzy logic controller The chapter concludes with a table of conditions which should be met for successful hydroponic crop production

Chapter three introduces fuzzy logic theory with an emphasis on its use in controllers An explanation of the operation of each stage of a fuzzy logic engine is given with examples and diagrams

Chapter four will deal with the development of a deterministic model of the cropping house It will describe the equations governing each of the major processes affecting mass and heat flow within the cropping house and will show how these heat flows and mass flows can be balanced using four differential equations In addition it will present qualitative and quantitative validation of the model

Chapter five shows the comparison between the response of the real cropping house to changing external climatic conditions and the response of the model with environmental data measured at the real system over the same time period It will reccomend changes which might improve the performance of the model

Chapter six describes the construction and operation of the miniature cropping house It also describes the elements of the control system for the miniature cropping house These elements are as follows

- Controller instrumentation circuits
- Control output circuits
- The low-level service routines which perform the sampling and control the PWM signals and serial communications
- The controller code for the simulation of the full control system and for the micro-controller

Chapter seven discusses the results and findings of the project and makes recommendations about possible improvements which could be made to the model and to the control system

Chapter eight is the conclusion

Appendix A contains additional experimental results, which are relevant to this work

Appendix B contains the memory map of the micro-controller unit and the flowcharts for the service routines for the micro-controller

Appendix C lists the parameters which were used in the model of the cropping house and the values they take in the original model and the modifications made to improve the model's performance

Appendix D derives an equation used in the work

Appendix E is the bibliography

Chapter 2: Hydroponics

2.1 Introduction

This chapter outlines the Nutrient Film Technique (NFT) It also deals with the basic requirements and constraints of an NFT system It forms the basis for the rule-based control approach developed in later chapters, by summarising some of the control objectives in a linguistic fashion The control problem may be broken into two distinct halves, the aerial environment and artificial root support and nutrition This chapter is partitioned accordingly The first part of the chapter deals with the aerial environment and discusses factors in the design of a cropping system, which affect the content and temperature of the air in the growing house and its interaction with the plant canopy The second section deals with the factors influencing the behaviour of the root systems of the plants

2.2 Aerial Environment

The control of the temperature, moisture content and CO_2 concentration of the air in greenhouses is desirable in colder climates to accelerate the growth of plants Indeed the first recorded controlled environment for growing plants appears to be the growing of off-season cucumbers for the Emperor Tiberius during the first century AD No significant advances were made in growing plants in an enclosed environment until greenhouses first appeared in 17th Century England These houses were heated using fresh compost which decomposed producing a source of CO_2 and heat (Jenson and Collins 1983)

Climate control is of course also needed for hydroponics-based cropping houses This section discusses the ways in which the aerial environment affects the growth of plants in an NFT cropping system

2.2.1 The Effects of Air Temperature on the Growth of Plants

Optimum air temperature values depend, as do many other parameters, on the particular cultivar being grown However researchers have found that an air temperature range of 15°C to 22°C during daylight hours seems to produce generally good results and that the efficacy of a certain regime may be affected by root temperature This will be discussed later in this chapter Air temperatures for NFT can be allowed to drop to low levels at night Air temperatures at night of 5-15°C have been reported to have the effect of delaying the ripening of fruit in tomato plants but have no other detrimental effects It is important to keep the nutrient temperature reasonably high if the air temperature is allowed to drop Graves (1985), has reported that winter lettuce grown at an air temperature of 4°C had twice as much mass if they were grown at a solution temperature of 17°C than at 8°C

The simplest way to heat a cropping house is to use a convection heater The problem with this approach is that heat is not spread evenly around the enclosure, and a temperature gradient results In larger structures water pipes are used to carry heat to remote parts of the house (Canham 1984) In this study, it will be assumed that the heat transfer from the heated nutrient solution will be sufficient to heat the Vegetable Propagation Unit

2.2.2 Cooling the Air by Ventilation

During the summer months, it becomes necessary to remove surplus heat by ventilation, since the cropping house tends to trap heat Heat storage, which is desirable in Winter is a disadvantage in the Summer months Ventilation introduces its own problems however Aphids, greenfly and other pests are abundant in the summertime and unless adequate filtering is installed will multiply within the environment provided by the grower Fumes and particles from cars and incinerators will also affect the growth of the plants

2.2.3 Using Glazing to Reduce Heat Losses

The type of glazing material used influences the thermal properties of the cropping house Glass which is the traditional glazing material, has largely been supplanted by other newer and cheaper materials such as polycarbonates which are good insulators There is a trade off here, because the optical transmission coefficients of polycarbonates tend to be lower than that of glass The optical transmission coefficients of the plastics also degrade with time and they attract dust particles (Mc Dowell 1994) It is advantageous to use the more robust plastics in a unit such as the one used in this work

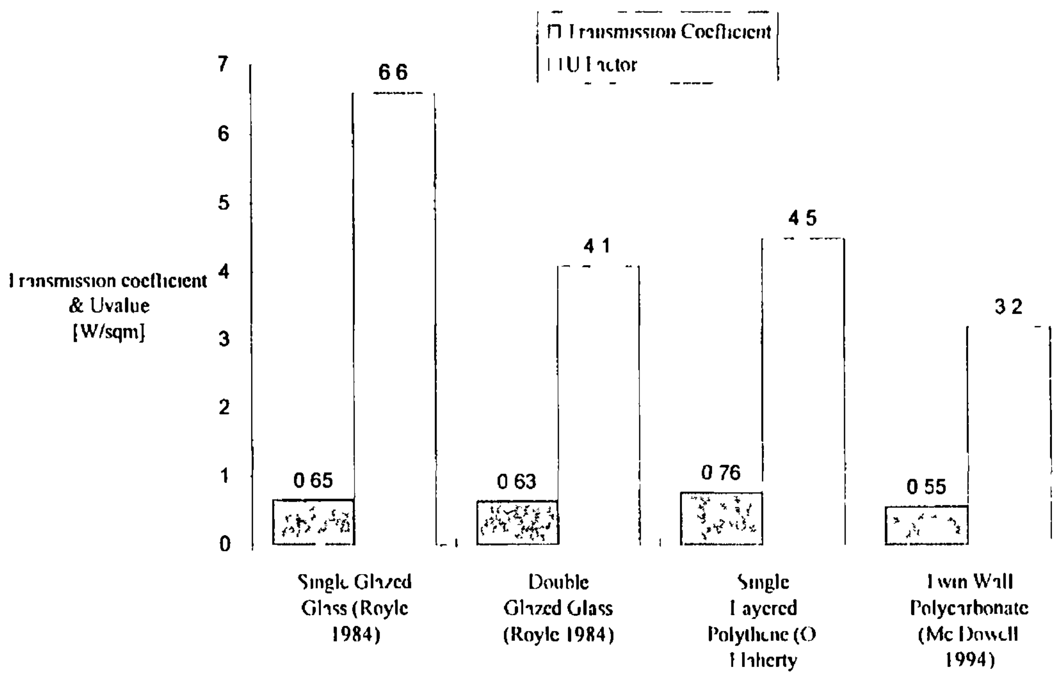


Figure 2 1 *Thermal and Optical Properties of Various Cover Materials*

Figure 2 1 above shows the optical and thermal properties of a range of cover media It is apparent from the chart, that as the thermal insulation of the greenhouse increases, the optical transmission coefficient tends to decrease Keen (1990), reported the discovery of a heat absorbing liquid which would which was unharmful to plants and only allowed the wavelengths needed for photosynthesis through to the plants, thus relieving the need for ventilation

In northern Europe, where light levels drop to one third of their optimum level in the autumn and winter, light levels are a major restriction to plant growth The popularity of new materials with higher thermal resistances but lower transmission factors has led commercial vegetable growers to look at ways of improving light levels in their greenhouses Some methods of improving light levels include, reflective curtains or adjustable reflectors on the north wall of the greenhouse and vertical south roof greenhouses, which catch virtually all of the incident light in the winter time when the sun is in the south (Bailey 1984) The inside surfaces of the gable ends in the Vegetable Propagation Unit may be silvered to enhance light levels, however it is important to avoid using potential toxins Reflectors may be clipped onto the outside of the unit for a further improvement in light intensity if required

2.2.4 Control of Carbon Dioxide Levels within a Greenhouse

Carbon Dioxide is essential to plant growth *Photosynthesis*, which is the process used by plants to generate organic compounds that make up new tissue, requires carbon dioxide as a raw material Plants with an adequate mineral supply may experience a limitation in yield due to insufficient light and CO_2 levels The two principal means of replacing the CO_2 absorbed by plants are CO_2 enrichment and fan ventilation

2 2.4 1 CO_2 Enrichment

CO_2 levels in a greenhouse can be increased by employing ***CO_2 enrichment*** The idea of enrichment as the name suggests is to supply additional CO_2 to the plants Commercial growers use CO_2 enrichment during the winter and early spring Enrichment brings the added advantage that valuable heat is not lost through convection to the external environment A concentration ***lift*** (where a lift is understood to be an increase in a measured quantity from outside levels to those measured inside), from the ambient 340 vpm to 1000 vpm is common (Hand 1986a) As temperatures rise in late spring, it becomes necessary to ventilate, to limit the temperature lift in the enclosure due to solar heat gain It then becomes impractical to use enrichment, since the CO_2 is immediately lost by ventilation

Some growers use enrichment to keep concentration at the ambient level of 340 vpm This method is called ***partial enrichment*** The advantage of this scheme is that no CO_2 is lost to the external environment since no concentration gradient exists

2 2 4 2 The Drawbacks of CO2 Enrichment

Enrichment is not without its drawbacks however Burning materials such as Natural Gas or Butane to release CO_2 will also generate trace quantities of other gases, such as nitrogen, which may affect the growth of the crop (Hand 1986b) Compost also releases a quantity of CO_2 during fermentation This enhances the growth of plants in traditional greenhouses (Meath 1993), but is not feasible in a hydroponic system Yeast also releases CO_2, but only in relatively small quantities and the life span of an active yeast plant is typically 4-5 days (Yeast products 1994) For large scale installations, bottled CO_2 is too expensive to use, but in miniature houses like the one under consideration here, it could be used effectively The main restriction on bottled CO_2 is availability With only one major supplier of industrial grade CO_2 in the country it is difficult to guarantee a steady supply

The cost of CO_2 sensors is another drawback A typical commercial automatic CO_2 sensor can cost anything between £500 and £3000 Though CO_2 test kits are available for about £200 (Hand 1986b) For a small unit this cost is prohibitive In chapter 5, a possible solution to this problem will be suggested

2 2 4 2 Ventilation to Prevent CO_2 Depletion in the Cropping House

It is important that the CO_2 levels do not drop far below ambient, as this decreases the photosynthetic rate of the plants Hand (1986a) found that at an air temperature of 20°C, the photosynthetic rate decreased by 9% in bright light and 6% in dull light for a 10% drop in CO_2 concentration below the ambient 340 vpm Hand, and Farm Electric (1973 after Gaastra 1959) note that photosynthesis almost ceases when adequate light is available and CO_2 concentration drops below 50 vpm This of course is undesirable and ambient levels are required where possible So in the absence of CO_2 enrichment, it becomes necessary to ventilate to ensure that CO_2 levels are adequate particularly during periods of bright sunshine when the plants are photosynthesising, but also at night when the plants are respiring and there is a build-up of CO_2 in the cropping house

2.3 Control of the Rhizosphere

The term *rhizosphere* can be used to describe the vicinity of the root In conventional greenhouses, this area is not directly controlled However in hydroponics-based cropping systems, there is no soil to protect the roots from extremes of temperature or to protect against excessively rich and potentially toxic mineral supplies

2.3.1 The Nutrient Film Technique

Hydroponics is a word which is used to describe methods of growing plants in soil-free nutrient solutions Artificial materials such as rockwool, sand or sawdust may replace soil to support the root systems of the plants Woodward grew plants in a soil-less culture in 1699 The first true hydroponics systems were developed independently for laboratory use by Sachs and Knapp in 1860 The first full-scale commercial application of hydroponics was reported by Gericke in 1940 He also in passing, coined the word hydroponics (Jenson and Collins 1983)

The ***Nutrient Film Technique (NFT),*** which will be considered in this work and is illustrated in figure 2 2, is called a ***liquid hydroponic*** system since it requires no root support medium The Nutrient Film Technique was developed by Dr Allen Cooper of the Glasshouse Research Institute, Littlehampton, United Kingdom in 1966

In NFT horticulture, a thin film of nutrient flows over the plant roots Capillary attraction ensures that a thin film of water covers the root surface, separating it from the air Water flowing over the roots becomes aerated so that the roots are able to assimilate sufficient oxygen to meet the plants needs NFT was first developed as a research tool for monitoring the unrestricted root growth of tomatoes In Coopers original scheme, single truss tomato plants were grown with their roots held between two slightly sloping sheets of polyethylene

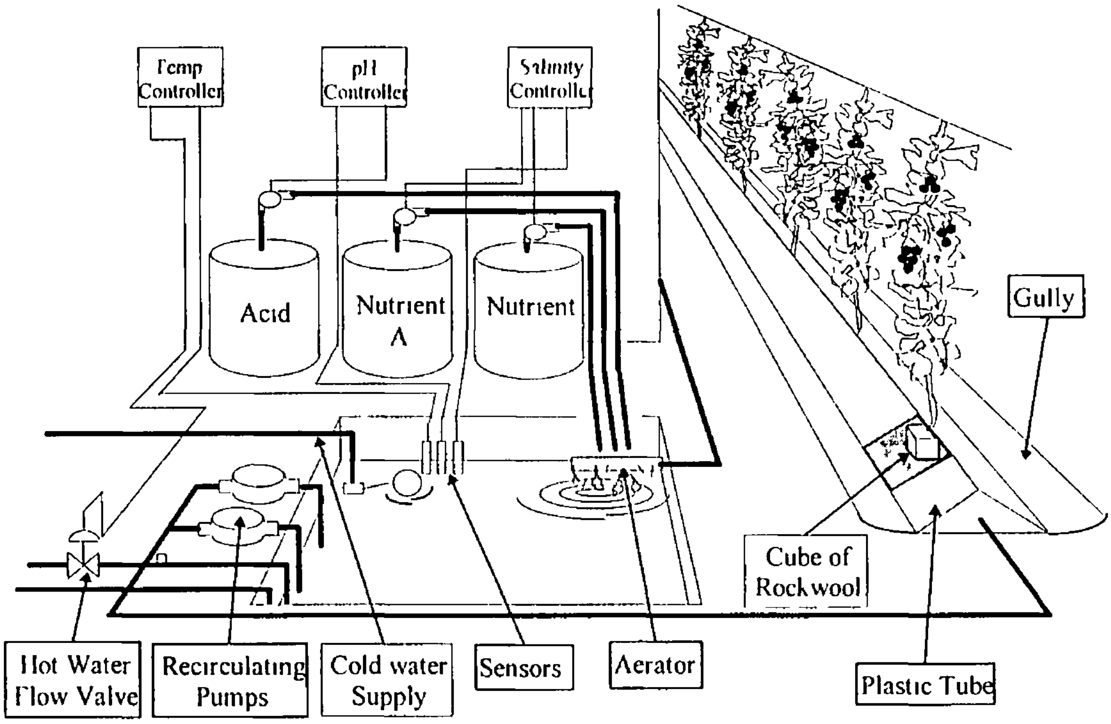


Figure 2 2 *A Modern Commercial High Volume NFT Cropping System*

A thin film of ***nutrient solution*** was then allowed to circulate at a pre-set temperature and bathe the root systems In 1972 the method was used to grow cucumbers Cooper reported his findings in 1973 and showed that NFT could be used for high density crop production Other advantages of the techniques are

- Economic use of plant nutrients
- Crop production where no soil exists, eliminating need for soil sterilisation
- Conservation of soil ecosystems
- Isolation of crop from soil (to reduce risk of disease, salinity problems)
- Control of conditions in rhizosphere to optimise mineral ion uptake
- Rapid crop turnover
- Minimal exposure of rhizosphere to pathogens such as wilt, fungi and nematodes

Between 1973 and 1985 the technique was adopted widely by horticulturists However due to the rising costs of oil, prohibitive initial capital costs and the level of expertise required to use the technology effectively, the original method ceased to be cost effective Modified NFT techniques were then developed Teagasc's Kinsealy Research Station conducted extensive trials on NFT in the mid 1980's They presently prefer an aggregate technique in which they allow nutrient to propagate through enclosed rockwool ***Rockwool*** is a mesh of benevolent recycled mineral threads through which plant roots are permitted to spread The fine mesh causes capillary action to take place, thus permitting water to reach roots (Maher 1993) There has been much controversy however, as to which strategy produces the best results (Cooper 1983), and NFT is still used by commercial growers in north County Dublin (Fisher 1994)

2.3 2 The Water Supply in an NFT System

A plentiful and regular supply of aerated water is essential for any hydroponics system A typical tomato plant in a protected environment will consume about 1 3 litres of water on a bright summer day Winsor (1980), discovered that tomatoes lost water at 15 ml/hr/plant at night, but losses rose to 135 ml/hr/plant on a cloudless summer day Adams (1980) noted that the water uptake for cucumbers is twice that for tomatoes and varies linearly with incident radiation. Modern commercial systems generally contain sufficient water so that the nutrient is replaced once a day (Hurd and Graves 1981). The amount of Oxygen dissolved in the nutrient solution will also affect the flow rate. This matter will be discussed later in this chapter.

2.3.3 Mineral Requirements of Plants

Different plants have different mineral requirements and so, unwanted and potentially toxic ions may build up in the solution. Even if the solution is not toxic, the unwanted ions may prevent osmosis of the desirable nutrients into the root. These problems are of major concern for large volume growers. Consequently, conductivity and pH control systems are used to monitor and control the salinity and acidity of the nutrient. These control systems are difficult to maintain and are often dependent on the crop type. A major disadvantage of NFT is that since there is no solid material enclosing the roots, there is nothing to act as a buffer against toxicity in the nutrient supply. It is desirable to keep pH levels between pH 5.5 and pH 6.5, where optimum ion uptake occurs (Graves 1985).

The quantity of nutrient in a hydroponic solution does not have to be as high as in conventional systems since the flow guarantees that the nutrient gets to the root. This is not the case in conventional systems where the root depends on diffusion for its supply of nutrient. For lettuce, salinity of between 1500 μScm^{-1} and 1800 μScm^{-1} is recommended (Burrage & Varley 1980). Of course, conductivity is only a measure of the quantity of salt in the nutrient, and is virtually unaffected by the amount of trace elements present. It also depends on the type of nutrient used as some solutions contain chelated compounds which have lower than average conductivities for higher concentrations.

Nutricrop which is the commercial nutrient used in this work, contains chelated compounds The suppliers recommend a conductivity of 200-600 μScm^{-1} From tests conducted on plants, a conductivity of 400 μScm^{-1} was found to produce satisfactory results

2.3.4 The Effects of Root Zone Warming

Root temperature is known to be a critical determinant of the productivity of hydroponic systems Root zone warming is known to increase the rate of fruit production It has been shown that control of the root temperature can shorten or lengthen growth cycle of tomatoes (Hurd and Graves 1984),(Maher et al 1993) After the energy crisis in the 1970's, growers began to research using reduced night-time air temperatures (Jenson and Collins 1983) Whenever air temperatures below 12^{o}C are used for NFT systems, it is necessary to keep solution temperatures within the range 13^{o}C - 15^{o}C, to prevent reduced uptake of nutrients (Moorby and Graves 1980) Nutrient in an unheated NFT system may become cold enough to check root growth severely Evaporative cooling may cause the nutrient temperature to drop below the air temperature (Graves 1985) NFT is readily adaptable to root zone warming

Solution temperature is relatively inexpensive and simple to control accurately, whereas a control system for soil temperature would be expensive to install and operate An acceptable optimal range for nutrient temperature in full sunlight is 25^{o}C with an acceptable optimal value of just over 20^{o}C (Grower Books 1982) It is known that fruit picking in plants grown in an NFT solution, is accompanied by a period of root death It has been found that root temperatures of 25^{o}C around picking time in an early tomato crop can increase the yield of fruit, but will not shorten the delay caused by low air temperatures (Hurd and Graves 1984).

2.3.5 The Need for an Adequate Oxygen Supply to Roots

Roots need a constant supply of oxygen. Since oxygen is virtually insoluble in water, it is undesirable to have the roots more than partially submerged in nutrient. A mature tomato plant requires 20 ml of oxygen per hour (Graves 1985). NFT resolves this problem by allowing water and air to mix freely, thus guaranteeing an abundant supply of oxygen to the root. Increases in water temperature decrease the saturation concentration of oxygen in the water. At 25^{o}C the saturation concentration is 8.5 ppm (Jackson 1980). This means that if the root is submerged in the nutrient that the water would have to be passing the root at a rate of 0.65 ls^{-1}. If the roots are only partially submerged however, oxygen may be absorbed directly from the air so this value is an upper limit on the flow rate.

2.3.6 Other Considerations

Care must be taken when choosing materials for an NFT system. Wavin Plastics warn against the use of galvanised fittings which can lead to a build-up of unwanted substances in the solution to toxic levels. Some plastics however, are also dangerous to plants. Among those which have been found to have detrimental effects are ABS and Plasticised PVC. Where it is necessary to use a metal, it is preferable to use stainless steel fittings. Though stainless steel is difficult to shape and expensive to buy, it is relatively inert. Another danger to plants comes from stabilisers and pigments for otherwise safe plastic fittings which may also contain toxins. The catchment tank for small scale systems is often constructed of fibreglass, since this is generally safe to use but subject to the same constraint (Graves 1985) It is prudent therefore to request 'food handling grade materials' when ordering materials which may come into direct or indirect contact with the nutrient (Grower Books 1982)

2.4 Review of Limits and Optimum Values of Parameters in an NFT Control System

This chapter has summarised currently available information regarding factors determining optimal productivity in NFT systems Desirable ranges and optimal values of physical parameters which affect plant growth derived from the preceding discussion are tabulated below

Table 2 1 *Limits for Controlled Parameters in an Environmental Control System for NFT*

Parameter	DAY	NIGHT
Relative Humidity	< 85%	Same
Nutrient Temperature	20 - 26°C 24°C Optimum	13 - 15°C
Nutrient Flow Rate Past Roots	0 125 $lmin^{-1}$	Same
CO_2 Concentration	Near 340vpm	Same
Nut Solution Conductivity Using Chelated Compounds	200 - 600 μScm^{-1} 400μScm^{-1} Optimum	Same
Air Temperature	15 - 22°C	5 - 15°C
Nutrient Solution pH	pH5 5 - pH6 5	Same

Table 2 1 can be shortened to include only those quantities which will be dealt with in this study The night-time nutrient solution temperature range has been relaxed to allow for the power limitations of the water heaters Digital control of conductivity and pH of the nutrient solution will be left for later work

Table 2 2 *Limits and Preferred Values for Controlled Parameters in the Miniature Cropping House*

Parameter	DAY	NIGHT
Air Temperature	15 - 22°C	5 - 15°C
Relative Humidity	< 85%	Same
CO_2 Concentration	Near 340vpm	Same
Nutrient Temperature	20 - 26°C 24°C Optimum	8 - 15°C
Nutrient Flow Rate Past Roots	0 125 $lmin^{-1}$	Same

The values shown in table 2 2 will now form the basis for a control strategy which will attempt to keep these parameters within these ranges or at the appropriate values It is apparent from table 2 2 above, that some form of rule-based approach would be suitable for transforming the above set of constraints into a control strategy The next chapter will describe one such a rule-based control strategy which may be used to control the environment inside the cropping house

Chapter 3: Fuzzy Logic Control

3.1 An Introduction to Fuzzy Logic Control

Agricultural science like medicine, is not always an exact science. As can be seen from chapter 2, many of the control requirements for an NFT system are not easily transferred into a classical control strategy. Growers frequently tend to use their senses and expert judgement rather than instrumentation when making decisions which may affect the crops. As a result, it is difficult to obtain optimum figures for humidity, air temperature, nutrient temperature, and CO_2 concentration for a particular cultivar. In addition, these requirements may often contradict each other, may depend on stage of growth and will almost certainly be expressed in a linguistic way.

Since the control strategy for regulating the environment in an NFT system relies on rules, it is necessary to use some form of rule-based control. One form of rule-based control is called fuzzy logic control. The following discussion examines the operation of a ***fuzzy logic engine***, which is an all-purpose fuzzy logic system with an emphasis on its use as a controller.

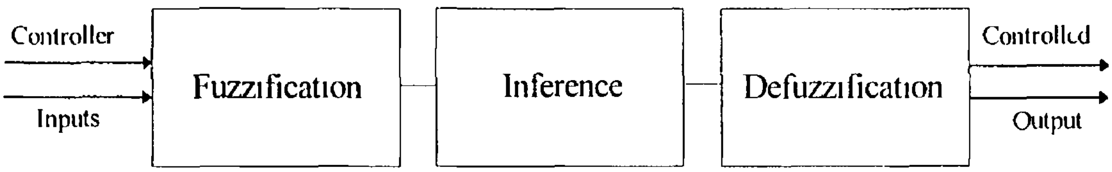


Figure 3.1 *Elements of a Fuzzy Logic Controller*

Figure 3.1 shows the three main processes at work in a fuzzy logic controller. Fuzzification is a means of converting a measured value into its equivalent fuzzy representation. Fuzzy inferencing allows this information to be combined with fuzzy rules to form a conclusion which will still be in the fuzzy domain Finally, defuzzification as the name suggests, is the process of converting the output of the inferencing mechanism back into a non-fuzzy output value which can then be applied to the plant The following sections briefly describe the operation of a fuzzy logic controller

3.2 Introduction to Fuzzy Logic

Fuzzy logic was first conceived as an extension of multi-valued logic, by Lotfi Zadeh of the University of California at Berkeley in 1962 Zadeh describes fuzzy logic as a translation mechanism which translates a human solution to a problem, into the language of fuzzy rules For instance a driver of a car relies on judgement to decide if the car in front is too close and responds by adjusting the accelerator The text of an appropriate fuzzy rule for this situation might be IF THE CAR IN FRONT IS TOO CLOSE, THEN SLOW DOWN The point at which the driver eases back on the accelerator is not clearly defined since the transition from a safe distance between cars, to an unacceptable one is gradual This gradual change in the suitability of a term such as TOO CLOSE to describe a situation, is quite commonly encountered and can be readily described using the idea of partial set membership, which is central to fuzzy logic

The idea of ambiguity is inherent in the way in which we describe the world around us Information transferred using everyday language may include ideas such as the adjectives "VERY" and "SLIGHTLY" which are not easily described using existing mathematics Fuzzy logic also has features which capture this additional information and it is therefore well suited for storing linguistic knowledge

The principal difference between crisp logic and fuzzy logic is that while crisp logic only allows for membership or non-membership of a set, fuzzy logic permits an element to be a partial member of a set In a crisp logic system for instance, one might judge the temperature of water in a shower to be a member of the set HOT and not a member of the set COLD This does not allow for uncertainty in the definition of the terms HOT and COLD Using fuzzy logic however, we might say that shower temperature is HOT to degree 0 7 and COLD to degree 0 3 This allows the sets HOT and COLD to overlap The numbers 0 7 and 0 3 are an indication of the extent to which a temperature measurement belongs to each set They are known as ***grade of membership values*** and are usually signified by the symbol μ A function which is used to describe the degree of membership for any member of a fuzzy set is called a ***membership function*** Functions of this type are shown in figure 3 2 below

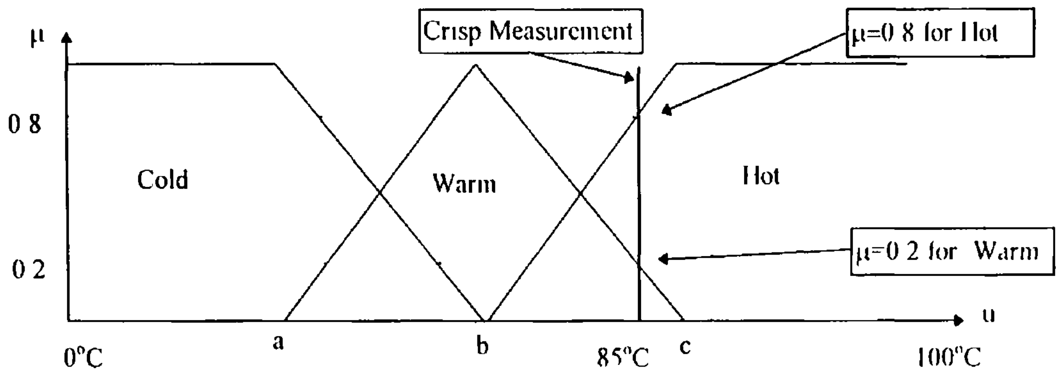


Figure 3 2 *Fuzzification of a Crisp Measurement Using Triangular Sets*

3.3 Fuzzification

Figure 3 2 shows the membership functions of three ***fuzzy sets***, which are being used to describe a temperature The words used to describe each set are called ***fuzzy labels*** The space on which the sets exist is called a ***universe of discourse U***, which in this case lies between 0°C and 100°C Notice that the ***crisp measurement*** of 85°C has a non-zero membership of the sets **Hot** and **Warm**

The sets shown above may be represented by a set of ***linear splines*** $L(u, a, b, c)$ as follows -

$$L(u,a,b,c)\begin{cases} 0 & for\ u \le a \\ (u-a)/(b-a) & for\ a < u \le b \\ (u-c)/(b-c) & for\ b < u \le c \\ 0 & for\ u > c \end{cases} \qquad \textbf{Eqn 3 1}$$

where a, b and c are any three consecutive points on U as shown above and u is the crisp measured input which is also on U

Membership functions do not necessarily have to be piecewise linear Indeed, bell shape functions favoured by statisticians are frequently used when precise definitions of fuzzy sets are required The ***S-function*** $s(u, a, b, c)$ approximates these functions using quadratic approximations as follows

$$s(u,a,b,c)\begin{cases} 0 & for\ u \le a \\ 2[(u-a)/(c-a)]^2 & for\ a < u \le b \\ 1-2[(u-c)/(c-a)]^2 & for\ b < u \le c \\ 0 & for\ u > c \end{cases} \qquad \textbf{Eqn. 3 2}$$

Notice that the membership values for the S-function, shown in figure 3 3, are less likely to be near the ambiguous value of 0 5 than those generated by the linear splines for the same crisp input The obvious shortcoming of this type of membership function is that it requires more computation S-functions are useful for applications such as medical diagnosis where a high degree of precision is required and there are relatively few time constraints

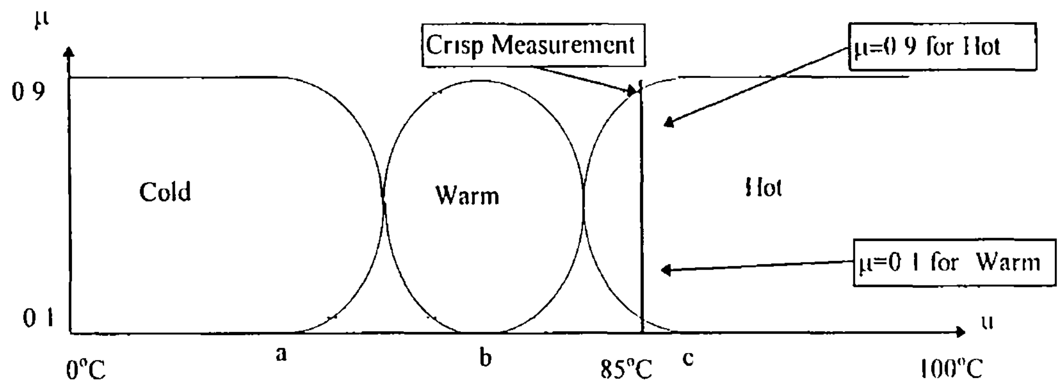


Figure 3 3 *Fuzzification Using S-function Membership Functions*

For this work however, it will be sufficient to define sets using linear splines A fuzzy set may be represented as a set of ordered pairs of an element u and its associated grade of membership which may be determined by evaluating the membership function at that point

$$F = \{(u, \mu(u))\,|\, u \varepsilon U\} \qquad \textbf{\textit{Eqn 3 3}}$$

Where U is the universe of discourse

Thus the first stage of the fuzzy logic controller, called fuzzification, takes each crisp measurement u and assigns a value which correspond to its degree of membership of each of the fuzzy sets available to it across the universe of discourse The crisp measurements are now said to be ***fuzzified***

3.4 Inferencing

The inferencing stage extends the linguistic description so that the fuzzified measurements suggest fuzzy "results" This is done by ***fuzzy inferencing*** Fuzzy inferencing is a method which uses data from one universe of discourse to form conclusions in another (Dexter 1992) We shall see that the inference mechanism uses so called ***fuzzy operators*** to implement the mathematical equivalent of statements such as IF SHOWER IS HOT THEN MAKE TEMP VERY LOW These statements are called ***rules*** The first part of the rule, called the rule ***premise*** is composed of ***antecedent sets*** The second part of the rule, the part after the THEN, is called the ***consequent*** A collection of fuzzy rules is called a ***fuzzy rulebase*** The example below which shows part of a fuzzy rulebase, illustrates these terms

____________________________Rule_____________________________

__________________Premise____________________

___Antecedent_____ ____Antecedent_____ __Consequent_

IF SPEED IS HIGH AND DISTANCE IS SHORT THEN BRAKE HARD

IF SPEED IS MEDIUM AND DISTANCE IS SHORT THEN BRAKE MEDIUM

IF SPEED IS LOW AND DISTANCE IS SHORT THEN BRAKE OFF

As can be seen above, the phrases IF SPEED IS HIGH and AND DISTANCE IS SHORT are antecedents in the first rule When they are combined they form the phrase IF SPEED IS HIGH AND DISTANCE IS SHORT This longer phrase is the premise of the rule Finally the consequent of the first rule is THEN BRAKE HARD

The fuzzy operator referred to above is called a ***t-norm*** T-norms map the grade of membership of each set on the input universes of discourse to a ***Degree of fulfilment*** of a fuzzy rule on the output universe The degree of fulfilment of a rule is a measure of how appropriate it is to use that rule to respond to the crisp measurement Examples of t-norms are the ***product*** function and the ***min*** function The degree of fulfilment of the fuzzy rules are said to ***qualify*** the consequent sets The usual effect of such operators is that the shape of the set is changed Qualification using the product (scaling) and the min (clipping) t-norms is shown below in figure 3 4

The *maximum values* of the qualified consequents form a single fuzzy set which is called a *fuzzy composition* The fuzzy compositions resulting from scaling and clipping are shown at the bottom of figure 3 4

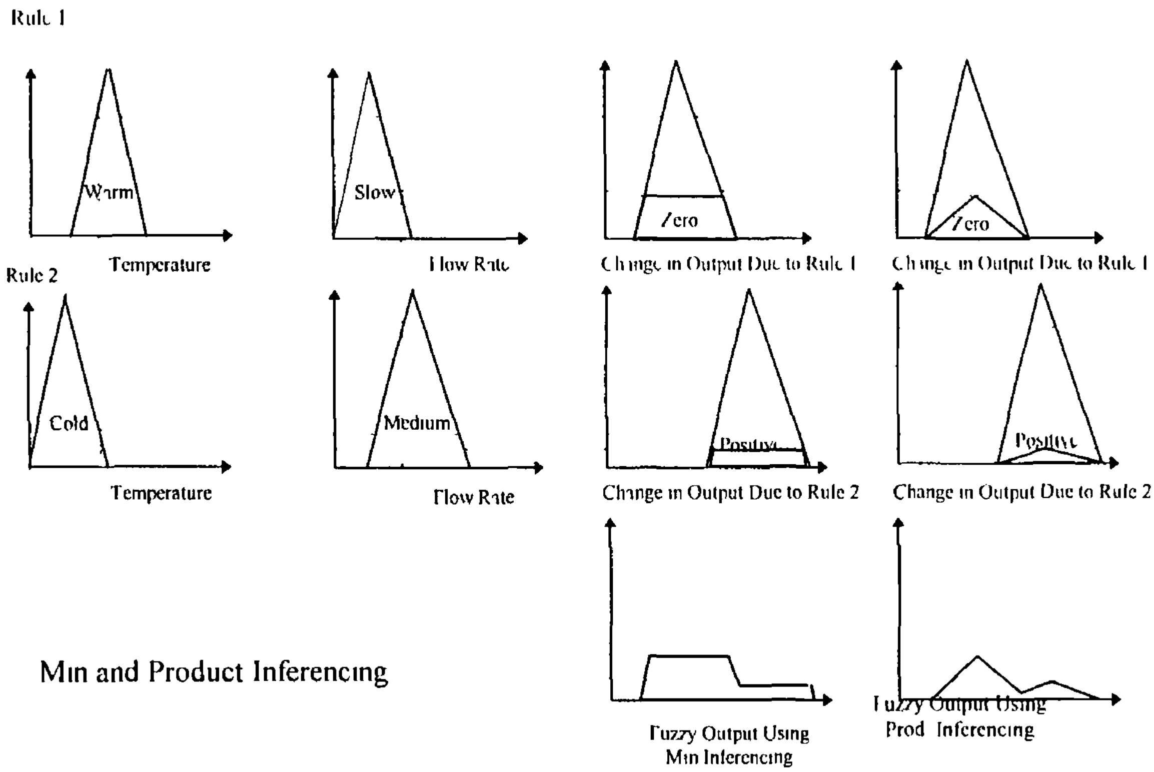


Fig 3 4 *Min and Product Inferencing*

Figure 3 5 below shows a two dimensional plot of the output resulting from a range of non-fuzzy inputs to a controller It shows the contribution of the rule to a range of control efforts

IF INPUT1 IS SET1 AND INPUT2 IS SET1 THEN OUTPUT IS +0 5

In this case the premise is a two dimensional fuzzy set The two dimensional membership function of this set is shown in figure 3 5 (Degree of Fulfilment of Rule) This membership function may be considered to be a plot of the degree of fulfilment of the rule for every combination of input values IP1 and IP2 Figure 3 5 (Defuzzified Outputs) is composed of the weighted degrees of fulfilment of four such rules For the rule shown above, the weighting is +0 5 Figure 3 5 (Defuzzified Outputs) is called a fuzzy control surface A control surface will exactly mimic the fuzzy logic controller However, if a lookup table or a set of splines (Harris 1993), is used to deliver the required action, the linguistic knowledge contained in the fuzzy rule-base is lost

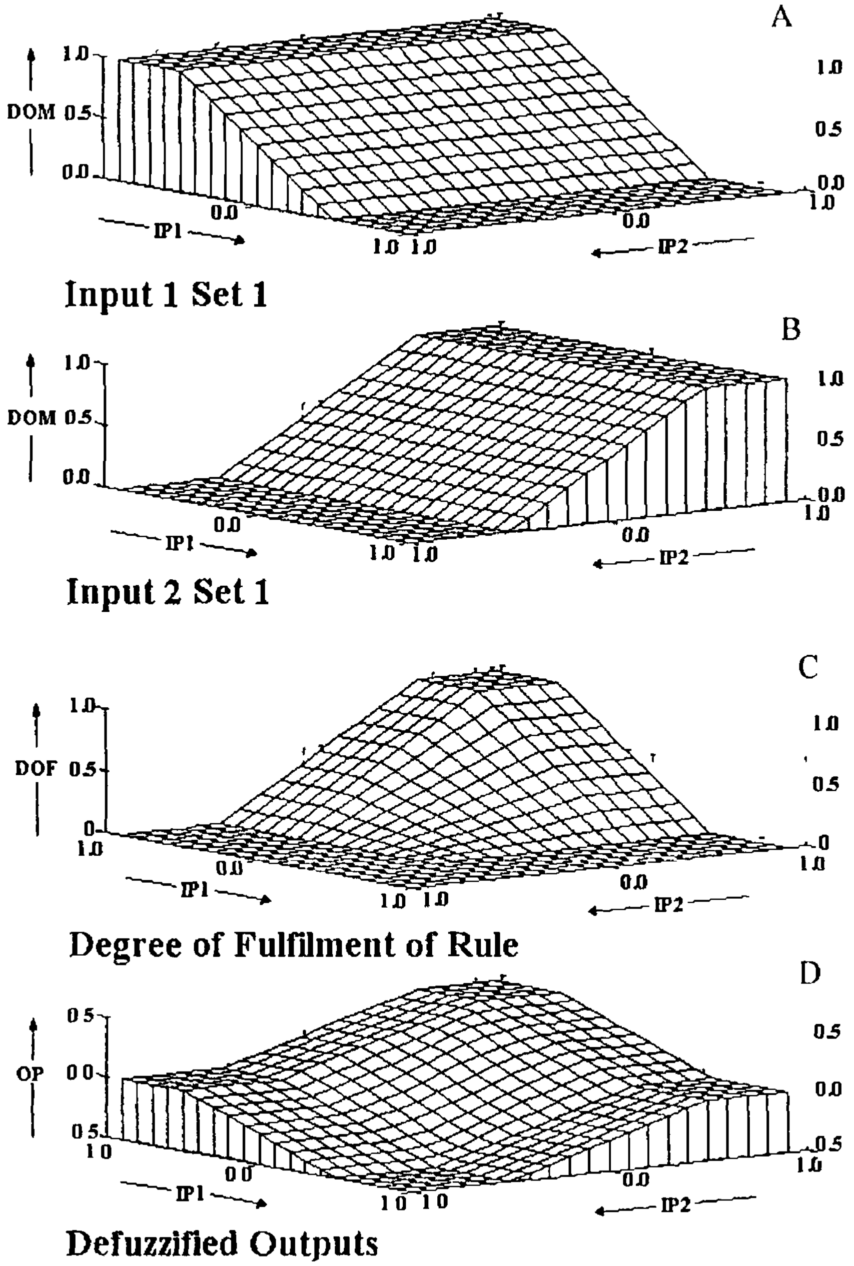


Figure 3 5 *Generation of a Fuzzy Control Surface Using Product Inferencing*

3.5 Defuzzification

Once the fuzzy output composition has been determined, the output must be ***defuzzified*** Defuzzification is the process of producing a crisp output from a fuzzy set Various defuzzification strategies exist Among the most popular are ***Height Defuzzification*** and ***Centroid Defuzzification***

3.5.1 Height Defuzzification

This defuzzification technique takes the weighted sum of the product of the position of fuzzy output singletons and their corresponding activation levels Equation 3 4 shows how the crisp output v^* is calculated

$$v^* = \frac{\sum_{i=1}^{n} u_i\, dof_i}{\sum_{i=1}^{n} dof_i} \qquad \textit{Eqn 3.4}$$

where $\mathbf{dof_i}$ is degree of fulfilment of the i^{th} rule

Height defuzzification is computationally efficient since it does not require computation of a fuzzy composition

3.5.2 Centroid Defuzzification

Centroid defuzzification results from implementation of the following formula

$$v^* = \frac{\sum_{i=1}^{n} \mu_{fu\ union}\, u_i}{\sum_{i=1}^{n} \mu_{fu\ union}} \qquad \textit{Eqn 3 5}$$

Where $\mu_{fuzzy\ union}$ is a function of u resulting from taking the ***supremum*** of all the qualified fuzzy sets Supremum is a word used to describe a function which will select the greater of two grades of membership if given a choice (Lyons 1993) Of the two methods, centroid defuzzification which is sometimes referred to as ***centre of area defuzzification,*** is more computationally intensive but produces a smoother control action than height defuzzification

3.6 The Reason for Using Fuzzy Logic in Environmental Control

A commonly voiced objection to fuzzy logic controllers is that they are primarily of use where a model of the plant does not exist and otherwise, more conventional control strategies should be used Conventional non-linear controllers may be created by using control surfaces or lookup tables which will determine the output of the controller for different input values Unfortunately these methods require the designer to be familiar with control system theory They may also be quite time consuming to design PID controllers are easier to design and are used extensively in industry, but PID controllers are not always suitable for controlling non-linear systems like the one discussed here In contrast, fuzzy logic controllers may be used to quickly translate heuristic expert knowledge such as that given in table 2 1 into a control strategy Modern commercial fuzzy logic development packages are quite user-friendly and the level of understanding of the system necessary to design a fuzzy controller is moderate

Simple deterministic models of environmental systems like the one introduced in the next chapter are rarely extremely accurate So in effect, even though the model will mimic the system, and the user may change the parameters it will only give an indication of how the real system will behave The low-pass nature of the set shapes in a fuzzy controller permits it to cope well with inaccuracies between model and system and a well designed fuzzy controller may continue controlling even in the event of sensor failure It is this feature which has prompted its use in backup control systems for nuclear reactors (Bernard Et Al 1985)

3.7 Fuzzy Logic and Expert Control

The first application of fuzzy logic control was for the control of an experimental steam engine (Mamdani and Assilian 1975) Since then, fuzzy logic has been applied to a large variety of control problems Among the more unusual are flight control of a model helicopter (Schwartz and Klir 1992), and intelligent washing machines and rice makers (Mamdani 1992)

Fuzzy logic control appears to date, to have been used chiefly in situations where little is known about the dynamics of the plant Although Mamdani (1993) suggests that it is this conservative attitude among Europeans which has allowed Japanese researchers to become world leaders in fuzzy logic research

In recent years, fuzzy logic has been used increasingly for environmental control (MacConnell et al 1993), (Tobi and Hanafasu 1991) The lack of understanding of the physical processes occurring in such systems makes it difficult to control them using standard control techniques Earlier in this chapter, it was mentioned that climate control systems for cropping houses have the additional difficulty that the optimum climate for plant growth may not be known It is not surprising therefore that fuzzy logic control should be applied to this type of problem

As we shall see later, the most difficult aspect of controlling the unit is the control of humidity/air temperature/CO_2 concentration It is to this aspect of the control problem that fuzzy logic control will be applied Since the controller will be performing the same task as a grower in deciding what the values of the above parameters are appropriate for a given set of external conditions, the control may be termed ***"Expert Control"*** From the preceding explanation of fuzzy logic, it becomes apparent that fuzzy rulebases may be easily formed from the relatively vague expert knowledge of the grower The more linear processes such as nutrient temperature and conductivity will be controlled using standard control techniques

The rule-base for the expert fuzzy controller will be chosen using a combination of knowledge gained by observation from table 2 1 and from consulting with experts This issue will be further addressed in chapter 5

3.8 Further Reading

Over 9000 papers, books and reports have been published on fuzzy logic since 1965 (Harris et al 1993) Cox (1992) Schwartz and Klir (1992) and Self (1990) are three articles which give a simple introduction for those who have no experience of the technique The Motorola Fuzzy Logic Tutorial is a particularly useful introduction to the topic and is available for a token fee from Motorola's Document Supply Centre in the U K (Lee 1990a, 1990b) has produced a concise overview of fuzzy logic for those who wish to delve deeper into the topic Arguably the most readable work on the links between fuzzy logic and neural networks is Harris (1993)

Chapter 4: Model Of Miniature Cropping House

4.1 Introduction

The purpose of a greenhouse is to provide an energy efficient and favourable growing environment for plants The former usually results in large and expensive-to-run commercial greenhouses The considerable cost of using a full-scale greenhouse to test a particular control strategy, led engineers and environmental physicists to develop mathematical models that mimic the behaviour of such systems These models can be used to aid the understanding of the behaviour of the greenhouse under different environmental conditions Dent and Blackie (1979) give the following additional uses of models of agricultural systems

- They are a means by which experimental studies may be guided
- Results of such work can be easily accumulated and assessed
- They are a platform to guide the development of new systems

The complexity of a model should reflect the purpose for which it is designed For example, a model of the dynamics of an aircraft for a flight simulator would need to be more accurate and hence more complex, than a similar model for use in a computer game simulation

Due to the degree of non-linearity of the parameters in models which describe environmental systems, as well as the amount of interaction, the creation of environmental models may be problematic Later, it will be seen that in the model described here there is interaction between the inside air temperature, nutrient solution temperature and inside humidity, all of which are output variables in the model The chief sources of non-linearities are the equations describing humidity, CO_2 concentration and the fan characteristic

4 2 Types of Mathematical Models used For Describing Environmental Systems

Mathematical models of environmental systems such as greenhouses can be divided into three main categories,

- ***Deterministic Models*** may be developed from elements of environmental physics
- ***Heuristic Models*** depend on expert knowledge of the cropping house and may be accumulated in rules that will govern the response of the model to external stimuli, or may simply take the form of an empirical characteristic equation
- ***Identified Models*** use identification algorithms to determine the relative significance of each parameter in a model rather than relying on physical principles

Models may also be dynamic or static A ***static*** model predicts the final value that each output variable will take, when variables or other parameters in the model are changed A ***dynamic*** model also takes account of the storage capacities of some variables in the model For this reason, the dynamic model can be used to study the behaviour of a system, as external conditions change over time

A deterministic greenhouse spatial model can be zero dimensional, one-dimensional or three dimensional Zero Dimensional or ***bulk parameter*** models assume that conditions in each element of the model are homogeneous ***One*** *dimensional models* assume that conditions in the greenhouse will only change as a function of height *Three dimensional models* on the other hand, also allow for changes in parameters at different positions in a horizontal plane, in addition to changes due to height

The non-linearities and interaction effects mentioned at the end of section 4 1 affect deterministic and heuristic models in particular, since the nonl-inearities may be difficult to describe using standard physics or may not be well understood in a linguistic sense These difficulties may be overcome in some cases, by replacing the deterministic/heuristic models with identified models, which are known to be good at mimicking the system for which they are created Identified models however are chiefly suited to modelling systems whose dynamics do not change over time In addition, they are generally only accurate for mimicking conditions close to those under which they were identified Consequently, most models involve a combination of some or all of the above three approaches For this work, the model will be predominantly deterministic and based on plant physics There will however, be elements of heuristic and identified modelling

4.3 Controlled Variables in a Commercial Hydroponics-Based Cropping System

The main controlled variables in a conventional greenhouse are as follows

- Air temperature
- Humidity
- CO_2 concentration

A hydroponics system requires the control of some additional quantities These are

- Nutrient temperature
- Nutrient concentration
- pH of nutrient

This chapter will follow the development of a mostly deterministic model that will predict the behaviour of the first four of these parameters namely, air temperature, humidity, CO_2 concentration and nutrient temperature within the miniature cropping house

Seginer and Levav (1971), have identified the need for researchers to develop models which include only ***primary boundary conditions*** Primary boundary conditions are environmental parameters affecting conditions inside the greenhouse which are easy to measure and are unaffected by the existence of the greenhouse (Kindelan 1980) An example of a primary boundary condition is the intensity of light incident on the outside surfaces of the cropping house
A ***secondary boundary condition*** is a parameter which is affected by the existence of the cropping house The intensity of light incident on the crop canopy inside the cropping house, is a secondary boundary condition

Using secondary boundary conditions makes the cropping house model less useful, since it then requires information about conditions inside the cropping house A model using only primary boundary conditions, can operate using only meteorological data from the intended location of the cropping house The deterministic model introduced in this work will therefore use primary boundary conditions only

Many control strategies require the designer to provide a mathematical model of the plant, before the controller can be implemented At least some knowledge of the plant is required in almost all cases For example, before tuning a PID controller for optimum performance in a particular application, it is usual to perform some form of system identification such as, using a process reaction curve to determine the steady state gain and the time constant of the system

Fuzzy logic control requires trials to be conducted before the controller designer will be familiar enough with the controlled system to create a fuzzy rule-base and fuzzy sets This process can be made easier if a model exists on which the controller may be tested initially and then fine-tuned on the real system

The first part of this chapter will consider the development of the model This will be followed by qualitative and quantitative assessments of its performance

4.4 Development of the Deterministic Model of an NFT Cropping System

Initial work on dynamic deterministic models for greenhouses was done by Businger (1963) who developed a steady state model of the environment inside a greenhouse This was followed by probably the most referenced and comprehensive work on deterministic models by Seginer and Levav (1971) They developed a static one dimensional static model of a greenhouse similar to that of Businger and extended it to three dimensions Work by Udink Ten Cate (1983) on a bulk parameter dynamic deterministic greenhouse model was extended and adapted to model a mushroom growing tunnel by Hayes (1991), whose equations described the heat and mass fluxes occurring between the internal air, the external environment and the crop

Meath (1993) further developed Hayes' model with particular emphasis on the equations describing humidity in the mushroom house Mushroom houses have concrete floors and concrete has a large thermal capacity Consequently, the temperature of the floor changes very slowly relative to the air temperature Thus Meath did not include an equation describing the floor temperature dynamics

Hydroponic cropping systems include a relatively large quantity of a solution of water and nutrient concentrate The thermal capacity of the volume of water in the hydroponics based vegetable cropping house, is relatively low compared to that of a concrete floor and consequently the dynamics are substantially faster This means that they are much closer in reaction time to the dynamics of air temperature and thus cannot be neglected Since the temperature of the nutrient-water mixture is to be controlled, it is necessary to extend the Meath and Hayes models to include water temperature

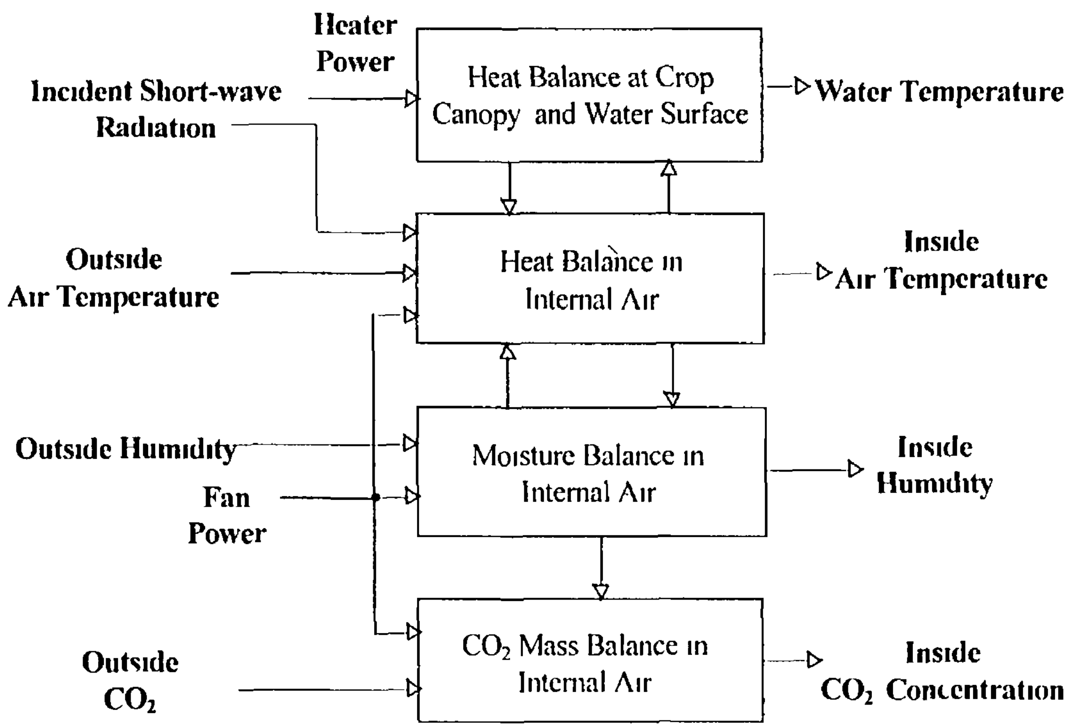


Figure 4.1: *Block Diagram of Model of Miniature Cropping House*

Figure 4 1 above shows the inputs to the model and the interaction between equations The model accepts incident solar radiation, external air temperature, external humidity and outside CO_2 concentration as uncontrolled inputs Water temperature and internal air temperature, humidity and CO_2 concentration are affected by the water heater and fan speed respectively, as indicated Fig 4 2 shows how these parameters are to be measured and controlled in the real system

4.5 Assumptions for Deterministic Model of Miniature Cropping House.

Before showing the set of equations which define the model, it is necessary to state the assumptions under which the model was constructed These are listed below

- Solar radiation which has been transmitted through the cover, reaches only the floor and/or the plant canopy and not other parts of the structure and does not directly heat the air inside the enclosure
- All surfaces radiate long wave radiation like black-bodies
- Short-wave radiation absorbed by the floor, is re-emitted as long-wave radiation in the form of heat
- The significant dynamic factor in the water temperature balance, is the thermal capacity of the tanks and not that of the trays
- The resistance of the stomata in the plants to heat and moisture transfer, is a function of ventilation rate only
- The nutrient solution temperature is uniform throughout the unit
- The air within the cropping house is perfectly mixed

The last two conditions are a consequence of using a bulk-parameter model where the output variables are not a function of position within the cropping house The issue of the stomatal resistance will be addressed in section 4 7 8 in this chapter

4 6 Equations Describing Environment within NFT-Based Vegetable Cropping House

The model consists of four differential equations which describe the mass balances of water vapour and of CO_2 and heat balances in the air and at the nutrient and crop canopy As a result, the differential equations govern internal air temperature θ_a, nutrient solution temperature θ_w, internal humidity Γ_a and internal CO_2 concentration Φ_a, as follows

$$\frac{d\theta_a}{dt} = +K_1(\theta_w^4 - \theta_a^4) + K_2(\theta_a^4 - \theta_c^4) + K_3(\theta_a - \theta_c) - K_4(\theta_a - \theta_c) \qquad Eqn\ 4\ 1$$

$$\frac{d\theta_w}{dt} = K_5 I_h + K_6 Q_{so} + K_7(\theta_a^4 - \theta_w^4) - K_8(\theta_w - \theta_a) + K_5 I_h + K_9 f(q_v)(e_s - e) \qquad Eqn\ 4\ 2$$

$$\frac{d\Gamma_a}{dt} = K_{10}(\Gamma_c - \Gamma_a) + K_{11} I_h + K_{12} f(q_v)(e_s - e) \qquad Eqn\ 4\ 3$$

$$\frac{d\Phi_a}{dt} = K_{13}(\Phi_c - \Phi_a) - K_{14}\left(\Phi_a - \Phi_{meso}\right) \qquad Eqn\ 4\ 4$$

Where Q_{so} is the heat due to short-wave radiation incident on a horizontal surface outside the cropping house, $f(q_v)$ is some function of the wind velocity q_v, and e and e_s are the vapour pressure and the saturation vapour pressure respectively The coefficients K_i of the terms in the equations, will be dealt with individually in the following section, which explains the major heat transfer processes which occur in a cropping house and shows how they can be described analytically

4.7 Heat and Mass Transfer Mechanisms in Glasshouses

This section introduces the individual terms describing heat and mass transfer which contribute to the heat and mass balance equations of section 4.6. Each term is described independently, is modified to suit the model and linearised where possible. The following section will show how these terms may be combined to form the four differential equations which constitute the model.

4.7.1 Short Wave Radiation

The difference in the intensity of short-wave radiation between summer and winter months is largely attributable to latitude, since this determines the angle of the solar azimuth and also the length of the day, at any particular time of the year. In Ireland and Great Britain for instance, the total energy supplied by the sun may be up to ten times less in a winter month than in a summer month. On a clear summer's day outside a greenhouse, a typical value for the flux of solar radiation would be 800 Wm^{-2}. Dense clouds can reflect up to 70% of incoming solar radiation. Typically about 44% of total radiation is considered to be ***photosynthetically active***. Of course this figure varies depending on the type of plant (Electric Council 1973). In addition, if the plant is grown in a closed space such as a greenhouse or miniature cropping house such as the one studied here, the radiation flux is attenuated by the glazing.

The co-efficient which quantifies how much light will get through the glazing of the cropping house is called the glazing transmission coefficient τ_c. If the incident radiation Q_{so} is measured in Wm^{-2} to coincide with meteorological measurements and the total flux inside the cropping house Q_{si} is measured in W, then the short wave radiation flux incident on the entire plant canopy is

$$Q_{si} = \tau_c(1-\alpha)A_c Q_{so} \qquad \textbf{\textit{Eqn. 4.5}}$$

Where A_c is the surface area of the cover and α is the ***albedo*** of the plant, which is the fraction of incident radiation which is reflected by the plant surface The above treatment assumes that there is no ***specular reflection,*** or in other words, light is incident on the glazing at an angle which is approximately normal to the surface and so is transmitted through it, rather than reflected

4.7.2 Measuring Short Wave Radiation Using a Light Sensor

In this work, the intensity of incoming solar radiation is measured using a light sensor which produces a voltage output which is a linear function of the intensity of the incident short wave radiation At zero intensity, the device outputs 0 V, while at an intensity of 200 Wm^{-2}, the output voltage saturates at approximately 4 V This can be modelled by the following light intensity to voltage characteristic

$$V_{si}=0\ 02\ Q_{si}$$

where Q_{si} is the intensity of the solar radiation in Wm^{-2} and V_{si} is the output voltage

4.7.3 Long Wave Radiation

Much of the short-wave radiation which falls on leaves and other surfaces is absorbed and re-emitted as less energetic long wave radiation The amount of radiation emitted per second by one square meter of the radiating surface Q is expressed by the Stefan-Boltzmann Law

$$Q = \sigma\theta^4 \qquad \textbf{\textit{Eqn 4 6}}$$

Where ***Stefan's constant*** σ is 5 67 10^{-8} $Wm^{-2}K^{-4}$ and θ is the temperature of the emitting surface For radiation exchange between two different media with temperatures around 22 5°C and with area of interface equal to A_s, this is approximately,

$$Q_{lw} = 4\theta^3 \sigma A_s(\Delta\theta) \qquad \textit{Eqn 4 7}$$

where $\Delta\theta$ is the difference in temperature between the two media (See appendix d) For a plant whose ratio of leaf surface area to covered surface area is given by the leaf area index L_{ai}, the amount of long wave radiation can be approximated by the following linear equation

$$Q_{lw} = 5\,9 A_s L_{ai}(\Delta\theta) \qquad \textit{Eqn 4 8}$$

where θ is in °C or in K This is the approximation which is used in the model to describe radiative heat loss from the canopy and the nutrient solution surface

4.7.4 Conduction

Conduction is a form of heat transfer produced by a sharing of momentum between molecules in a fluid or by free electrons in a metal In micrometeorology, conduction is important in relation to heat flow in the soil and solid surfaces, but not in free air (Monteith 1973) The loss of heat through conduction Q_c through a cross section of a solid such as a leaf which is at temperature θ_{hot} at one side and θ_{cold} at the other, can be described by the following equation

$$Q_c = U_c A_c(\theta_{hot} - \theta_{cold}) \qquad \textit{Eqn 4 9}$$

where U_c is the ***thermal conductivity*** of the material and A_c is its cross-sectional area Equations of this type will be used later to describe conduction through the cover and through the walls of the nutrient reservoir tanks, which means that U_c and A_c in the above equation will represent the thermal conductivity, and surface area of the cover and the tanks respectively

4.7.5 Ventilation

Ventilation is necessary to remove surplus solar heat admitted into the greenhouse after it has been converted into sensible heat and latent heat of vapourisation in the inside air It is also required to prevent the decrease in concentration of CO_2 which will retard the growth of plants experiencing high levels of solar radiation (Morris 1971)

In a conventional greenhouse, CO_2 depletion is not critical, since decay of compost releases comparatively large quantities of CO_2 which enrich the air and promote plant growth due to the resulting acceleration of photosynthesis However there is no compost involved in hydroponics and hence no CO_2 enrichment

The fan used in his work is a PAPST 12 V d c fan which produces variable and reproducible air flow-rates between 4 ms^{-1} and 6 ms^{-1} for applied voltages in the range 5 V(cutoff voltage) to 11 V (maximum allowed voltage) The performance of the fan in this voltage range can be modelled by the following second order empirical equation

$$q_v = 6\ 1\ 10^{-4} V_{fan}^{2} + 3\ 7\ 10^{-3} V_{fan} + 5\ 6\ 10^{3}\ [m^3 s^{-1}] \qquad \textbf{Eqn 4.10}$$

where V_{fan} is the applied voltage and q_v is the resulting ***volumetric*** air flow rate through the cropping house q_v is the measure of ventilation which is used in the simulation of the cropping house This equation is derived in appendix A

The ventilation system in the miniature cropping house extracts air from the interior, through a vent This creates a region of low pressure inside the house which causes air to pass through small grills in the gable ends of the house to bring the air pressure back to atmospheric pressure

If q_v is volumetric flow rate, and ρ_a and c_{pa} are the density and specific heat capacity of air respectively, then the heat lost by ventilation by the cropping house is

$$Q_v = q_v \rho_a c_{pa} (\theta_a - \theta_i) \qquad \textbf{Eqn. 4 11}$$

This assumes of course, that there is no short circuiting of the air flow The positions and distance between the fan aperture and the exhaust grills ensures that this assumption is valid The equivalent equations for mass flux of CO_2 and water vapour are

$$M_v = q_v (\Phi_a - \Phi_e) \qquad \textbf{Eqn 4 12}$$

and

$$W_v = q_v (\Gamma_a - \Gamma_e) \qquad \textbf{Eqn. 4 13}$$

respectively, where M_v and W_v are the net volumes of CO_2 and water vapour drawn into the cropping house due the a volumetric air flow q_v, and $\Phi_a - \Phi_i$ and $\Gamma_a - \Gamma_e$ are the gradients in absolute humidity and CO_2 concentration respectively between the inside and outside air

4.7.6 Convection and the Diffusion of Heat

The simplest method of representing heat losses by convection is known as ***Newton's Law of Cooling*** This states that under constant conditions, the rate of heat loss per unit area of a body Q_{cv} will be proportional to the difference in temperature between the body, which in this case is the crop canopy, and its surroundings as follows -

$$Q_{cv} = \rho_a c_{pa} \frac{(\theta_s - \theta_a)}{r_H} \qquad \textbf{Eqn. 4 14}$$

where θ_s is the temperature at the plant canopy surface, θ_a is the temperature of the surrounding air, r_H is the ***boundary layer resistance*** and ρ_a and c_{pa} are the density and ***specific heat capacity*** of air respectively (White 1974), (Monteith 1973) For a crop canopy with a total leaf surface area $A_c = A_t L_{ai}$, this becomes

$$Q_{cv} = \rho_a c_{pa} A_t L_{ai} \frac{(\theta_s - \theta_a)}{r_H} \qquad \textbf{Eqn 4 15}$$

The boundary layer resistance r_H is a non-linear function of ventilation rate but for this work is taken to be constant at 577 sm^{-1}

4.7.7 Evaporation, Transpiration and Condensation

All objects that contain water can dissipate water vapour In the case of soil and water, this dissipation is called ***evaporation***, which is a physical process For plants and animals it is called ***transpiration,*** and is regarded as a biological process The reverse of both processes is called ***condensation***

4.7.7.1 Evaporation

Since evaporation cools the evaporating surface, the humidity of the air can be determined by comparing the temperature of a sufficiently ventilated wet bulb and a dry bulb The vapour pressure e is

$$e = e_s - \gamma(\theta_a - \theta_s) \qquad \textbf{Eqn 4.16}$$

e_s is the saturation vapour pressure, which is assumed to be the vapour pressure at the crop and water surface Monteith (1973) gave an alternative means of determining e as follows

$$e = \frac{\Gamma_a(273 + \theta_a)}{217} \qquad \textbf{Eqn 4 17}$$

The above equation requires knowledge of the dry bulb temperature θ_a and the absolute humidity Γ_a

4.7.7.2 Transpiration - Evaporation from Plants

Vapour originates in the substomatal cavities of plant leaves The vapour concentration gradient between the ambient air and the substomatal cavity causes water vapour to diffuse into the air from this cavity Air in the substomatal cavity is assumed to be at or near 100% relative humidity θ_s is the temperature of the crop and water surface The ***psychrometer constant*** ,γ is expressed as -

$$\gamma = \frac{c_{pa}P}{\lambda\varepsilon} \qquad \textbf{\textit{Eqn 4 18}}$$

where λ, P and ε are the latent heat of vapourisation of water, atmospheric pressure, and the ratio of molecular weights of water vapour and air respectively λ is a means of converting from partial pressures to temperature Using Newton's Law of Cooling again and incorporating eqn 4 13, the latent heat loss λE from the crop and water surface due to evapo-transpiration is expressed as -

$$\lambda E_p = \frac{\rho_a c_{pa} A_{cr}(e_s - e_a)}{\gamma r_s} \qquad \textbf{\textit{Eqn 4 19}}$$

Latent heat loss is partially driven by water vapour partial pressure gradient $e_s - e_a$ Loss of latent heat by the canopy is accompanied by an increase in moisture in the air inside the cropping house This is given by

$$E_p = \frac{\rho_a c_{pa} A_{cr}(e_s - e_a)}{\lambda \gamma r_s} \qquad \textbf{\textit{Eqn 4 20}}$$

where r_v is the resistance of the boundary layer to evaporation If $\gamma^* = \gamma \frac{r_v}{r_H}$, then the above equations can be expressed as

$$\lambda E_p = \frac{\rho_a c_{pa}(e_s - e_a)}{\gamma^* r_H}$$ **Eqn. 4 21**

$$E_p = \frac{\rho_a c_{pa}(e_s - e_a)}{\lambda \gamma^* r_H}$$ **Eqn. 4 22**

Some of the vapour loss from the water and crop canopy is due to absorption of heat Q at the surface Equations 4 21 and 4 22 can be modified to account for this additional evaporation as follows (Monteith 1973)

$$\lambda E = \frac{\Delta Q + \rho_a c_{pa}(e_s - e_a)/r_H}{\Delta + \gamma^*}$$ **Eqn 4 23a**

$$E = \frac{\Delta Q + \rho_a c_{pa}(e_s - e_a)/r_H}{\lambda(\Delta + \gamma^*)}$$ **Eqn 4 23b**

Penman (1946), developed a version of equations 4 23a/4 23b which included an empirical equation accounting for changes in wind velocity which replaces the term $\frac{\rho_a c_{pa}}{r_H}$ in Monteith's equation The advantage of Penman's original approach is that r_H does not need to be measured Penman's original equation was modified from Imperial units by Stigter to yield the following form which is still widely used by plant physicists today (Rosenberg, Blad & Verma 1983)

$$f(q_v) = 0\ 00021(1 + q_v/160)\ JK^{-1}m^{-2}s^{-1}$$ **Eqn 4 24**

It is the above form of the equation which will be used in this work At high ventilation rates (air speed over canopy typically over $1ms^{-1}$), the resistance to flow in the vapour phase, between the substomatal cavity and the ambient air is significant (Rosenberg, Blad & Verma 1983) This resistance is called the stomatal resistance but does not affect evaporation since ventilation is kept very low as shall be seen in the next chapter

4.7.8 CO_2 Assimilation by Plants

Green plants use a process known as photosynthesis to extract solar energy and convert it in to primary sugars by the light intermediated reaction,

$$6CO_2 + 12H_2O \xrightarrow{light\ 0.469\ MJ\,mol\,CO_2^{-1}\ chlorophyll} C_6H_{12}O_6 + 6H_2O + 6O_2$$

These primary sugars are then converted into more complex sugars starches and cellulose which are the materials for plant growth. CO_2 from ambient air is allowed to pass through the stoma, where it diffuses through the cells walls into the cytosol.

Photosynthesis can be described by the equation

$$M_p = \frac{\Phi_a - \Phi_{meso}}{r_s} \qquad \textbf{\textit{Eqn 4.25}}$$

where the CO_2 concentration potential $\Phi_a - \Phi_{meso}$ exists between the air and the chloroplasts and r_s is the stomatal diffusion resistance, as before. r_s is a function of ventilation rate but also of light intensity, leaf temperature, leaf water potential and possibly water vapour pressure deficit.

This information has been discovered by experimentation (Rosenberg, Blad and Verma 1983), and it is difficult to derive equations from first principles which accurately account for the influence of the above parameters. However typical values for r_s for different light intensities and CO_2 concentrations in the air, can be determined empirically. Rosenberg, Blad and Verma (1983), give a general empirical equation which relates stomatal resistance to incident short-wave radiation as follows

$$r_s = 3000e^{-Q_n/120} \qquad \textbf{\textit{Eqn 4.26}}$$

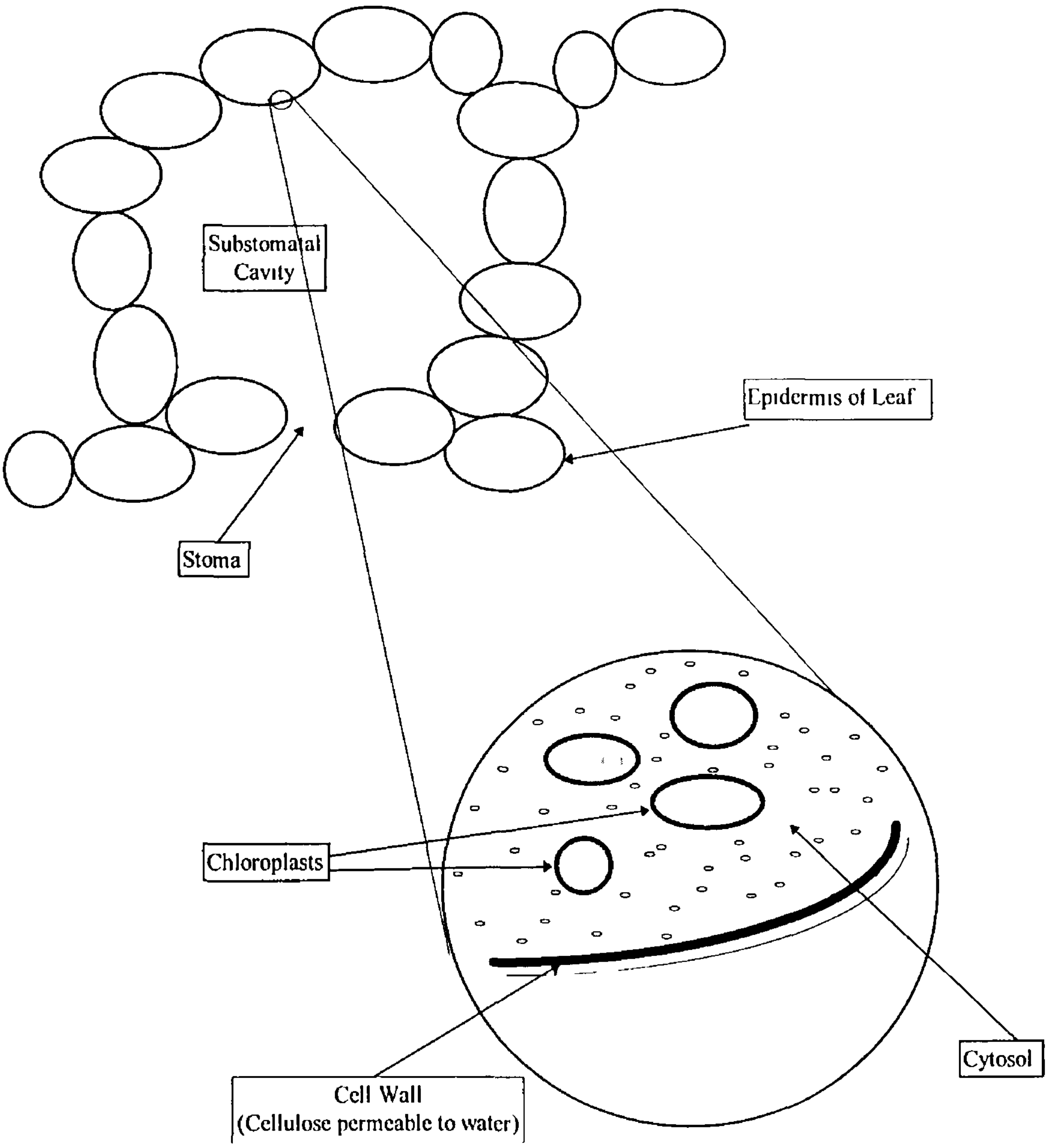


Figure 4.2: *Diffusion of CO_2 into the chloroplasts*

Stomatal resistance is not solely a function of light intensity Gaastra (1957), Monteith and Unsworth (1990), and Stoutjesdijk (1992) have all conducted experiments that indicate the level of CO_2 assimilation for different light levels and CO_2 concentrations, for tomatoes and corn The results of these experiments could be used to develop cultivar-specific relations between these parameters However this would require a considerable amount of time to correlate the necessary information and to develop which mimicked the CO_2

assimilation process of each cultivar and is thus outside the scope of this work The approach taken here will be to use the simple equation for stomatal resistance given above for estimating CO_2 uptake

4.8 Derivation of Model of Cropping House

This section will combine the terms described in the last section to form the full deterministic model of the cropping house This initial version of the model will be modified after studying its performance qualitatively and quantitatively As stated earlier in this chapter, the model is composed of four differential equations, each one describing a mass or heat balance in the air, or a heat balance in the nutrient solution Each equation will be dealt with in a separate sub-section

4.8.1 Heat Balance in Internal Air in the Cropping House

The first differential equation describes the heat balance in the air inside the unit This heat balance can be derived from Fig 4 3 below as follows

$$\begin{aligned} \textit{Rate of Heat Storage in Air} = {} & \textit{SW Rad from Water and Crop} \\ & -\textit{SW Rad Lost to Ext Env} \\ & +\textit{Heat in from Ventilation} - \textit{Conduction to Ext Env} \end{aligned}$$

Or in mathematical form,

$$\rho_a c_{pa} v_a \frac{d\theta_a}{dt} = Q_{wa} - Q_{ac} + Q_v - Q_c \qquad \textit{Eqn 4 27}$$

where

$$Q_{wa} = 5\ 9L_{at}A_t(\theta_w - \theta_a) \qquad \textit{Eqn 4 28}$$

$$Q_{ac} = 5\ 9\tau_c A_c(\theta_a - \theta_c) \qquad \textit{Eqn 4 29}$$

$$Q_v = \rho_a c_{pa} q_v(\theta_c - \theta_a) \qquad \textit{Eqn 4.30}$$

$$Q_c = U_c A_c(\theta_a - \theta_c) \qquad \textit{Eqn 4 31}$$

4.8.2 Heat Balance at Nutrient Solution and Plant Canopy Surface

The second differential equation mimics the temperature of the water surface and the canopy Heat flows in the cropping house can be seen in figure 4 3 , which leads to the following heat balance

$$\begin{array}{rl} \textit{Rate of} = & \textit{SW Rad on Canopy} + \textit{Heat from Heater} \\ \textit{Heat Storage} & - \textit{Heat Rad to Air} - \textit{Heat from Crop by Convection} \\ \textit{in Water} & - \textit{Latent Heat Lost to Air} \end{array}$$

Or more explicitly,

$$\rho_w c_{pw} v_w \frac{d\theta_w}{dt} = Q_{st} + Q_h - Q_{aw} - Q_{conv} - \lambda E \qquad \textit{Eqn 4 32}$$

where -

$$Q_{st} = \tau_c(1-\alpha)A_c Q_{so} \qquad \textit{Eqn 4 33}$$

$$Q_h = V_h I_h \eta_h \qquad \textit{Eqn 4 34}$$

$$Q_{wa} = 5\ 9A_t L_{at}(\theta_w - \theta_a) \qquad \textit{Eqn 4 35}$$

$$Q_{conv} = \frac{\rho_a c_{pa}(\theta_w - \theta_a)}{r_h} \qquad \textit{Eqn 4 36}$$

$$\lambda E = \frac{\Delta V_h I_h \eta_h + \rho_a c_{pa} f(q_v)(e_s - e)}{\Delta + \gamma} \qquad \textit{Eqn 4 37}$$

where η_h is the efficiency of the heaters and other parameters are the same as introduced earlier in this chapter

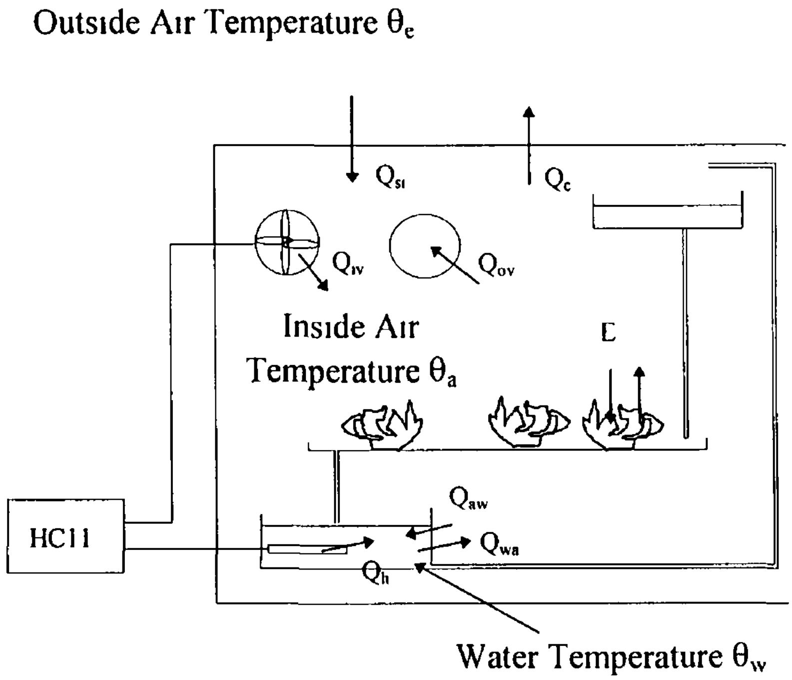


Fig 4.3: *The Cropping House Showing Heat Flows*

4.8.3 Moisture Mass Balance at Inside Air

Moisture balance within the cropping house is illustrated in figure 4 4 and is modelled by the third differential equation as follows

Rate of Change of Moisture = Net moisture in due to + Moisture
Content Inside Air Ventilation from Crop Canopy

which can be re-written as follows

$$v_a \frac{d\Gamma_a}{dt} = W_v + E \qquad \textit{Eqn 4 38}$$

$$W_v = q_v(\Gamma_e - \Gamma_a) \qquad \textit{Eqn 4 39}$$

$$E = \frac{\Delta V_h I_h M + \rho_a c_{pa} f(q_v)(e_s - e)}{\lambda(\Delta + \gamma)} \qquad \textit{Eqn 4.40}$$

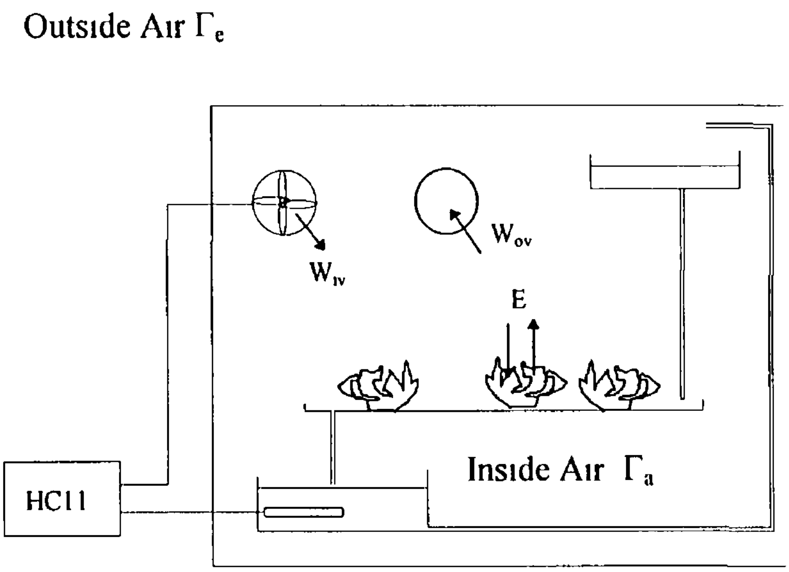


Figure 4.4: *The Cropping House Showing Moisture Flows*

4.8.4 CO_2 Mass Balance in Inside Air

Finally, CO_2 mass balance inside the cropping house is modelled by the fourth differential equation and supplementary equations as follows

Rate of Change of

CO_2 Conc = *Net CO_2 in due to Ventilation - CO_2 lost to Crop due to Photosynthesis*

of Inside Air

This leads to the following set of equations

$$v_a \frac{d\Phi_a}{dt} = M_v - M_p \qquad \textbf{\textit{Eqn 4.41}}$$

$$M_v = q_v(\Phi_i - \Phi_a) \qquad \textbf{\textit{Eqn 4 42}}$$

$$M_p = \frac{(\Phi_a - \Phi_i)}{r_s} \qquad \textbf{\textit{Eqn 4.43}}$$

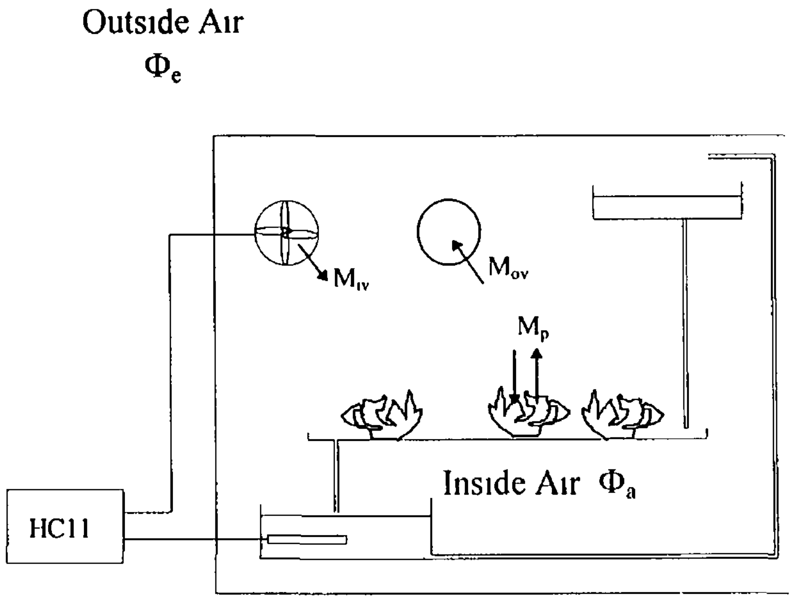


Figure 4.5: *The Cropping House Showing CO_2 Flows*

4.9 Development of the Model of the Cropping House in the Matlab-Simulink Simulation Environment.

The differential equations describing the model of the cropping house were implemented as a script file in the Matlab/Simulink simulation environment for windows Script files of this type are called ***Matlab S-Functions*** An S-function may be linked to a user-configured graphical interface using the Simulink simulation tool Figure 4 6 below, shows the Simulink block diagram used to process and display the input and output variables that affect and are affected by the model

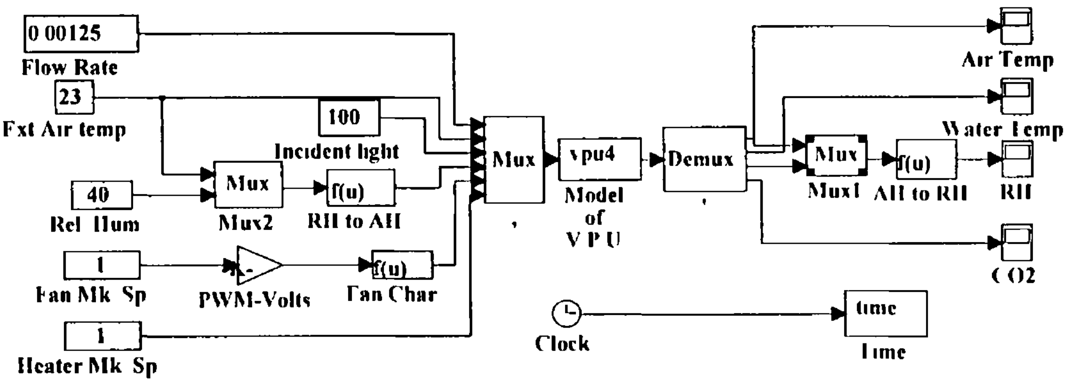


Figure 4 6 *Simulink Block Diagram Showing the Cropping House with Changeable Inputs and Displaying Model Outputs*

4.10 Steady State Characteristics of the Deterministic Model of the Cropping House

This section examines the steady state characteristics of the model Using ***Matlab***, a computer package for mathematical computation and simulation, the steady state form of the model equations will be evaluated for a range of input conditions A qualitative assessment of the performance of each element of the model is given

The set of graphs given in figure 4 7 are an indication of how each variable in the model responds to external stimuli such as incident light intensity and external air temperature

4.10 1 Steady State Characteristic of the Inside Air Temperature

Figure 4 7 below shows the inside air temperature as a function of ventilation rate and of water temperature for the original model By setting the rate of change of θ_a to zero, which is what happens under steady state conditions

$$\theta_a = \frac{\left(5.9A_t L_{at} + U_{poly}A_{tank} + \dfrac{\rho_a c_{pa} A_t L_{at}}{r_h}\right)\theta_w + \left(5.9A_c + q_v\rho_a c_{pa} + U_c A_c\right)\theta_e}{5.9A_t L_{at} + U_{poly}A_{tank} + \dfrac{\rho_a c_{pa} A_t L_{at}}{r_h} + 5.9A_c + q_v\rho_a c_{pa} + U_c A_c}$$

Eqn 4 44

which is a linear function of the nutrient solution temperature θ_w and the external air temperature θ_e if the ventilation rate q_v is held constant This means that, the air temperature inside the cropping house θ_a will increase if either nutrient temperature θ_w, or external air temperature θ_e, increase as in the real system The air temperature is a non-linear function of ventilation rate as follows

$$\theta_a = \frac{A + Bq_v\theta_e}{C + Bq_v} \qquad \textbf{\textit{Eqn 4 45}}$$

As the ventilation rate q_v becomes dominant, θ_a asymptotically approaches θ_e and this effect is independent of the value θ_w, as shown below in figure 4 7

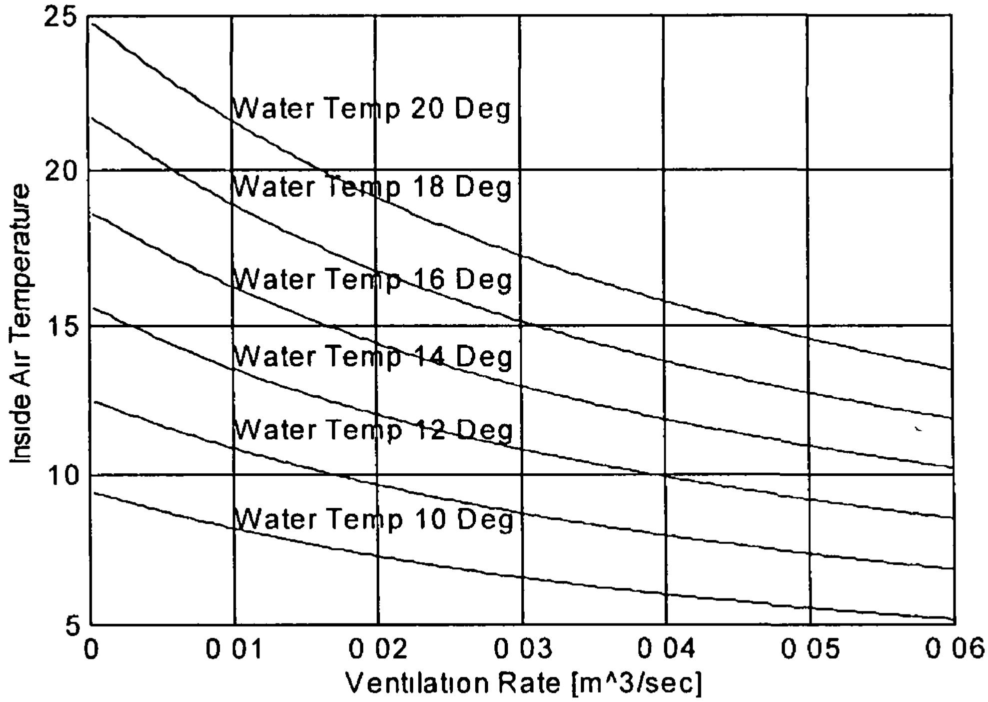


Figure 4 7 *Steady State Inside Air Temperature Versus Ventilation Rate for Different Water Temperatures with Outside Air Temperature at 0°C, and heater power at 400W*

This is expected, since an increase in the ventilation rate in the real system will force more of the outside air into the cropping house, thus causing the internal air temperature to approach the outside air temperature

4 10.2 Steady State Nutrient Solution Temperature Characteristics

The steady state nutrient solution temperature is given by,

$$\theta_w = \frac{Q_h + Q_{si} + \left(5\,9A_tL_{ai} + U_{poly}A_{tank} + \dfrac{\rho_a c_{pa} A_t L_{ai}}{r_h}\right)\theta_a + U_{poly}A_{tank}\theta_c - \lambda E_c}{5\,9A_tL_{ai} + 2U_{poly}A_{tank} + \dfrac{\rho_a c_{pa} A_t L_{ai}}{r_h}} \qquad \textbf{Eqn 4.46}$$

which is in the form,

$$\theta_w = Q_h + A\theta_a + B\theta_c + C \qquad \textbf{Eqn 4 47}$$

which means that θ_w is a linear combination of θ_a, Q_h and θ_e As before, any increases in these quantities will result in an increase in the nutrient temperature θ_w Any non-linearities in this equation come from the evaporation term λE_c, which is a non-linear function of θ_a as shown below

$$\lambda E_c = \frac{\Delta Q + 0\,00021(1 + q_v/160)\left(e_s(\theta_a) - \dfrac{\Gamma_a(273+\theta_a)}{217}\right)}{(\Delta + \gamma^*)} \qquad \textbf{Eqn 4 48}$$

Consideration of equation 4 48 shows that λE_c and thus θ_w are linear functions of Γ_a if the air temperature θ_a and the ventilation rate q_v are kept constant, since the equation is then of the form -

$$\lambda E_c = K_1 + K_2(e_s - K_3\Gamma_a) \qquad \textbf{Eqn 4 49}$$

It is also apparent from equation 4 49 that as Γ_a increases, the vapour deficit e_s-e_a decreases, which decreases the evapo-transpiration rate λE_c This agrees well with the real system

Figure 4 8 below, demonstrates the linear relationship expressed by equation 4 47 for nutrient temperature and heater power

It can be seen that increasing the heater power increases the nutrient temperature and that nutrient temperature increases with external air temperature This also coincides with the real system where an increase in heater power or external air temperature will result in an increase in the temperature of the nutrient

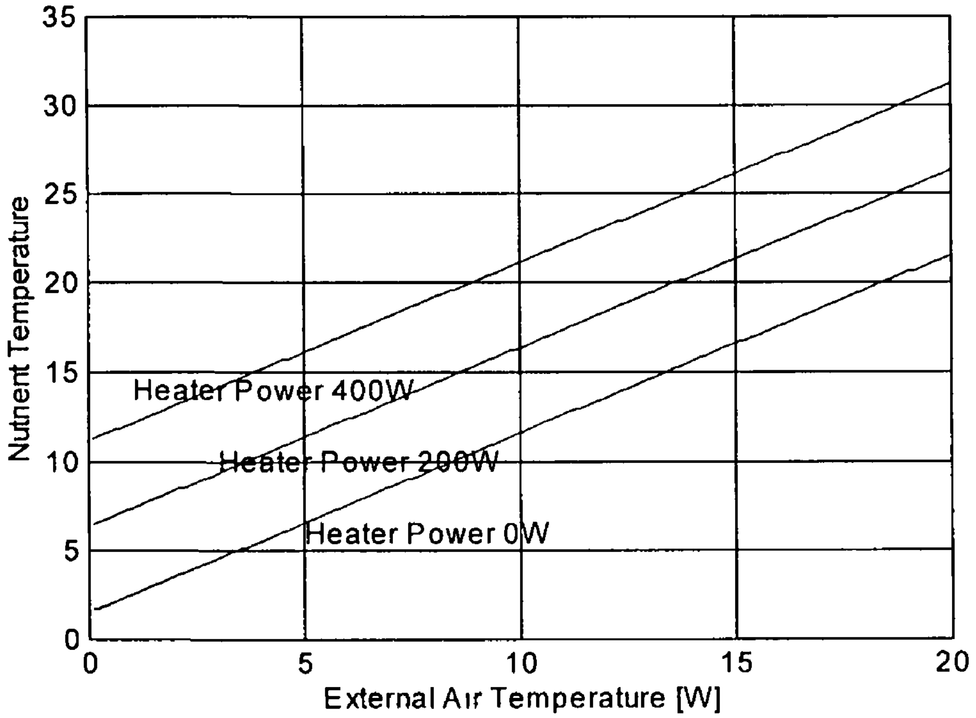


Figure 4.8 *Steady State Nutrient Temperature Versus External Air Temperature for Different Heater Powers with the Inside Air Temperature in Thermal Equilibrium with the Temperature of the Nutrient*

4 13 3 Steady State Inside Absolute Humidity Characteristics

The steady state absolute humidity inside the cropping house is given by the equation

$$\Gamma_a = \frac{q_v \Gamma_e + \dfrac{0.8\left(\Delta\left(Q_{si} + Q_h\right) + 0.08\left(1 + \dfrac{q_v}{13800}\right)\right)}{\Delta + \gamma^*}}{q_v + 0.064\dfrac{1 + \dfrac{q_v}{13800}}{\Delta + \gamma^*}} \qquad \textbf{\textit{Eqn 4.50}}$$

The absolute humidity is a measure of the mass of water vapour in 1 m^3 of air. As before for air temperature, the absolute humidity is a non-linear function of the ventilation rate. Figure 4.9 below shows the variation of absolute humidity within the cropping house with ventilation for different outside humidities. As the ventilation rate increases and more air from outside the cropping house is forced inside, the internal absolute humidity Γ_a, asymptotically approaches the outside absolute humidity Γ_e.

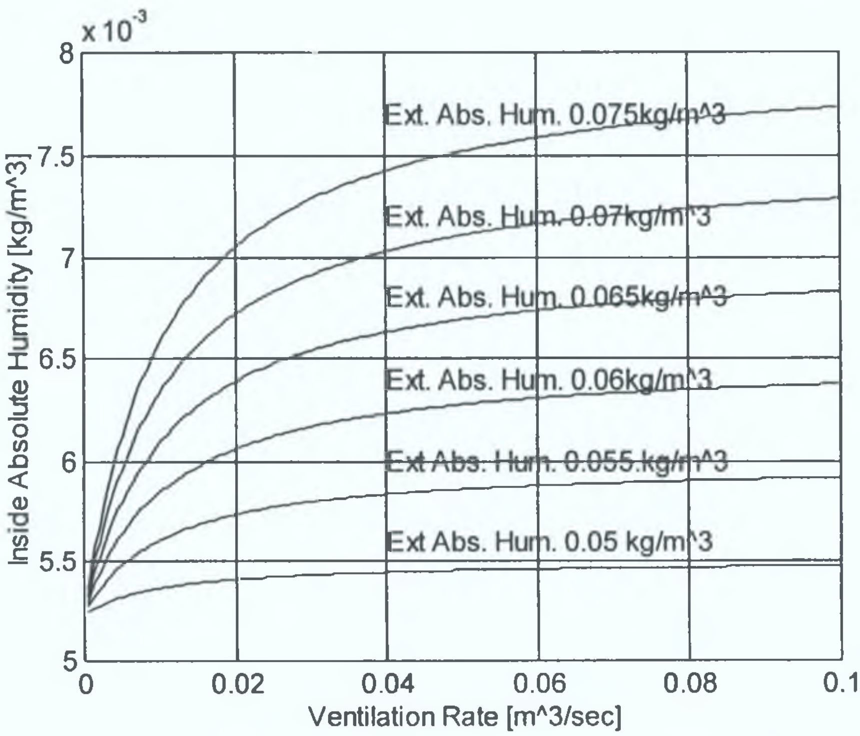


Figure 4.9: *Steady State Inside Absolute Humidity Versus Ventilation Rate for Different External Absolute Humidities.*

It is apparent from equation 4.50, that Γ_a is also a linear function of Γ_e at a constant non-zero ventilation rate. This means that, if the external humidity increases diffusion and ventilation ensure that the humidity inside the cropping house increases also

4.10.4 Steady State Inside CO_2 Concentration Characteristic

The steady state CO_2 concentration within the cropping house is given by,

$$\Phi_a = \frac{q_v \Phi_e + \frac{\Phi_{meso}}{r_s}}{q_v + \frac{1}{r_s}} \qquad \textit{Eqn 4 51}$$

where the stomatal resistance r_s is approximated by equation, 4 26

$$r_s = 3000 e^{\frac{-Q_{st}}{120}}$$

which was introduced earlier in this chapter Consideration of equation 4 26 shows that Φ_a is a linear function of Φ_e, if q_v and Q_{st} are kept constant, and a non-linear function of r_s and q_v Figure 4 10 below shows the effect of ventilation rate on the inside CO_2 concentration for different incident light intensities using the above approximation for r_s The inside CO_2 concentration asymptotically approaches outside ambient concentration as the ventilation rate increases The higher the incident light intensity, the greater the photosynthetic uptake, which means that a greater ventilation rate is required to keep the CO_2 concentration inside the cropping house near ambient levels This is also apparent from figure 4 10

Consideration of the set of curves in figure 4 10 shows that the above approximation results in a CO_2 concentration which is independent of light intensity at a zero ventilation rate In the real unventilated system however, an increase in incident light, would result in a decrease in the CO_2 concentration within the cropping house The solution to this problem is to assume Φ_{meso} to be a linear function of the light intensity

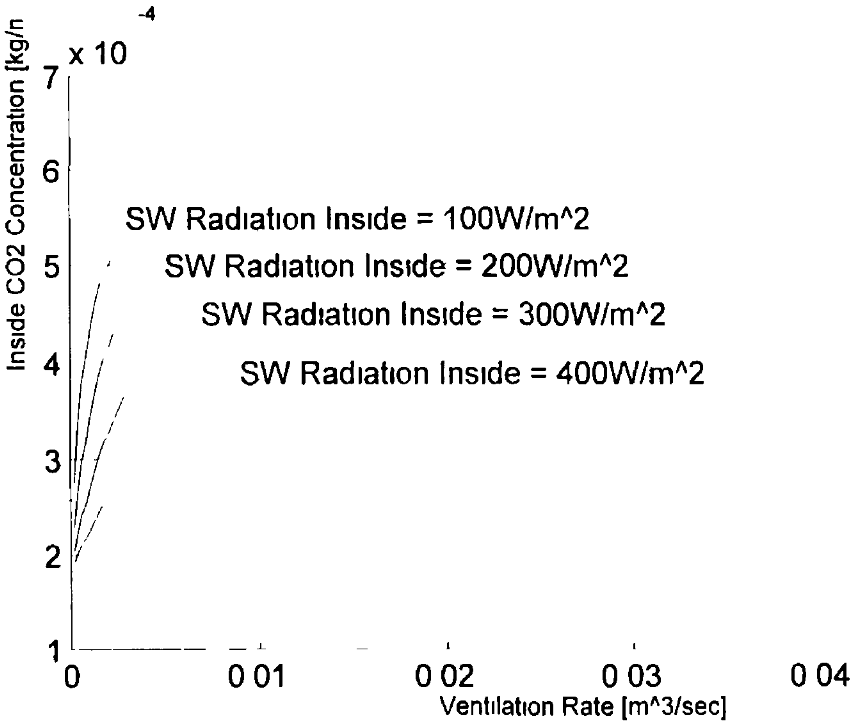


Figure 4 10 *Steady State Inside CO_2 Concentration Versus Ventilation Rate for Different Levels of Incident Solar Radiation*

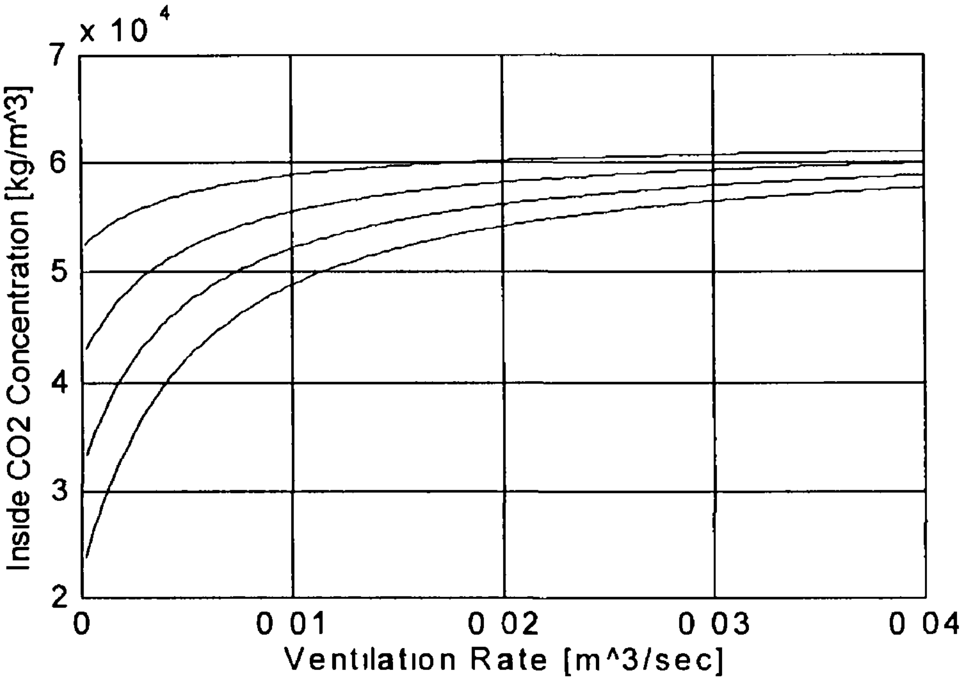


Figure 4 11 *Steady State CO_2 Concentration versus Ventilation Rate for Different Mesophyll CO_2 Concentrations*

Figure 4 11 shows the result of taking Φ_{meso} as a linear function of Q_{si} The coefficients for this approximations would need to be determined empirically and would result in secondary boundary conditions, which are beyond the scope of this work The original equation given by Rosenberg, Blad and Verma (1983), gives a good approximation of the dynamic responses of the real system as will be seen in the next section For the above reasons, the original approximation was selected to describe CO_2 transfer

4.11 Summary

This chapter has described a deterministic model of a miniature cropping house, which was written in the Matlab/Simulink simulation environment It has also described and assessed the performance of the model both qualitatively and quantitatively The next chapter will compare the behaviour of the model of the cropping house to the behaviour of the real system with the same time-varying external climate It will point out weaknesses and suggest modifications which may be made to the model based on the results of this set of simulation experiments, and it will show the result of other simpler modifications

Chapter 5: Model Validation by Comparison with Real System

5.1 Introduction

This chapter displays and assesses the dynamic responses of the cropping house model This is achieved by applying historical input data measured at the real system to the deterministic model of the cropping house and comparing the resulting modelled output data to the response data of the real system

The first section describes the experimental set-up for the data acquisition, while the subsequent sections deal with the responses of the differential equations of the model to the quantities representing changing conditions outside the cropping house The last section shows an example of how the model may be used to pinpoint improvements to the control system or the cropping house structure itself

5.2 Using Real Historical Data to Assess the Performance of the Cropping House Model

A series of three experiments was carried out on the miniature cropping house during the month of September 1994 Quantities affecting the model of the cropping house were measured over time on the real system These data were used to evaluate the performance of the model by comparing the real measured data with the modelled output The comparison of real and modelled data was accomplished by converting the raw data from the data-logger from Microsoft Excel format to a series of Matlab data files so that quantities corresponding to model input variables could be applied as inputs to the model It also allowed the quantities modelled by the simulation, such as air temperature inside the unit, to be directly compared with the equivalent quantities measured in the real system

A description of the data acquisition system is given in this section followed by an assessment of the comparison between the real and the modelled data

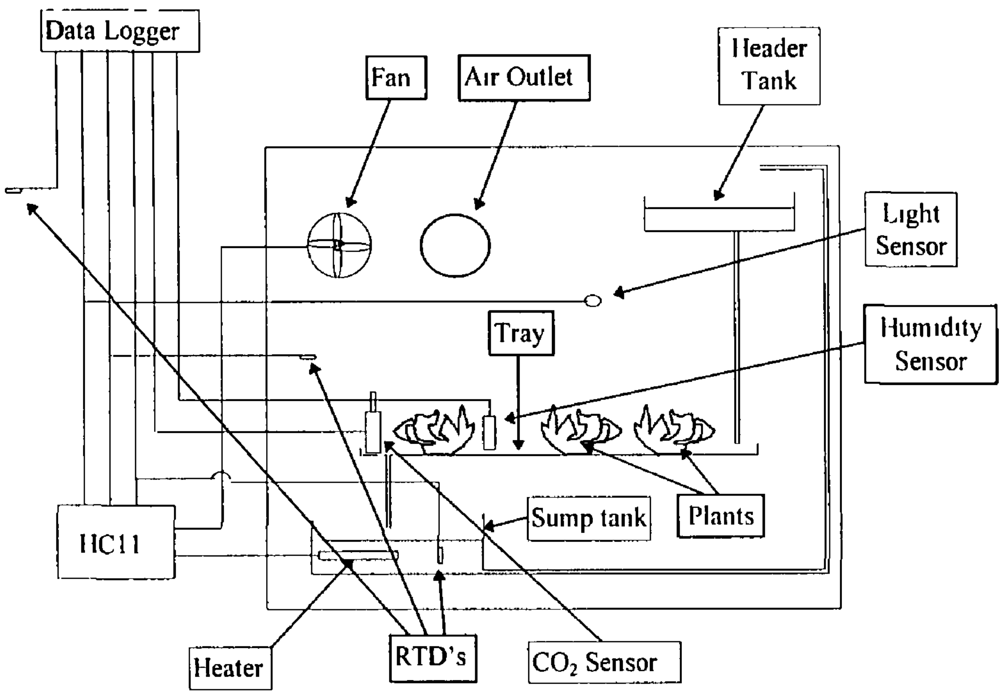


Fig 5.1: *The Cropping House with Controller and Data-Logger*

5.2.1 Data-Logger and Instrumentation

Figure 5 1 above shows the connections for the acquisition of data using a data-logger The data logger used in this work was an RIL CL0008 programmable chart-logger Eight analogue input channels can be configured for connection to Pt100 RTD's, output voltages in the range 0-10V d c , or a selection of output current ranges Data were stored temporarily in 256k of battery-backed RAM during the trials and was later saved to a file on a computer via a serial link

The file format was compatible with Microsoft Excel which made it easy to transfer data to virtually any other package

5.2.1.1 Temperature Measurement

Up to eight temperature measurements were taken simultaneously, although this depended on whether other parameters such as humidity, light level, and CO_2 concentration were needed Due to the remote position of the Unit, it would have been impractical to log all these parameters using the 68HC11, since the micro-controller requires a computer to be positioned nearby to log data For this reason the data-logger was used, thus allowing the data to be stored temporarily in static RAM and saved to disk after the trials

Eight Pt-100's were used to measure temperature They were light-duty laboratory sensors with a stainless steel outer casing which is non-toxic

5.2.1.2 Humidity Sensors

The external humidity was measured using an RS humidity/temperature sensor with 0-10V output (RS 256-253) This sensor accepted 0-12V d c supply voltage which made it suitable for measurements in the field as it could be connected to a 12V battery Humidities of up to 95% may be accurately measured using this sensor This was considered to be adequate for external conditions The output voltage signal was sent via a twisted pair to the data-logger

Humidity inside the unit was measured using a form of psychrometer Two Pt 100 platinum resistance thermometers were laid in close proximity to each other One thermometer, called the dry-bulb thermometer, was positioned in free air The second thermometer, called the wet-bulb thermometer was covered with damp gauze The wet-bulb thermometer reaches thermal equilibrium with the damp gauze surface which is cooler than the surrounding air because of latent heat losses due to evaporation The difference in measured temperature between the two thermometers can be used to determine the humidity of the air The advantage of this measurement technique is that it can measure humidities up to and including 100% relative humidity

5.2.1.3 CO_2 Sensor

The CO_2 concentration was measured using the ADC WA-470B-E Carbon Dioxide Transducer, which also produces a 0-10V output In this case it was necessary to use a dc-dc converter to convert the d c output from the battery to the $\pm 15V$ needed by the sensor The converter used for this purpose was a Computer Products NFC10-12D15

5.2.2 Configuration of Data Logging Equipment for the Data-logging Experiment and Other Boundary Conditions

The data-logging equipment as described above was used at the DIT college campus in Kevin Street Dublin on the 14^{th} of September 1994, over the three day period including the 16^{th} and 19^{th} of September 1994 and again on the 21^{st} of September 1994, to log data from the real system The parameters measured in the first one-day trial were as follows

- External air temperature
- Inside air temperature,
- Nutrient temperatures at the surface of the weirs of the top and bottom trays on each side of the cropping house

An average value for the nutrient temperature was calculated to match the uniform nutrient temperature of the cropping house model

For the three day trial, the above quantities were measured in addition to humidity inside the cropping house

Measurements of relative humidity and incident light intensity for the locality were obtained from the Meteorological Office in Glasnevin, Dublin Since these data were only available for hourly intervals, the information had to be modified to accommodate the faster sampling rate of the data logging system which was 6 samples per hour

5.2.2.1 Experiment to Investigate the Response of System to a Step Change in Heater Power.

The first one day trial was used to obtain the response of conditions inside the cropping house to a step change in heater temperature Before the trial started, conditions within the cropping house matched those outside Two 200 W heaters were turned on full as the trial commenced No ventilation was allowed as this would have dissipated much of the heat generated by the heaters and reduced the ***air temperature lift*** (the difference between air temperatures inside and outside) of the cropping house The accumulated data from this first trial are presented in figures 5 6 and 5 7

5.2.2.2 Investigation of the Effect of Changing Conditions over a Three Day Period

The three-day trial commenced with nutrient and air inside the unit in thermal equilibrium with temperature outside the cropping house At the start of the trial, the two 200 W heaters were once again turned on full and as before, the fan was kept off Thus the nutrient temperature and air temperature inside the cropping house were expected to rise at the start of the trial and provide a temperature lift inside the cropping house

Figures 5 2 to 5 5 in the next section show historical temperature data from this first trial, along with the response to the model to the same input data Figures 5 8 and 5 9 show the variation of humidity over time for the same three day period

5.2.2.3 The Variation of CO_2 Levels over One Day

The final one-day trial was used to measure CO_2 concentration in the cropping house The carbon dioxide sensor was calibrated using zero nitrogen and ambient CO_2 levels in the air as zero and full-scale reference points respectively The CO_2 sensor was connected to the data logger using an input configured for voltage signals between 0 V and 10 V Light intensity information for the one-day period was provided by the Meteorological Office, as in the first trial The sampling period for this experiment was set as before, at 6 samples per hour

The fan was switched off for this experiment in order to observe and quantify changes in CO_2 levels due to photosynthesis, in the absence of ventilation The nutrient temperature in the tanks was thermostatically controlled by the water heaters within the temperature range 16^{o}C to 20^{o}C The data from this experiment are presented graphically in figure 5 10

5.3 Dynamic Responses of the Differential Equations Describing Conditions Inside the Cropping House

This section compares the performance of the model with the performance of the real system The following three sub-sections show the performance of the original and altered elements of the model in response to historical data from the real system In the following sub-section, the responses of the nutrient and air heat balance equations in the cropping house are described The next sub-section deals with the moisture mass balance equation and the final sub-section describes the response of the CO_2 mass balance equation This section also describes the changes in the model which were required to improve its performance on the basis of the comparison

5.3.1 Dynamic Responses of the Air and Nutrient Solution Heat Balance Equations.

The nutrient heat balance equation has a larger time constant than the air temperature heat balance equation and it is this time constant which dominates the air temperature dynamics Figures 5 2 to 5 5 show the response of the air temperature and water temperature to changes in the external environment It is apparent from the graphs that both the modelled and real data show a substantial reaction to the step change in heater power, which occurs at the start of each plot

Consideration of equations 4 25 and 4 30 in the previous chapter shows that the water heater affects the nutrient temperature directly, whereas the air temperature is heated by sensible heat transfer Q_{wa} from the plant and nutrient surface Any inaccuracies in the time constant therefore, may be attributed to problems with the dynamics of the nutrient surface temperature

The total volume of water nutrient mix used for the original model is 50 litres However, only a fraction of this solution comes into direct contact with the air inside the unit Consequently, the dynamics are much faster than those predicted by the model During normal operation it takes 10 litres of nutrient to fill the trays Setting the apparent volume of nutrient solution at 12 litres, makes the model respond well to changes in outside conditions such as air temperature However, as can be seen from figures 5 4 and 5 5, this value for water volume causes problems with the responses of the model to the step change in heater power which occurs at the start of the trial It appears that the water temperature is not uniform throughout the cropping house, as assumed for the original model

A solution to this problem is to introduce an additional first order differential equation in the model which will simulate a temperature lag between the nutrient temperature in the tank and the temperature at the nutrient and crop surface In this way the model can still be kept as a bulk parameter model which fits the original assumptions This alteration is left for future work

The second major difficulty with the model is also due to the temperature gradient between the header tank and the lower tray in the cropping house Tests show that in the real system, the surface temperature varies by about 3-5°C under normal conditions The measured temperature shown in figures 5 3, 5 5 and 5 7 below are therefore calculated as the average of four measurements of nutrient temperature taken at different points in the recirculation cycle

Figures 5 2 and 5 3 show the variation of the air and water temperature in the original model The effect of the heater on these variables in the original model is too great The heater efficiency in the original model is 95% However, to allow for the thermal gradients which exist within the cropping house, it is necessary to decrease this figure to an apparent efficiency of 25%-27%

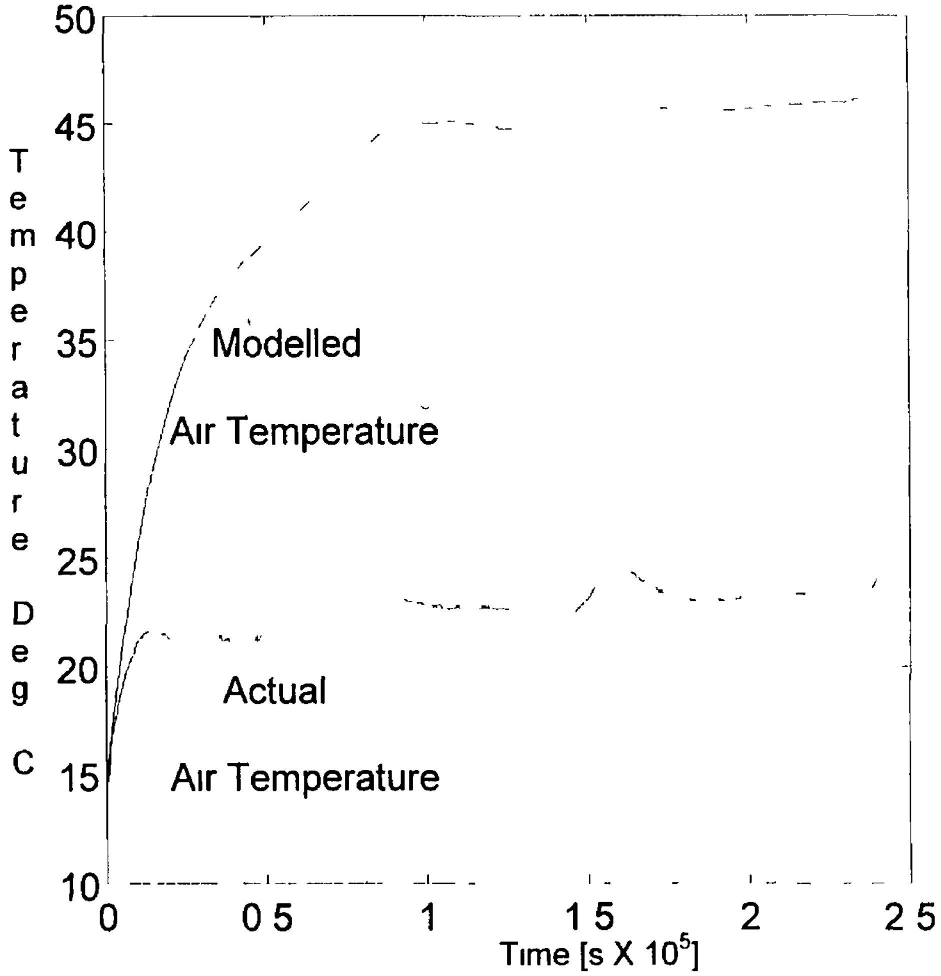


Figure 5 2: *Measured Response of Air Temperature Inside the Cropping House to External Conditions Between the 16th and 19th of September 1994 and the Response of the Original Model to Input Data Collected Over the Same Time Period*

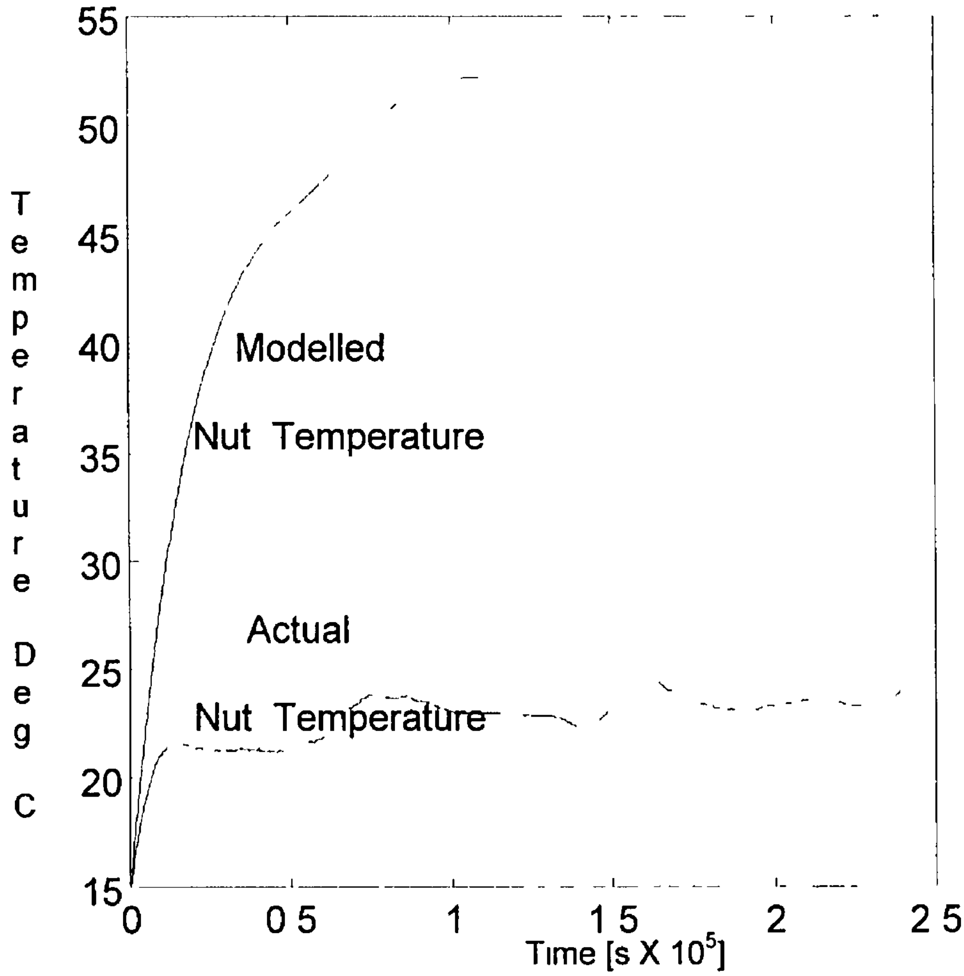


Figure 5 3 *Measured Response of Nutrient Solution Temperature in the Cropping House to External Conditions Between the 16th and 19th of September 1994 and the Response of the Original Model to Input Data Collected Over the Same Time Period*

Reduction of the apparent volume of the nutrient in the recirculation system to 12 l and the apparent heater efficiency to 25%, as recommended above dramatically improves the performance of the model as can be seen from figures 5 4 and 5 5 These changes result in what will be referred to as the ***modified model*** The modifications are a substitute for the inclusion of the additional differential equation

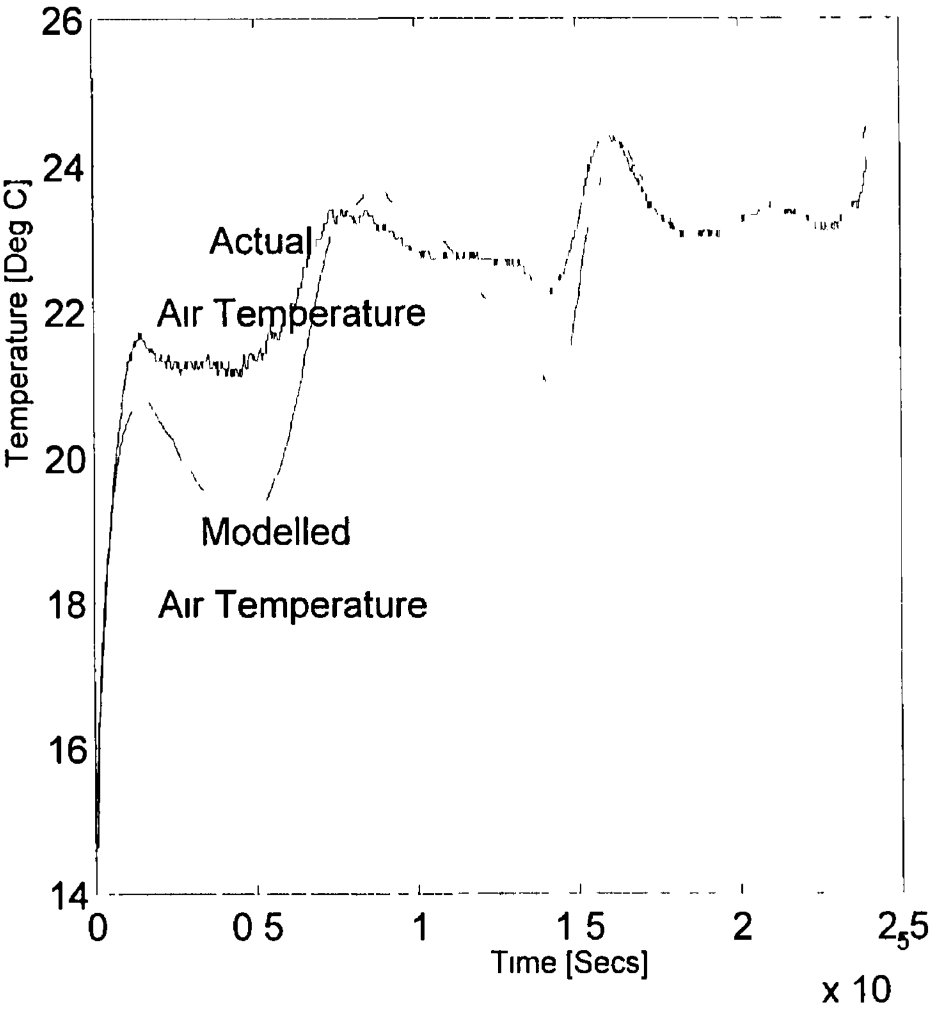


Figure 5 4· *Measured Response of Air Temperature in the Cropping House to External Conditions Between the 16th and 19th of September 1994 and the Response of the Modified Model to Input Data Collected Over the Same Time Period*

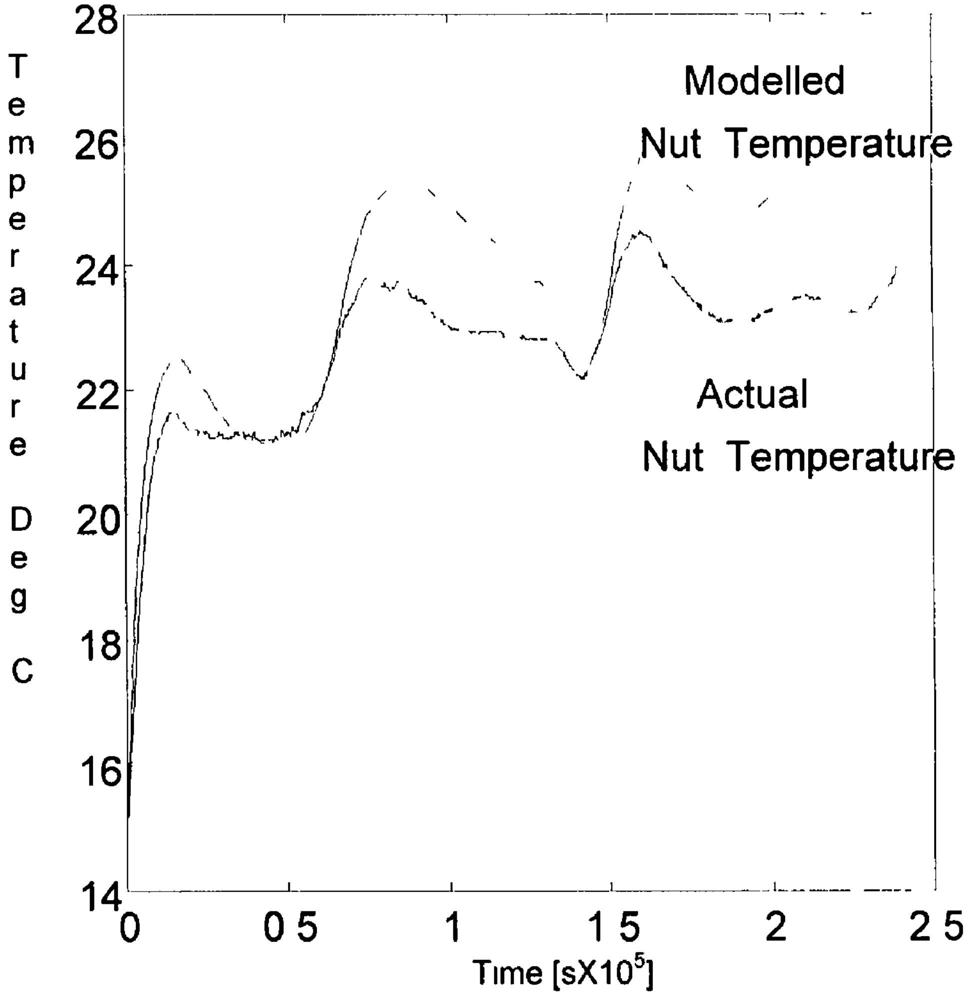


Figure 5.5: *Measured Response of Nutrient Solution Temperature in the Real System to External Conditions Between the 16th and 19th of September 1994 and the Response of the Modified Model to Input Data Collected Over the Same Time Period*

Figures 5 6 and 5 7 show the response of the modified model and the real system to a step change in power applied to the heater of 0 W to 400 W on the 14th of September 1994 Air temperatures outside the cropping house at this time were at 14°C, and the fan was off It can be seen that the unventilated cropping house provides a lift in air temperature of approximately 6°C With full ventilation, the inside air temperature drops to the external air temperature

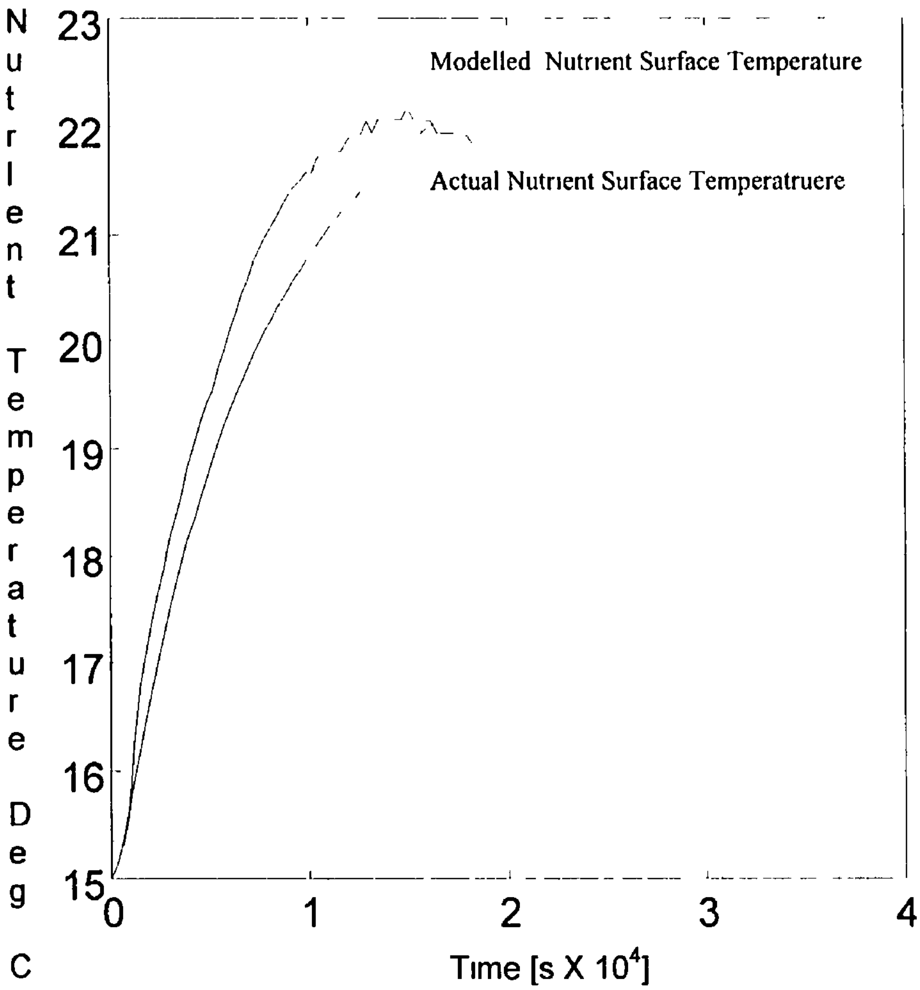


Figure 5 6· *Measured Response of Nutrient Solution Temperature In the Cropping House to a Step Change in Heater Power of 0 to 400W on 14th September 1994 and the Modelled Response of the Nutrient Temperature in the Modified Model with Input Data Collected Over the Same Time Period*

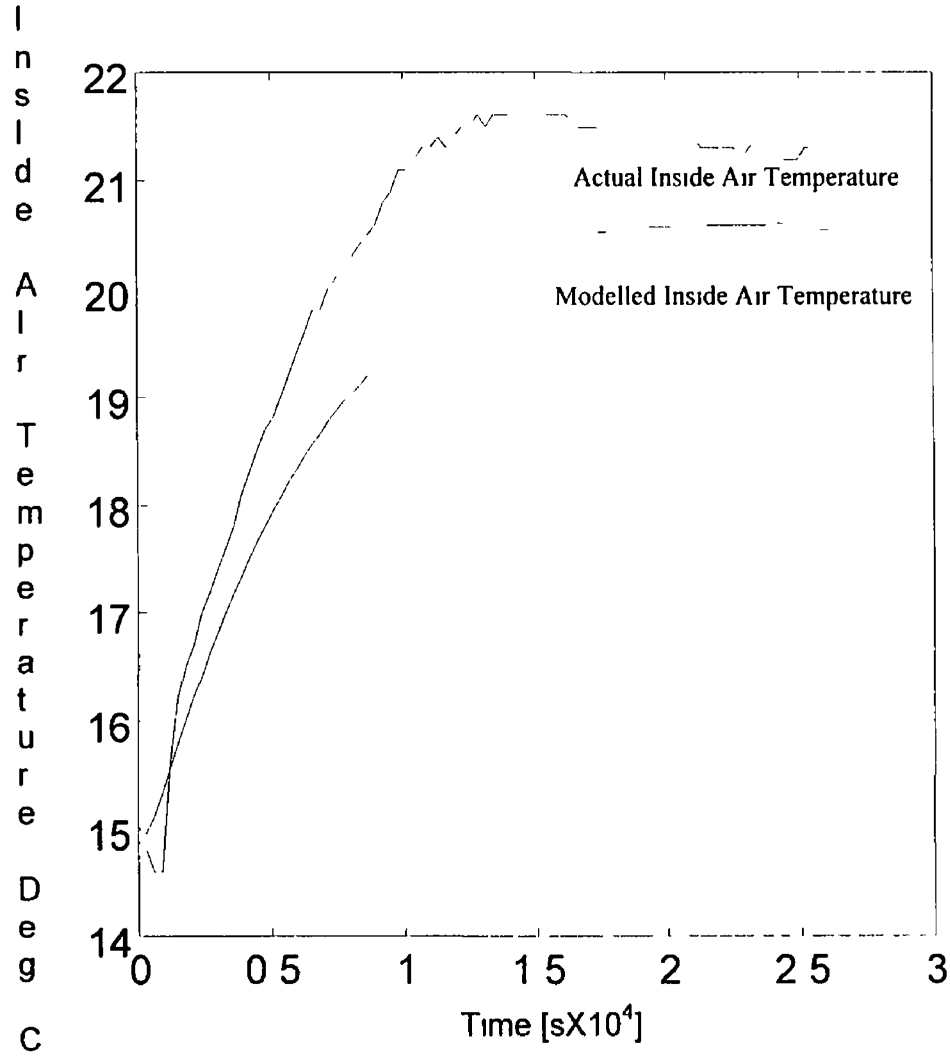


Figure 5 7: *Measured Response of Inside Air Temperature in the Cropping House to a Step Change in Heater Power of 0 to 400W on 14th September 1994 and the Modelled Response of the Inside Air Temperature in the Modified Model with Input Data Collected Over the Same Time Period*

It is apparent from the above two graphs, that the time constant associated with the nutrient heat balance equation, which dominates the dynamics, is slightly larger than it should be This could be rectified by further decreasing the apparent volume of the nutrient by roughly 20% It would be more correct however, to insert the additional differential equation mentioned earlier This is left for future work

5.3.2 Dynamic Response of the Water Vapour Mass Balance Equation

Figures 5 8 and 5 9 show the relative humidity inside the miniature cropping house over the three day trial period, starting on the 16th of September 1994 The first graph shows, as before the response of the original model

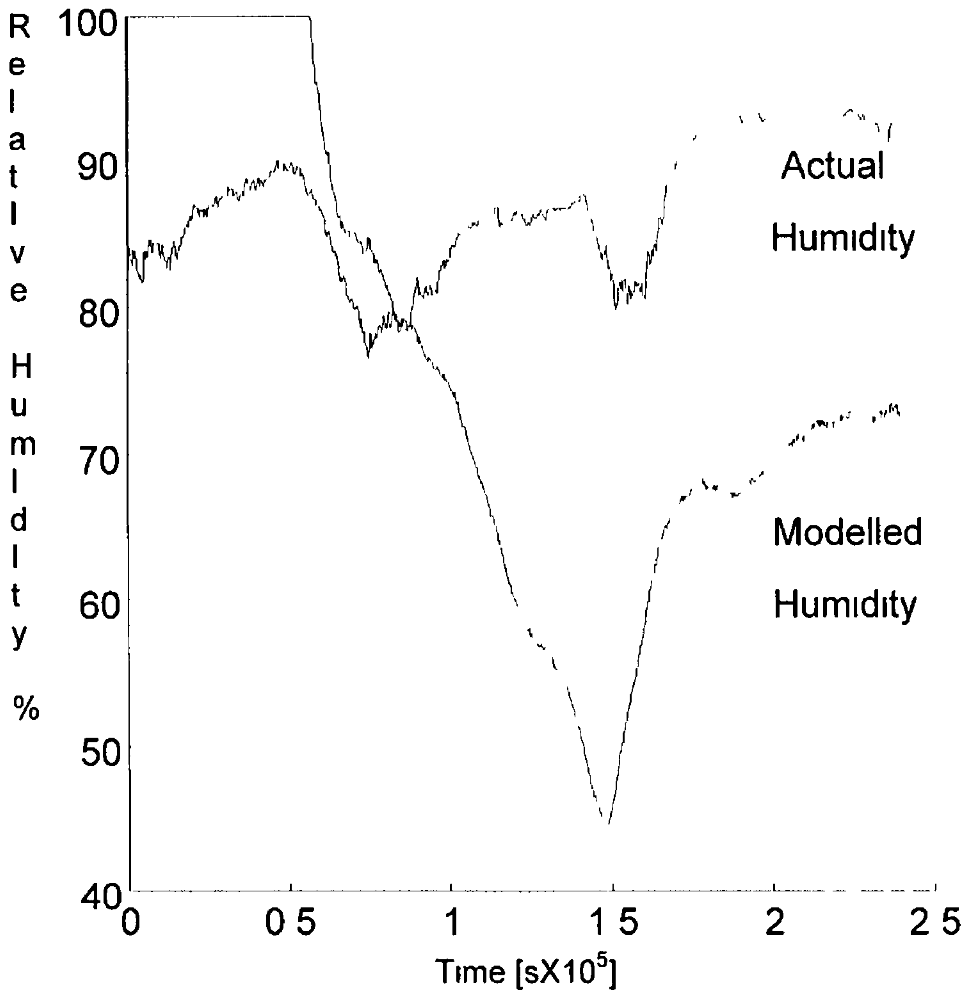


Figure 5 8 *Measured Response of Inside Relative Humidity in the Real System to External Conditions Between the 16th and 19th of September 1994 and the Response of the Original Model to Input Data Collected During this Time*

The humidity inside the cropping house is greatly influenced by the temperature of the nutrient solution and since the modelled nutrient solution temperature is incorrect, this produces large variations in the modelled humidity The correction of the nutrient temperature improves the agreement between the modelled and the actual humidity, but an offset still exists between the two data series The offset may be removed by including a resistance to the transfer of vapour due to sensible heat through the crop and the lid of the tray, r_d By inserting this term in equation 4 23 the following equation results

$$E = \frac{\Delta Q / r_d + f(q_v)(e_s - e_a)}{\lambda(\Delta + \gamma^*)} \qquad \textit{Eqn 5 1}$$

Figure 5 9 below shows the response of the model after replacing equation 4 23 with equation 5 1 This graph shows better agreement between the modelled and the actual humidity

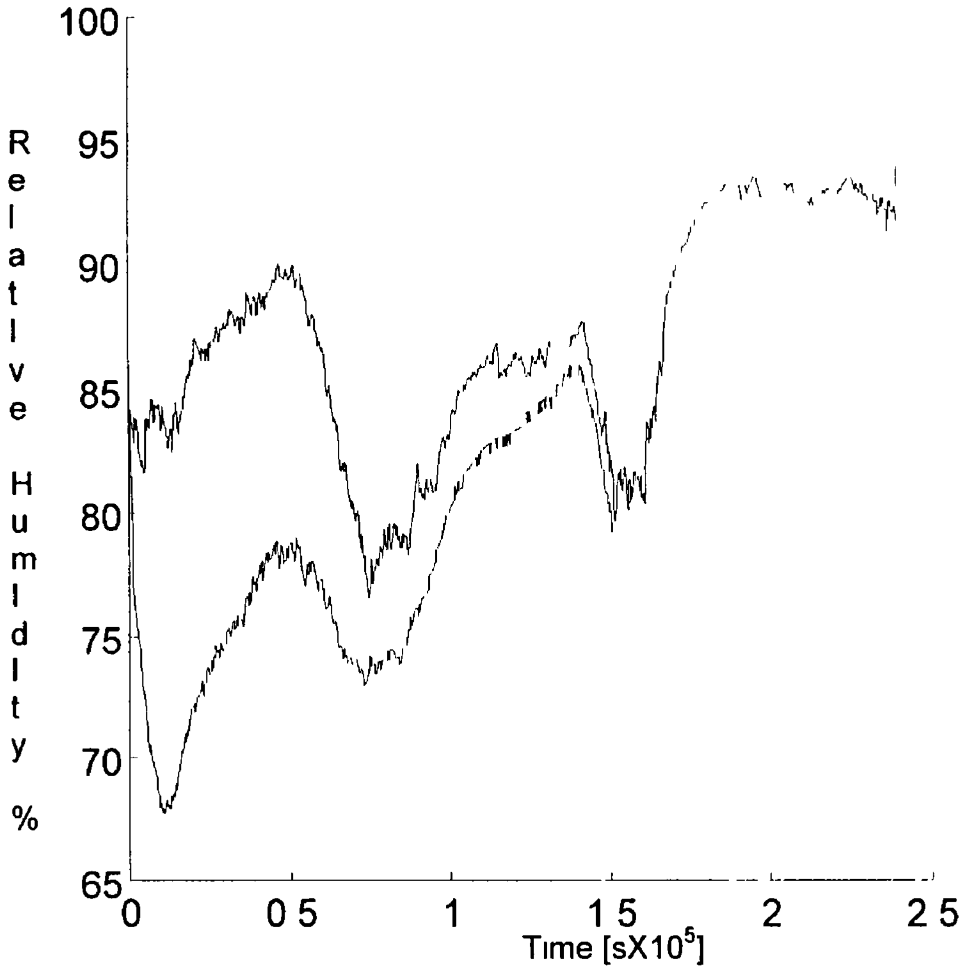


Figure 5.9: *Measured Response of Inside Relative Humidity in the Real System to External Conditions Between the 16th and 19th of September 1994 and the Response of the Modified Model to Input Data Collected During this Time*

The two plots stay within 5% of each other except where the modelled air temperature and nutrient solution temperature are inaccurate because of the problems with the dynamics of the nutrient heat balance equation which were discussed in the last section Even after this change however, it was found that the water vapour mass balance equation was sensitive to variations in temperature This element of the model requires more work to produce a robust and accurate humidity term It seems that the deterministic approach used in this thesis, is not suitable for describing humidity Deterministic equations describing humidity were found to be inaccurate or overly complex, often requiring information which is difficult to measure, such as resistances to vapour diffusion at the canopy An empirical approach, based on a simpler model structure is suggested as an alternative (Seginer and Levav 1971),(Young 1995) With accurate humidity sensors which measure high humidities, it should be possible to perform system identification to determine the coefficients of simplified versions of equations 4 23 and 4 38 of the last chapter

5.3.3 Dynamic Response of the CO_2 Mass Balance Equation

A separate one-day trial was conducted to investigate the CO_2 levels within the cropping house Figure 5 10 below shows the CO_2 concentration within the cropping house on the 21st of September 1994 and the response of the unmodified model There is an offset of 30 ppm between the real and modelled graphs This can be accounted for by the lack of a term describing respiration in the CO_2 mass balance equation Monteith (1973) indicated that plants respire at a rate of 1 to 2 g CO_2hr^{-1} independent of incident light levels

The main problem with any analysis of figure 5 10, is the fact that the CO_2 sensor proved to be troublesome Since the accuracy of the sensor is not known it is difficult to assess whether the model is performing well or the modelled CO_2 levels are coincidentally in the same range as those measured in the real system

The CO_2 sensor was originally used on the three-day trial, but the data from the sensor had to be discarded after the sensor malfunctioned after a day of operation It is assumed that the malfunction was due to the high humidities inside the cropping house The addition of a dehumidifier on the input to the CO_2 sensor might solve this problem

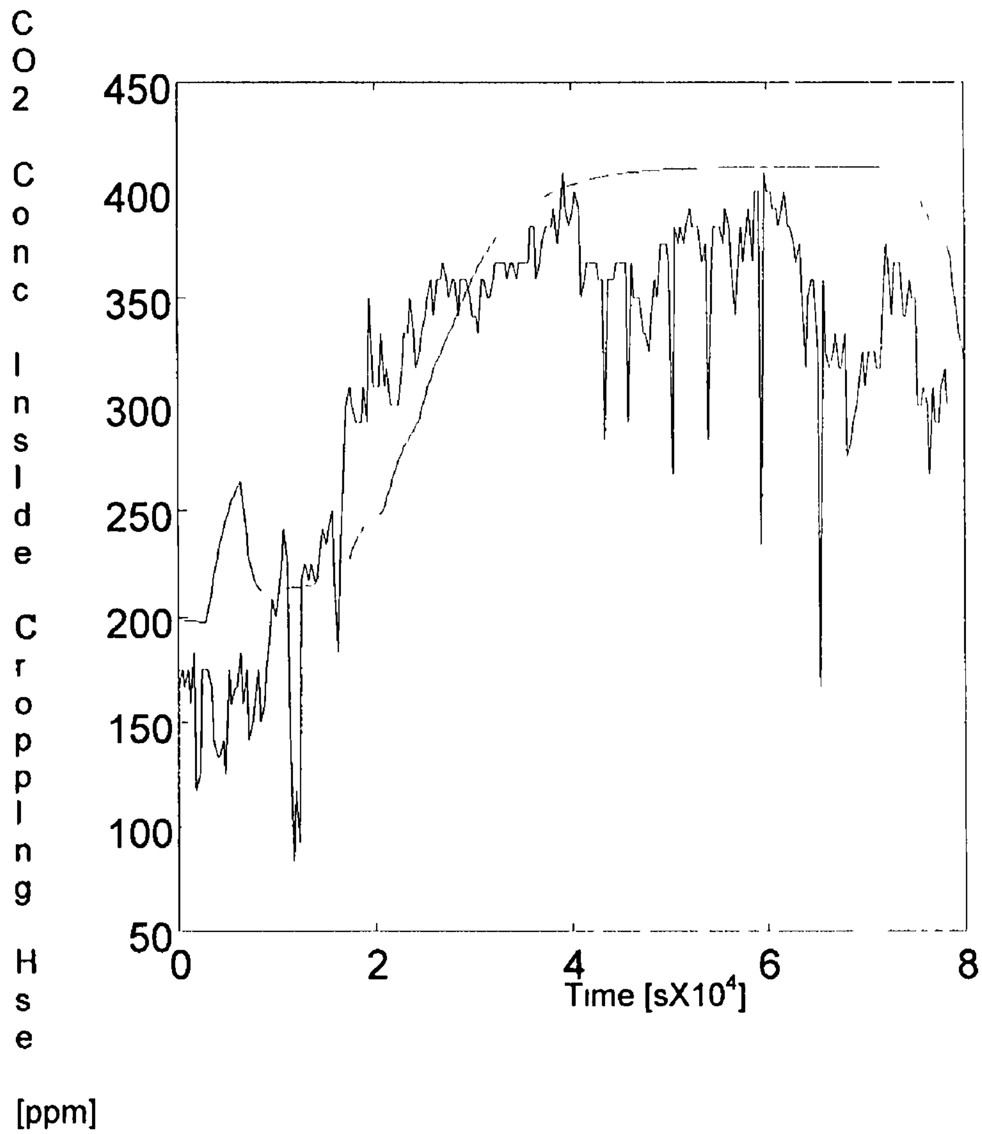


Figure 5 10 *The Measured CO_2 concentration within the Miniature Cropping House On the 21st September 1994 and the Response of the Model with Input Data Collected Over the Same Time Period*

The zero nitrogen required to calibrate the sensor was only occasionally available This is a practical problem which must be overcome before serious work on modelling CO_2 fluxes is carried out It would also be beneficial if a more accurate measuring system could be arranged This would allow future researchers to perform more detailed analysis of this part of the model

5.4 Using the Model to Determine the Significance of Heat Transfers within the Cropping House

This section is a demonstration of a simple use of the deterministic model of the cropping house One of the major concerns in any cropping house is where and how heat is being lost Using the modified model, the following information about heat transfers in the cropping house was obtained

With no solar radiation, zero ventilation, air temperature at 24°C, nutrient temperature 26°C, and external air temperature 16°C, the following modelled heat transfers were recorded

Q_{oc}	41 5W
Q_{wc}	1 1W
Q_{wca}	0 2 W
Q_{wa}	89 7 W
Q_{ae}	76 6 W
Q_c	31 9 W
Q_h	123 2 W

Table 5 1 *Heat Flows in the Cropping House*

The first observation about the above data is that the heat lost by conduction from the nutrient solution to the internal air Q_{wca} and to the outside air Q_{we}, are significantly less than the other heat losses This is due to the thermal insulating polystyrene cladding around the nutrient reservoir tanks By comparison, the heat lost by conduction through the glazing Q_{oc} is much greater

Though the heaters produce 400 W of heat, only 123 W arrive in the trays, 90 W are lost to the internal air due to convection from the heated nutrient surface Q_{wa} This is desirable if the ventilation is kept low since the air is heated to a temperature above the external air temperature However if the fan were turned on high the resulting heat loss by ventilation would bring the air temperature and nutrient temperature to potentially unacceptable levels The majority of the rest of the heat generated by the heater is dissipated by evapo-transpiration in the plant canopy E_c

Quite a significant portion of the heat inside the cropping house is lost by long wave radiation through the glazing This heat loss is difficult to reduce In general, the higher the optical transmission co-efficient the faster the plants grow However, high optical transmission coefficients usually mean comparatively large radiative heat losses also

Another interesting observation involves the existing fan in the cropping house Using equation 4 11, the equation which determines the heat lost through ventilation, for the same inside and outside temperatures and taking a maximum ventilation rate of 73 ls^{-1}, one obtains

$Q_v = 0\,073(1\,2)(1010)(26 - 16)$=884 W

Which means the original fan is capable of dissipating 884W of heat at full power This value is significantly larger the other heat losses outlined above, it appears that this fan is over-sized for the cropping house used in this work So based on the figures taken from the model, it is recommended that the present fan be replaced by a less one with a flow rate of 10 ls^{-1} as this would reduce the heat transfer due to ventilation Q_v to around 100 W

5.6 Summary

This chapter has assessed the performance of the model and its response to data from the real system Modifications based on the responses of the original model and the behaviour of the real system have improved its performance to an acceptable level The results from the modified model suggest that the inclusion of an additional equation would improve the dynamic performance of the inside air and nutrient heat balance equations The moisture mass balance equation was found to be sensitive to the nutrient solution temperature and this equation requires further work The CO_2 mass balance equation was the simplest of the four and appeared to produce acceptable results The main limitation with this final equation, involved the CO_2 sensor which was difficult to calibrate and relatively unreliable

The next chapter will deal with the simulation of the control system and the elements of the real control system which was developed for the cropping house

Chapter 6: Control System for Vegetable Propagation Unit

6.1 Introduction

The overall purpose of this project is to develop a digital control system for a miniature hydroponics plant growth unit The unit, which is called the vegetable propagation unit, is intended as an alternative to conventional vegetable growing techniques which will allow potential amateur growers with little growing space, to grow their own tomatoes, lettuce potatoes and other small-rooted plants It is envisaged that later versions of the unit will be used as inexpensive tools for research into factors affecting crop production

The control system for the cropping house is similar to one produced by Claudia et al (1993), who developed a low cost Motorola 68000 microprocessor-based system for controlling the environment in a miniature glasshouse Claudia's micro-controller monitored air temperatures at five different points in the greenhouse, humidity and CO_2 concentration Air temperature was controlled using hot and cold water pumps whereas nutrient temperature in this work is controlled by a set of electric water heaters In Claudia's controller, fans were controlled in an on-off fashion rather than the variable speed control presented here Another feature which was similar to the controller in this work was a serial communication module which sent sampled data along a 100 m long serial link to a dedicated personal computer which logged the data Included in the monitor program on the personal computer was a feature which performed statistical analysis of the data collected over one week

A block diagram of the control system for the vegetable propagation unit is shown in figure 6 1 The controller measures air temperature inside the unit, nutrient temperature and light intensity The first controlled output is heater power which directly affects nutrient temperature and indirectly affects air temperature The second is fan power which affects the air temperature and the CO_2 and moisture content of the air

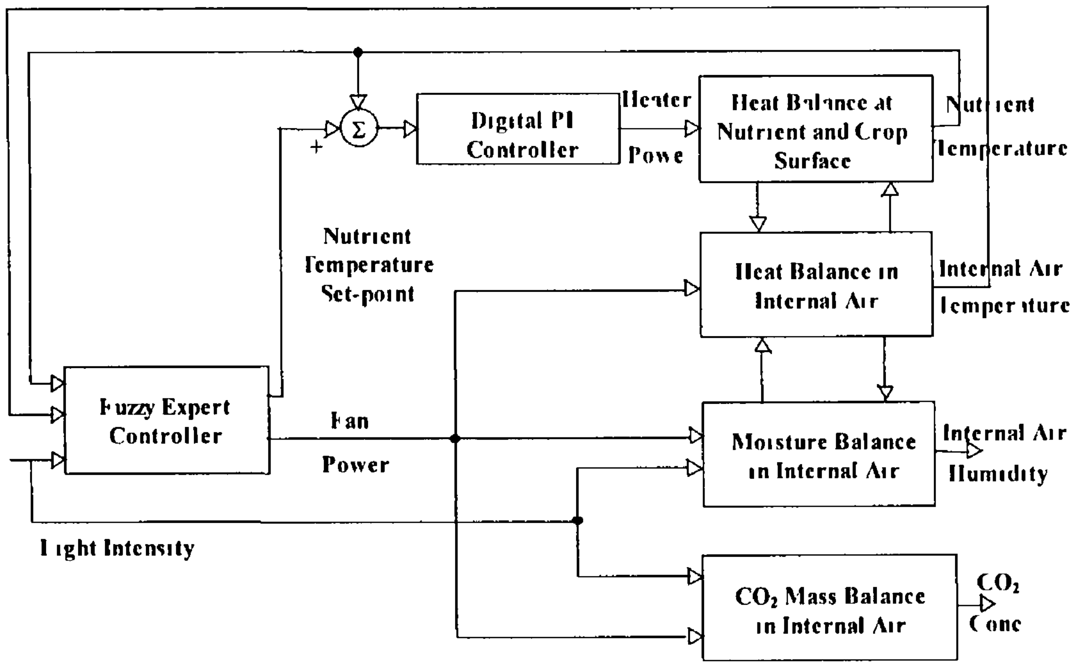


Figure 6 1 *Block Diagram of Control System for the Miniature Cropping House*

This chapter will give a brief explanation of heating and recirculation of nutrient in the unit and will also discuss the ventilation system This will be followed by a description of the controller hardware and development system and the data-logging system The controller software will be described under the headings of fuzzy logic expert control and PID control Finally, the response of the real system under control and the response of the simulated control system with the same boundary conditions, will be examined

6.2 The Construction and Operation of the Vegetable Propagation Unit

This section will describe overall design and the explain the operation of the miniature cropping house used for this study, which is called a vegetable propagation unit (VPU) The first sub-section will give an overview of the VPU This will be followed by more detailed descriptions of the ventilation in the unit and of recirculation of nutrient solution in the tanks and trays

6.2.1 Description of the Vegetable Propagation Unit.

The vegetable propagation unit is a compact hydroponics-based vegetable cropping house The unit which is illustrated in figure 6 2, consists of an A-frame structure on which six trays are suspended Three trays are positioned on each side of the unit Two sump tanks at the base of the unit and a single header tank at the apex fit into matching slots in the gable pieces The tanks are capable of holding 56 litres of nutrient but a typical value is around 36 litres

The gable ends are fixed to the tanks using a hand-tightened cross-wire which makes the unit rigid The ends are made from two layers of fibre-glass which enclose 4 cm of polystyrene foam to provide insulation The slots for the tanks are constructed from welded strips of Dexian During ventilation, a cavity in the centre of the gable ends is filled with incoming air which passes through perforations in the inner layer of fibreglass

The trays are positioned at an incline of one in fifty A weir and reservoir at the top of each tray provides a constant head of water which ensures that each tray receives a steady supply of the water nutrient mix Excess water runs down the weir pipe in the centre of each reservoir and into the next tray In this way, water cascades from the header tank at the apex of the A-frame, through each set of trays and into the two sump tanks in the base of the unit A connecting pipe between the two sump tanks ensures that the water level in the base is kept balanced

Pumps located in each of the sump tanks recirculate water returning from the trays The pumps are controlled by a float switch in the header tank which regulates the water level and ensures that water is evenly distributed between the sump tanks and the header tanks

Two 200 W aquarium heaters raise the water temperature in the header tank and are the only form of active heating in the unit A removable plastic cover on each tray minimises heat losses from the interior of each tray and so protects the plant roots against low air temperatures

A small d c fan set in one gable end of the unit expels air from the interior thus drawing air from outside through a series of perforations in the gables

6.2.2 Ventilation of the Vegetable Propagation Unit

The simplest form of cropping house ventilation relies on natural ventilation from the outside air This may be achieved using a gauze cover through which ambient air is allowed to percolate freely Unfortunately, this means that spores and insects reach the foliage of the plants In addition, using this method, the incident light levels inside the unit are diminished and night temperatures are the same as external ambient temperatures

The introduction of box section plastic glazing in place of the gauze cover, and controlled ventilation in the form of a small fan provides improved light levels while only allowing heat to escape the system when it is necessary to do so Control of the fan speed facilitates control of the air temperature as well as the CO_2 and humidity levels within the unit A PAPST 12 W 12 V d c fan which could supply 100 litres per second was chosen for this purpose The speed control of the fan will be addressed in the next section Air temperature is measured using a Pt100 RTD suspended inside the unit

6.2.3 Nutrient Recirculation in the Vegetable Propagation Unit

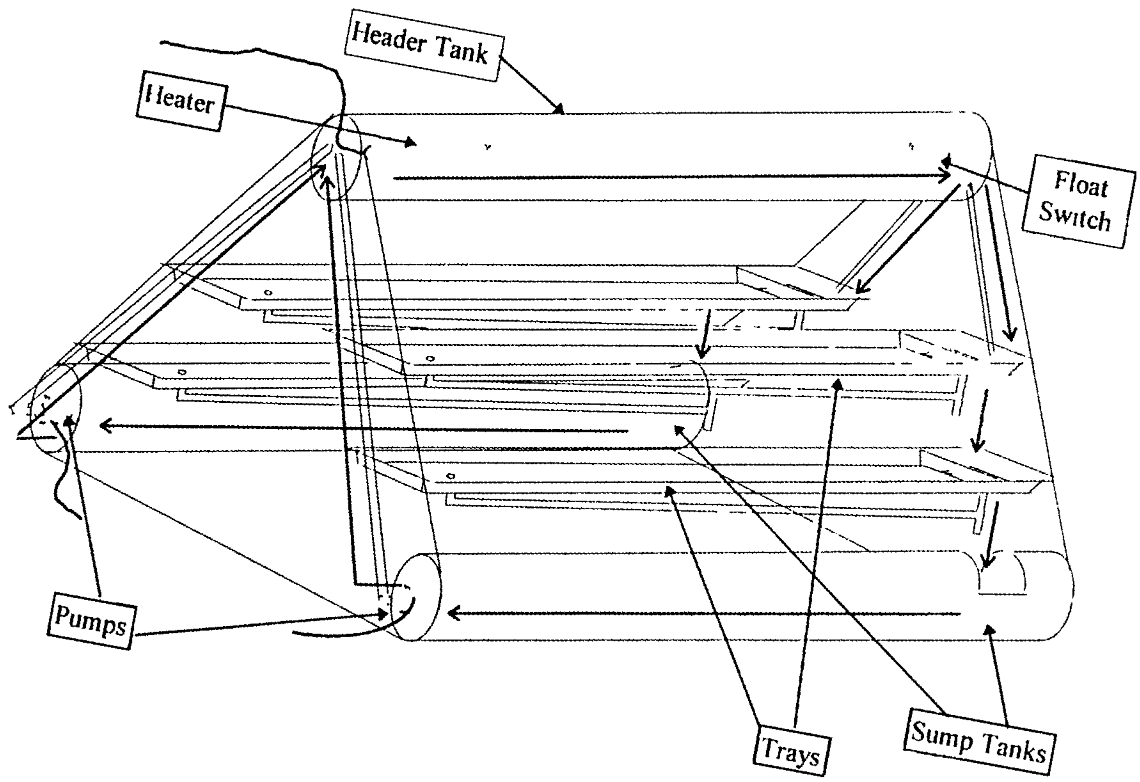
Tests conducted using a single pump to recirculate water from the sump tanks to the header tank at the top of the A-frame resulted in the formation of backwaters in the unit which meant under-utilisation of potential heat storage capacity A second pump was added to improve circulation and provide a fail-safe in the case of pump failure

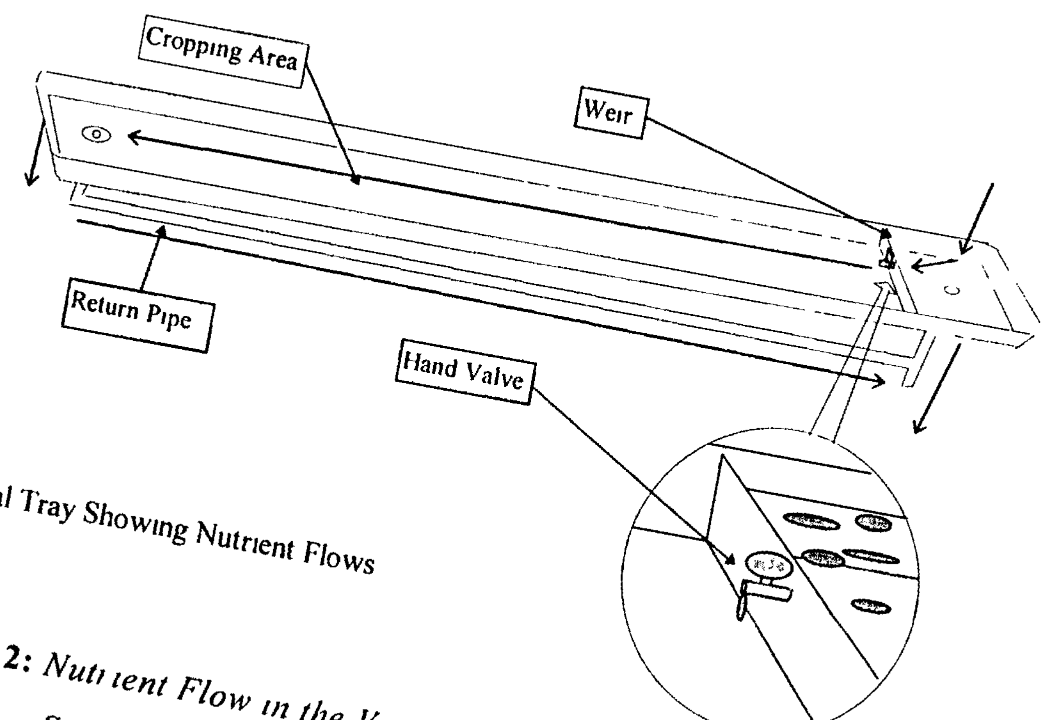
The full nutrient recirculation system is shown in figure 6 2 Nutrient is pumped to the header by the twin pumps mentioned above The incoming nutrient flows from the two sump tanks are allowed to mix before directing them into the centre of the header tank This feature was added to minimise temperature gradients in the header tank

The pumps are switched by a float switch which is located in the header tank, and a mechanical relay This arrangement ensures that a constant head of water is supplied to the trays below (Berry & Berigan 1993)

6.2.4 Nutrient Flow within a Tray

Nutrient is allowed to propagate down through the trays from the header tank using a gravity feed system Figure 6 2 shows the nutrient flow in a tray Nutrient enters the tray by a weir at the head of the tray A small portion of the nutrient flows through a small hand valve and down the length of the tray Each tray is tilted to allow a gradient of one in fifty, which is the preferred slope (Graves 1985) Excess nutrient flows over the weir where it is mixed with water returning from the end of the tray before entering the reservoir of the next tray





Individual Tray Showing Nutrient Flows

Figure 6.2: *Nutrient Flow in the Vegetable Propagation Unit and in a Single Tray*

6.2.5 Heating of Re-circulated Nutrient Solution

The simplest method for controlling nutrient temperature within the unit is to use two thermostatically controlled water heaters The problem with this scheme is that such heaters rely on a thermostat within the heater casing itself to control the temperature Investigation of a range of 200 W commercial water heaters revealed that the thermostats typically controlled water temperature to within 1°C but not necessarily at the required temperature One water heater over-heated the water by up to 4°C

Initial data-logging of the unit revealed that during normal operation of the unit, there was typically a 5 to 10°C temperature drop between the nutrient immediately surrounding the heater and the nutrient in the bottom tray Furthermore, this temperature depends on outside air temperature and so is subject to disturbance changes Since the temperature in the trays is the controlled variable and not the temperature of the water surrounding the heater, this method of heating the nutrient is not suitable for this application

Using ***digital control***, and a temperature sensor located in the weir of the bottom tray, it is possible to measure and control the water temperature in the trays directly Digital control also presents the additional advantage of relating the nutrient temperature set-point to air temperature, time of day, time of year, phase of cropping cycle and light levels With a correctly rated heater, it is also possible to keep temperature to within a fraction of a degree of the set-point temperature

Accurate digital control for part of the day, with a 5-10°C temperature lift at night can be accomplished using two of the aforementioned heaters with their temperature settings on maximum Power to the heaters may be controlled using pulse width modulation The next section presents the Motorola MC68HC11 micro-controller integrated circuit, which is the device chosen to implement digital control for this work

5.3 MC68HC11 Micro-controller Unit

This section summarises the main features of the 68HC11 micro-controller unit (MCU) This is followed by a more detailed description of the key elements of the MCU, which are necessary for the operation of a digital environmental controller

6.3.1 Summary of the Elements the 68HC11-Based Digital Controller

Computerised systems are commonly used for climate control in modern greenhouses Udink Ten Cate (1983), identified northern European countries such as Ireland, Denmark and The Netherlands as places where the non-ideal external climatic conditions necessitated using a digital controller to regulate the environment within a greenhouse Digital controllers such as the one described here have found applications in many environmental control systems This controller is intended for a miniature cropping system and so must be relatively simple and inexpensive to produce

A simple schematic diagram of the controller hardware is shown in figure 6 3 Comparison with figure 6 1, shows how each output affects the variables described in the mathematical model of the last chapter

Air temperature and nutrient temperature are measured using two Pt100 RTD's The resistance of the RTD's varies linearly with temperature Two bridge circuits convert the resistances of the RTD's to signals which are then amplified to voltages which are approximately proportional to temperature and are limited between 0 V and 5 V A light sensor measures the intensity of solar radiation within the unit and supplies a third 0-5 V voltage signal The three analogue voltages are accepted by the micro-controller

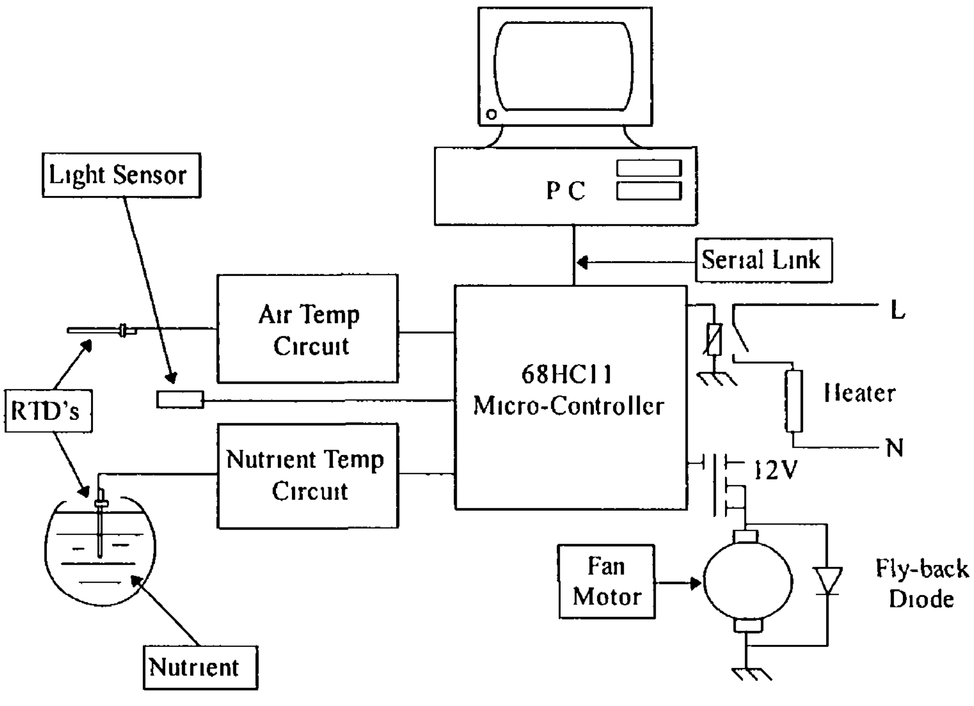


Figure 6 3: *Simplified representation of Digital Controller Hardware*

A serial link to the P C allows data relating to the control performance of the controller to be sent to the P C , where a program saves the data to dısk Two PWM sıgnals control the power to the water heater and fan by usıng an a c relay and an IGBT respectıvely to swıtch the currents to these controlled devıces Four lıght emıttıng dıodes are added for debuggıng purposes and for alarm ındıcatıon

6.3.2 Overvıew of the 68HC11 Mıcro-controller

The mıcro-controller used for thıs work ıs the Motorola MC68HC11E9, whıch ıs a member of the 68HC11 famıly of mıcro-controller ıntegrated cırcuıts The 68HC11 ıs an 8-bıt mıcro-controller wıth a nomınal clock frequency of 2MHz, whıch uses an extended versıon of the ınstructıon set of the 6800 famıly of mıcro-processors The extended ınstructıon set features ınstructıons for multıplıcatıon and dıvısıon of ıntegers

Addıtıonal on board facılıtıes ınclude -

- 8 analogue ınputs
- 16-Bıt tımer-counter / tıme of day facılıty
- Real tıme ınterrupt
- Serıal communıcatıon ınterface
- Serıal perıpheral ınterface
- Output compare to 16 bıt free-runnıng counter/tımer

Fıgure 6 4 shows the features avaılable on the 68HC11 and whıch ports are ınfluenced by each

The versıon of the 68HC11 used ın thıs work ıs called the 68HC11711E9CFS The E9CFS versıon of the ı c ıncludes 12kB of

EPROM, 512B of RAM and 512B of EEPROM A more detailed explanation of this i c may be found in Motorola 1991a and 1991b

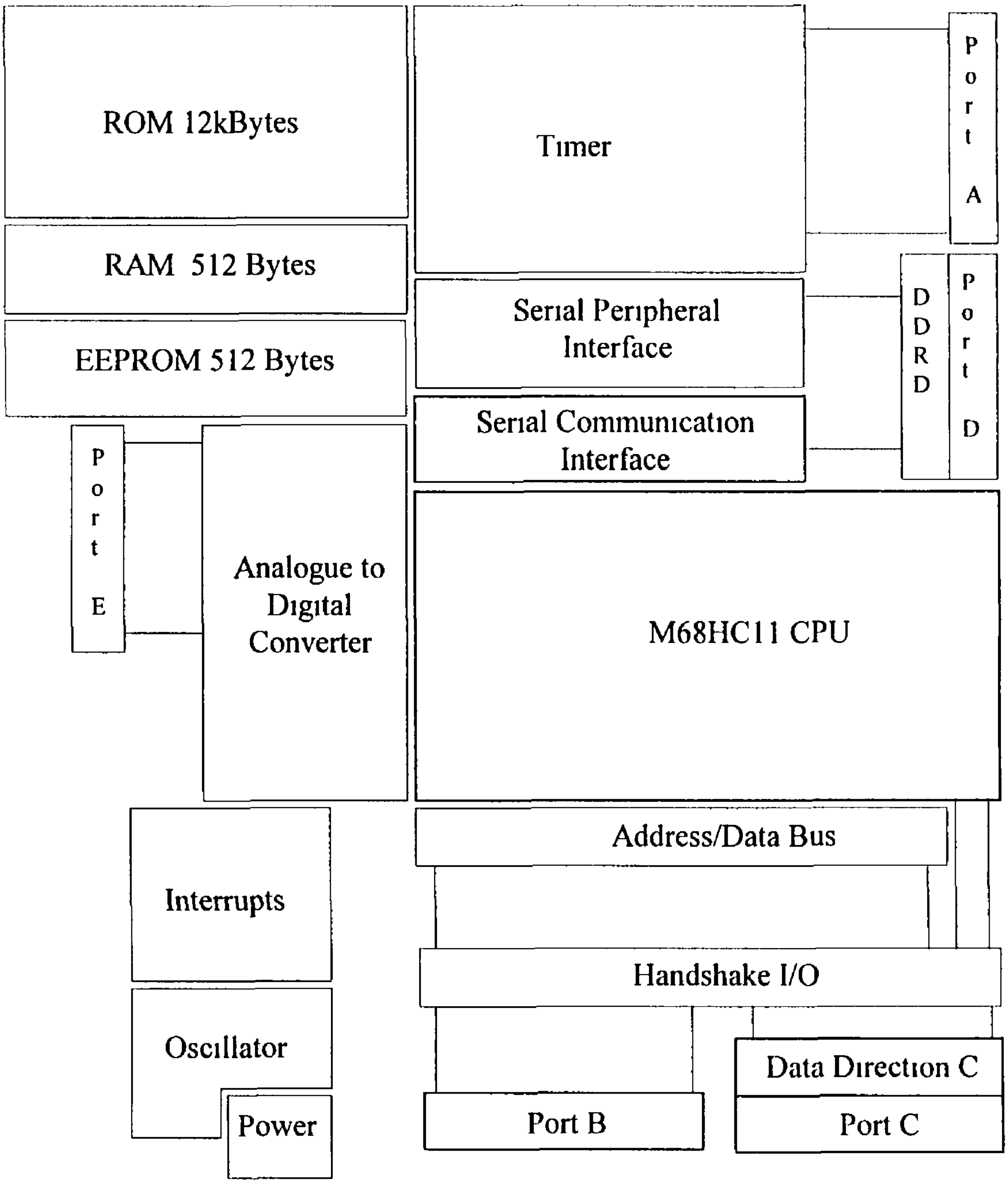


Fig 6.4 *Features of The 68HC11E9 Micro Controller Unit*

6.3.3 Using the 68HC11 as a Stand-alone Micro-controller

For this work, the 68HC11 micro-controller unit (MCU) was operated in single chip mode In this mode, the integrated circuit functions as a monolithic micro-controller without external address or data buses Port B, Port C, function as general purpose I/O, and Strobe A and Strobe B function as handshake lines This restricts total available memory to the capacity of the MCU itself, which is 12288 Bytes of ROM and 512 Bytes of RAM Due to this memory restriction, the service routines have been implemented in 68HC11 assembly language to minimise stack usage and size of controller code

The following sub-sections describe the main features of the assembly level software routines Flowcharts for these subroutines may be found in appendix B

6.3.4 Sampling of Temperature and Light Intensity

The 68HC11 includes an 8-channel multiplexed-input successive approximation analogue to digital converter (ADC), with a sample and hold circuit to minimise conversion errors caused by rapidly changing input signals Two dedicated lines (V_{RL} and V_{RH}) are provided as reference voltage inputs and these were connected to 0 V and 5 V respectively In the next section it will be seen that the control system was designed so that the analogue input voltage would not exceed these voltage limits The ADC was configured to convert four of the analogue input voltages in quick succession on receipt of a CONVERT instruction The analogue to digital conversion was controlled by the assembly routine **ADC**

The sample time for the ADC was determined by the internal timer facility on the 68HC11 The timer has 16-bit free-running counter which is clocked by the output of a programmable four stage prescaler which is in turn driven by the MCU E clock This counter is used by the micro-controller's Real Time Interrupt (RTI) function to effect a periodic interrupt which can be used for sampling The slowest actual sampling rate permitted by the RTI function is 32 ms which is much too fast for monitoring or controlling relatively slow systems such as the miniature cropping house However, by only acknowledging every thousandth sample for instance, the effective sample time was lengthened The RTI-based sampling system was initialised by the subroutine **RTIINI**

6.3.5 Serial Communications to the P.C.

The 68HC11 provides a full-duplex asynchronous Serial Communications Interface (SCI) with a standard NRZ format (one start bit, eight or nine data bits and one stop bit) and a variety of baud rates The SCI facility was used to provide a data link to a personal computer if needed A low level routine called **SCI** transmitted blocks of data from the controller to the Personal Computer at every sample instant

6.3.6 Using Pulse Width Modulation to Control Fan Speed

The output compare feature of the MCU comprises five 16-bit read/write registers with dedicated comparators for comparing against a 16-Bit free-running counter A match between the contents of one of these registers and the contents of the counter will generate an interrupt

The output compare facility was used in the low level interrupt service routine **OC1ISR**, to generate a fast changing pulse width modulated signal for controlling the speed of the d c fan Every time the counter matched the contents of the OC1 compare register, the OC1ISR routine added one period onto the OC1 compare register and one period plus an offset onto the OC3 compare register This offset was the difference between the last and the present control output The fast PWM was initialised by the routine **PWMINI** Calculation of the new compare value to achieve the PWM was achieved using the routine **CALOFF**

6.4 Controller Instrumentation and Control Output Circuits

This section briefly describes each of the instrumentation and control circuits which comprise the environmental controller Figure 6 5 below shows how these circuits are integrated to form the completed system

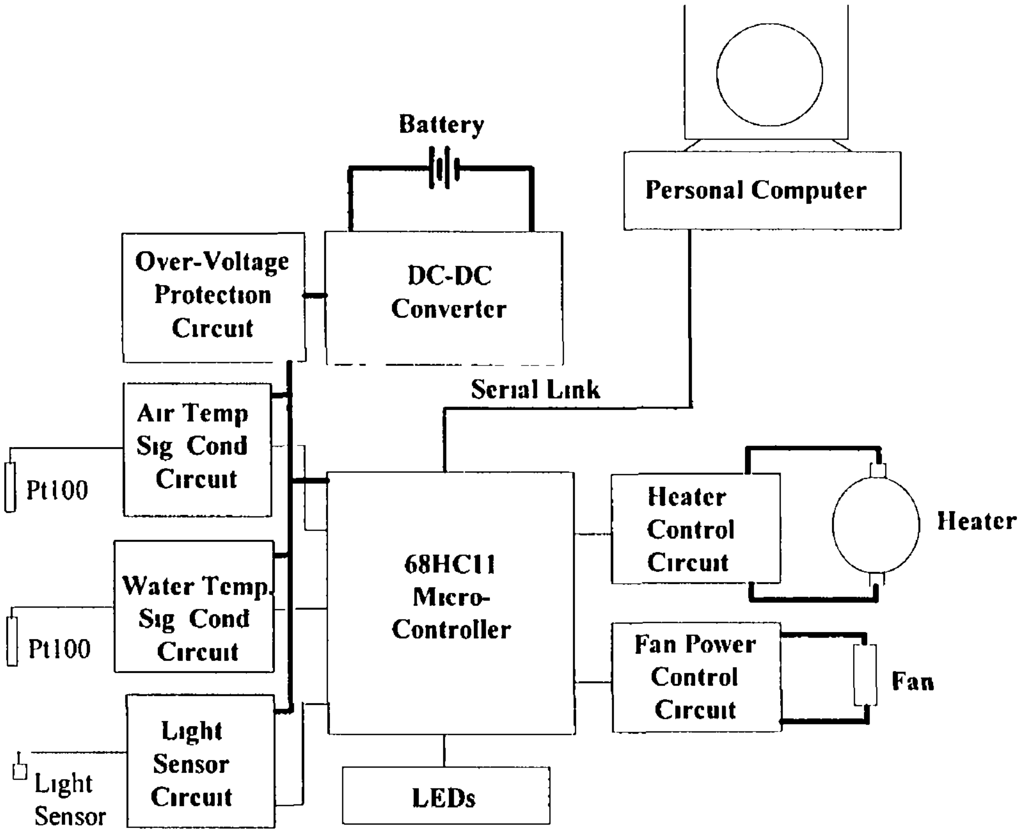


Fig 6.5: *Block Diagram of the Circuits for the Environmental Controller*

6.4.1 dc - dc Converter

The converter used in this work was a Radionics supplied NMXD1212 The input range of the converter is +/- 20% Maximum output noise is 25mV peak to peak and power efficiency is approximately 80% Coupling is provided around the converter circuit to reduce the effects of the noise

6 4.2 Over-Voltage Protection

Figure 6 6 below shows the over-voltage protection circuit for the dc-dc converter While the battery is being recharged, and the input voltage to the converter is below 14 V, a current path exists between the supply terminals and the converter inputs via the relay, which is in the non-activated state

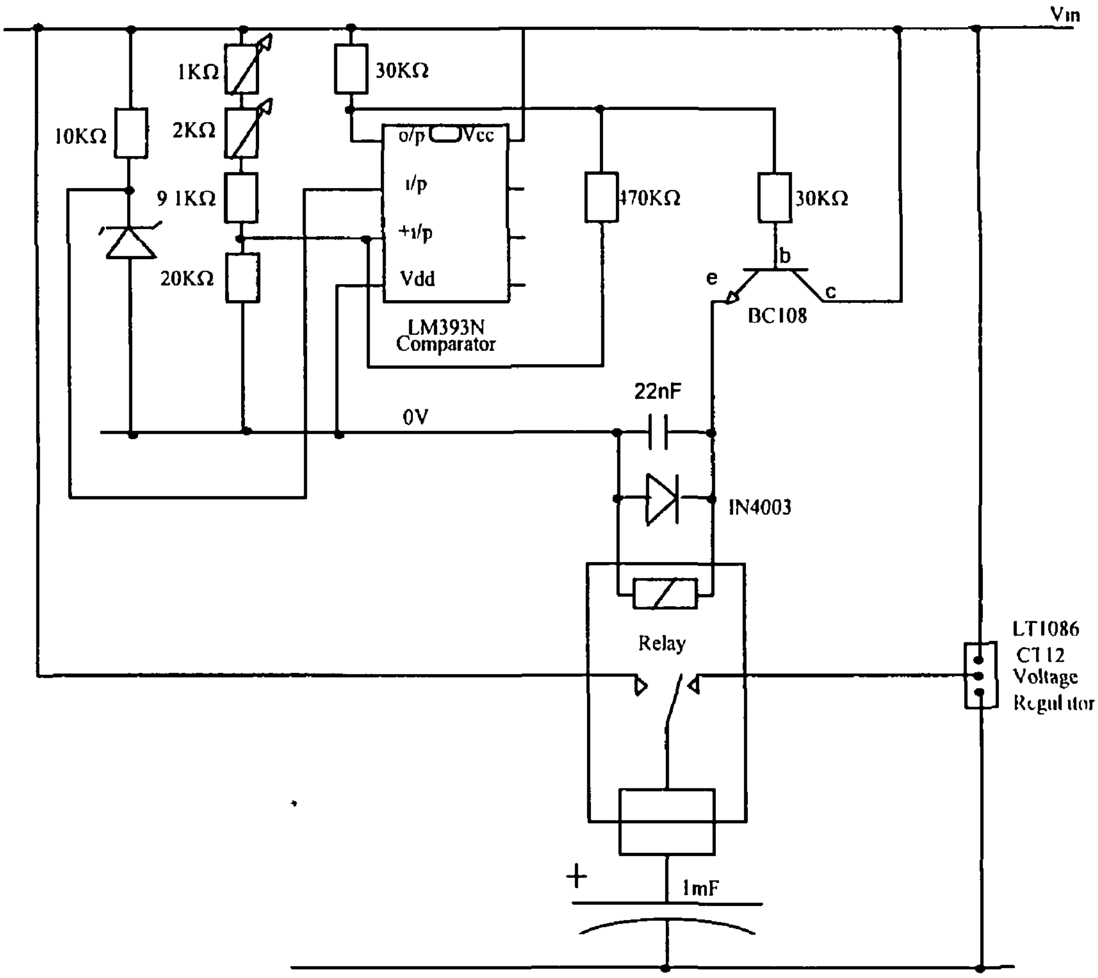


Figure 6 6. *Over-Voltage Protection Circuit for dc-dc Converter*

When the supply voltage goes above 14 V, the voltage on the non-inverting input of the comparator rises above the reference voltage supplied by the Zener diode on the inverting input and the comparator energises the relay via the transistor Hysteresis is required to aid the switching of the comparator because of the slowly rising value of the supply voltage during recharging When the comparator energises the relay, the converter is supplied from the power supply terminals, via a 12

V regulator and the relay The voltage at which the comparator switches can be altered by adjusting the potentiometer in the voltage divider

6.4.3 Micro-controller Operating Frequency

An 8 MHz resonator was used to clock the processor This was considered to be preferable to using the internal clock for the following reasons

- The resonator provides a much more stable oscillating frequency
- It oscillates at 11 times the frequency of the internal clock, thus allowing the processor to carry out more operations per second

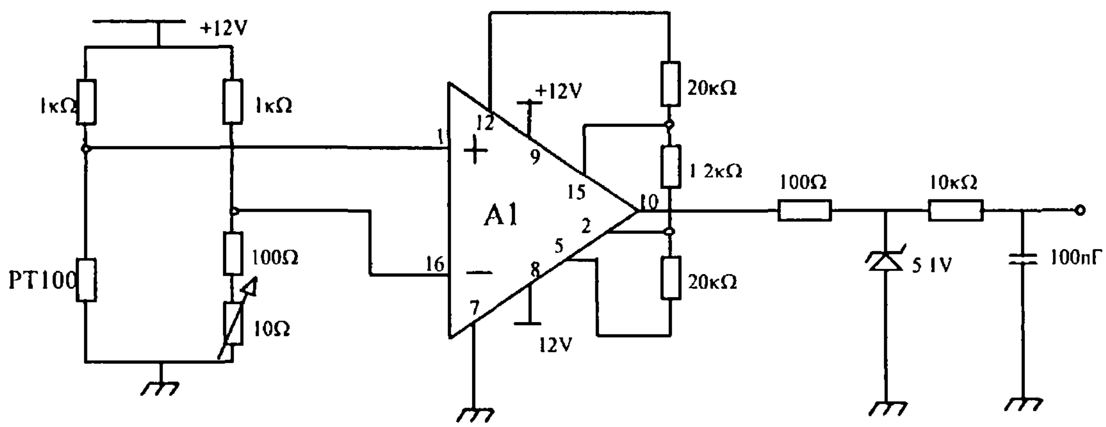
6.4.4 Temperature Sensing Circuit

Two Platinum Resistance transducers were used in conjunction with Wheatstone bridges and instrumentation amplifiers to measure temperature The resistance of these transducers varies directly with temperature between 100Ω at 0°C and 138 5Ω at 100°C

The temperature monitoring was chosen to be within the range 0°C-40°C , which corresponds to a variation in resistance of 15 54Ω Resistor values in the bridge circuit were selected so that the maximum output voltage from the bridge was 0 1519 V

This voltage, if inputted directly to the analogue to digital converter (ADC) circuit, would under-utilise the accuracy of the ADC For this reason the signal was amplified, subject to the constraint that the maximum allowed voltage for the analogue input ports on the 68HC11 is 5 V This requires an amplifier with a gain of 33 Figure 6 7 below shows the resulting circuit

The two final stages in the temperature circuit are to prevent the output voltage from the amplifier exceeding the 5 V limit and to filter any noise that may be transmitted to the 68HC11 The filter also serves to prevent any capacitive coupling between adjacent pins on the A/D The 5 V voltage limiter between the amplifier and the microprocessor consists of a resistor and a Zener diode in series between common ground and the amplifier output which acts like a voltage divider but will actually limit the voltage into the processor to 5 V The Zener diode limits any over-voltages from the amplifier, (i e when the air temperature in the VPU goes above 40°C), by drawing enough current to common ground, to keep the amplifier voltage output at 5 V



COMPONENTS A1 - ADJ625J Instrumentation Amplifier

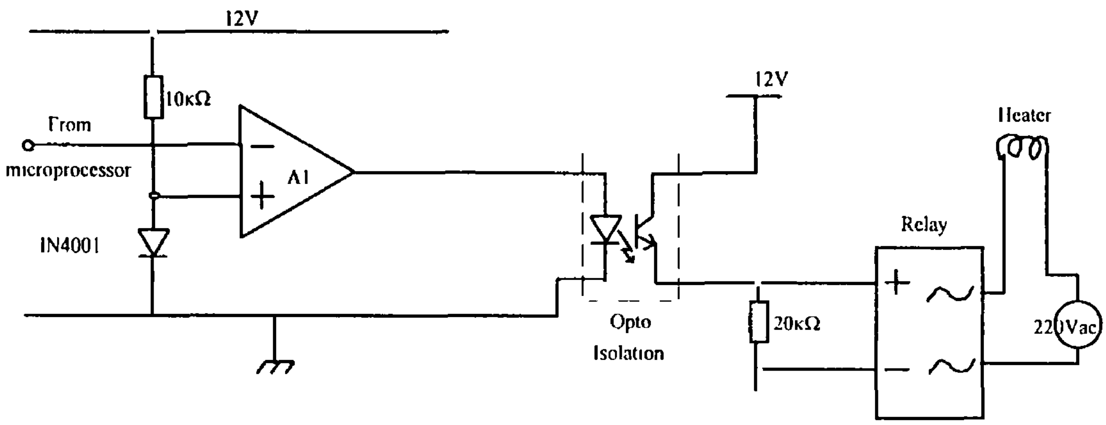
Fig 6.7. *Temperature Sensing Circuit*

6.4.5 Light Sensor

A Texas Instruments TSL250 Optical Sensor was used to measure light intensity This device produces an output voltage range of 10 mV to 5 V with a supply voltage range of 3 V to 9 V It is very sensitive to light with a responsivity of typically 90 $mV\mu W^{-1}cm^{-2}$ The output of this device was applied directly into an analogue input of the MCU

6.4.6 Control Output for Heater

The controller uses PWM to affect changes in the controlled variables A PWM signal with a period of 1mS is used to control the fan speed The signal controls an IGBT which switches the current to the fan A second PWM signal running at a frequency of 0 5 Hz controls the heater current via a solid state relay



Components A1 1/4 LM 339
RELAY - MP240D4 (Farnell)
Opto-Isolator - 4N25
Resistors 5% 25 watt

Fig. 6 8: *MCU Output Circuit for Controlling Heater Current*

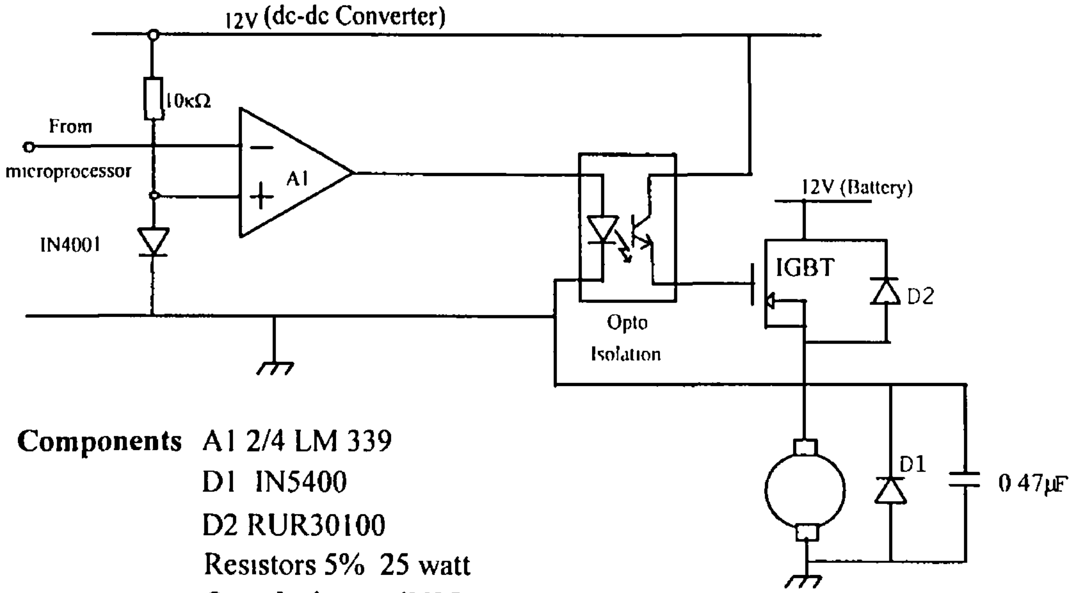
The controller output circuit for the heater which is shown above consists of a comparator and opto-isolator which control an a c relay The heater used was a 200 W aquarium heater The relatively slow dynamics of the heater enabled the use of the slow PWM signal to control the water temperature

6.4.7 Control Output for Fan Current

An insulated gate bipolar transistor (IGBT) was chosen to control the fan speed using the faster, output compare-based PWM signal This was for the following reasons

- The power requirements of an IGBT are considerably lower than that of a relay A typical mechanical relay draws 30 mA of current when activated, this current is large when compared with the 1 mA drawn by an IGBT in the same circumstances
- IGBT's are have a larger bandwidth and a longer mean time between failure than mechanical relays
- The cost of using an IGBT is significantly lower than that of a mechanical relay Snubber networks that are often used with IGBT's to limit di/dt and dv/dt are not needed in this case because of the low voltages and currents, and the high ratings of the IGBT's

Figure 6 9 below shows the fan speed control output circuit The fast output compare driven PWM signal is applied to the input of the second comparator in the dual comparator integrated circuit The comparator output drives the opto-isolator which in turn switches the IGBT The IGBT controls d c current to the fan



Components A1 2/4 LM 339
D1 IN5400
D2 RUR30100
Resistors 5% 25 watt
Opto-Isolator - 4N25
IGBT GT25J101

Fig 6 9 *MCU Output Circuit for Controlling Fan Speed*

6.4.8 The Complete Micro-controller System

The connections between the MCU and the sensing and control circuits are shown in figure 6 10 The two light emitting diodes were included to supply "computer operating properly" signals and were initially used to test the PWM routines Pull-up resistors in the form of 10 kΩ resistor networks, were added to terminate unused MCU pins The Texas Instruments TL7705ACP i c was used to control reset of the MCU

6.5 The Software Development System for the Digital Environmental Controller

The software development system for the controller consisted of eight basic elements

- A text editor
- The IAR "C" cross compiler for the 68HC11
- The IAR relocatable macro assembler for the 68HC11
- The IAR XLINK linker program for the 68HC11
- CSPY software emulation tool for the 68HC11
- PCBUG11, a software package which communicates with a purpose-built 68HC11 micro-controller chip via a serial link
- The Motorola 68HC11 EVBU evaluation board

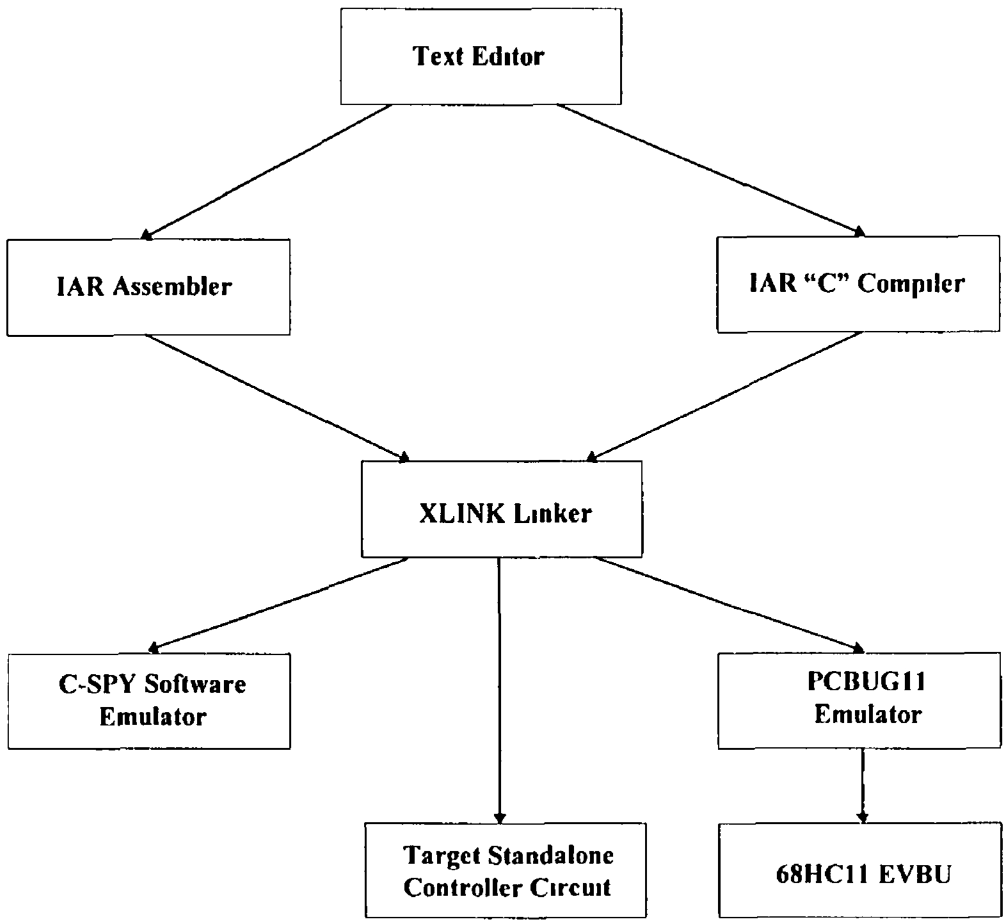


Figure 6 10 *The Software Development System for the 68HC11-Based Environmental Controller*

Figure 6 10 above shows how the various elements of the development system fit together The IAR compiler/assembler linker facility for the 68HC11 is a powerful tool which allows users to mix C source code for the 68HC11 with assembly level code IAR also supplies a compatible emulation tool for the 68HC11 called CSPY which was used for initial debugging of the source code after link time

The 68HC11 may be purchased as part of an inexpensive development kit This kit includes a 68HC11 evaluation board called the 68HC11 EVBU, an assembler and an "Emulator" package for the P C , called PCBUG11, which communicates with the evaluation board via a serial link PCBUG11 does not provide all the services of a full emulator, but does allow some programs to be single stepped and can look at memory and at the contents of registers This package was used for further debugging of the C source and 68HC11 assembly code

6.6 Controller Software

6.6.1 Introduction

The following sub-sections describe the software used in the controller to implement digital control of the environment within the cropping house The software may be divided into three main components which perform the following tasks -

- Assembly level service routines for serial communications, sampling of data, and pulse width modulation
- Direct digital control of nutrient solution temperature
- Fuzzy expert control of the environment in the cropping house

Each sub-section below will deal with one of these elements

The description of the code in the last two sub-sections apply also to the simulated version of the controller which is described in the next section

6.6.2 Direct Digital Control of Nutrient Solution Temperature

Control of the temperature of the recirculated nutrient solution was accomplished by using a digital PID controller which was written in "C" The control output value m_n at each sampled instant can be calculated from the previous control output value m_n and the last three control errors e_n, e_{n-1} and e_{n-2}, using the following equation

$$m_n = m_{n-1} + K_p\left\{\left(e_n - e_{n-1}\right) + \frac{Te_n}{T_i} + \frac{T_d\left(e_n - 2e_{n-1} + e_{n-2}\right)}{T}\right\} \qquad \textit{Eqn 6.1}$$

where K_p is the proportional gain, T is the sampling interval and T_i and T_d are the integral and derivative action times respectively The advantage of this form of the digital PID algorithm is that the change in the controlled variable, m_n-m_{n-1} can be applied directly as an input to a PWM waveform generator such as the one described in appendix B, thus reducing the amount of computation required at run-time

In this work, the set-point for the digital PID controller was provided by the fuzzy controller A fuzzy controller is low pass in nature and the inputs to the fuzzy controller, which are light intensity and inside air temperature will not change suddenly The set-point for the digital PID controller will therefore change slowly and so derivative kick is reduced

The control system may be considered to be a form of cascade control, with the higher level fuzzy controller providing the set-point for the PID controller, as may be seen from consideration of figure 6 1 at the start of this chapter The structure of the controller represented by equation 6 1 is similar to ones described by Ogata (1987), VanLandingham (1985) and Astrom and Wittenmark (1984) The controller settings used here are given in table 6 1 below

Parameter	Value
K_p	0 5
T_i	2000
T_d	500
T_s	200

Table 6 1 *Controller Settings for Digital PID Controller*

The sampling time T_s of 200 s was derived from the open loop step response of the system The apparent open loop time constant of the part of the system which includes the heater, nutrient temperature and the pt100 sensor is usually in the range 2000 to 5000 s Using VanLandingham's (1985) recommendation that the sampling period should be 5 to 20 times smaller than the smallest time constant in the system, a sampling time of 200 s is obtained This technique was used here However Franklin and Powell (1986), Levine(1995) and Astrom and Wittenmark (1990) all prefer use of the closed loop bandwidth to arrive at a final sampling time, since the closed loop bandwidth may be an order of magnitude different to the open loop bandwidth

The PID controller coefficients were initially taken from tests of the model The unsatisfactory performance of this set of parameters when applied to real system led to selection by trial and error The micro-processor based digital PID controller was used to control the water temperature of a vessel containing 35 l of water which was a typical value for the total nutrient volume in the cropping house The parameters which resulted from this trial were modified after observation of the process during the month of June 1995 In section 7 3 in the next chapter, this issue is discussed further

6.6.3 Control of Aerial Environment Using Fuzzy Logic.

Control of the climate within the cropping house was accomplished with the help of a fuzzy logic-based expert controller Traditionally, commercial growers have controlled the environment inside greenhouses by opening vents and switching boilers using rules based on the external climatic conditions In general for instance, the higher the incident light intensity at the plant canopy, the higher the desired air temperature, since a plant photosynthesises more efficiently at higher ambient air temperatures, below a threshold of approximately 26^{o}C

This example can be converted to the following fuzzy rule

IF LIGHT INTENSITY IS HIGH, THEN MAKE WATER TEMPERATURE SET-POINT HIGH

In this way, the degree to which the light intensity is HIGH, determines the degree to which the water temperature set-point should be made HIGH also

Probably the most crucial stage in designing a fuzzy controller is the acquisition of the expert knowledge of the system required for the creation of the rule-base and sets of the fuzzy controller The knowledge required for creation of the rule-base and sets was acquired in the following way

- A set of rules similar to the one shown above were first compiled after an informal discussion with a plant physiologist and an experienced grower
- The information was supported by reference to texts on plant physiology Table 2 1 in chapter 2 shows a summary of the results of this search

- The rule-base was then tested on the deterministic model of the system to see how it would perform
- Finally, the sets and rules were tested on the real system by running the controller continuously for four days and monitoring its performance

The following three main control rules were formulated for the fuzzy controller

Control Rule #1

If air temperature is very high then turn fan on high and nutrient temperature low

Justification Plants die after prolonged periods of temperatures which exceed 26°C

Control Rule #2

If the air temperature is very low, then make nutrient temperature high and turn fan off

Justification Plants die if temperatures drop near to freezing Heaters can only provide an appreciable temperature lift if the fan is off

Control Rule #3

If the above two conditions are not met then keep nutrient solution temperature at approximately 24°C and keep the unit well ventilated Higher light levels will need higher ventilation rates

Justification The main considerations during the day are cooling the cropping house and keeping the CO_2 levels high and humidity low At night however respiration involves a much lower mass transfer rate than photosynthesis and the main concern is to keep the cropping house heated so the ventilation should be kept low

Using the above control rules, the fuzzy sets and fuzzy rule-base shown below were created to effect control of the model and of the environment in the cropping house The selection of ranges for the controller inputs and outputs is derived from experience gained in initial trials with various prototypes of the cropping house between May 1993 and August 1994 The temperature range selected for the two pt-100 RTDs was $0^{o}C$ to $40^{o}C$ as the temperatures in the cropping house only transcends these limits in the most extreme conditions

Light sensors for horticulture usually associate a spectral band with light intensity figures A range of 0-250 Wm^{2} was found to be applicable to the bandwidth of the ORP 12 when used with lettuce plants

In appendix A, the voltage-speed characteristic of the fan is derived The data sheet for the fan states that the fan will not operate for applied voltages which are lower than 5 V In fact, the fan operates when the applied voltage is kept between 3 5 V and 12 V which corresponds to 30% to 100% of full fan power However since the fan was overrated, it was required to operate at no higher than 50% of full power as seen below If required fan power dropped below 30%, the fan stopped The nutrient temperature set-point for the PID controller was allowed to vary between $19^{o}C$ and $27^{o}C$

Note that the outermost sets of the output universes appear to exceed their boundaries This is because control action resulting from each of these outermost output sets never exceeds the centre of gravity of those sets Lyons (1993)

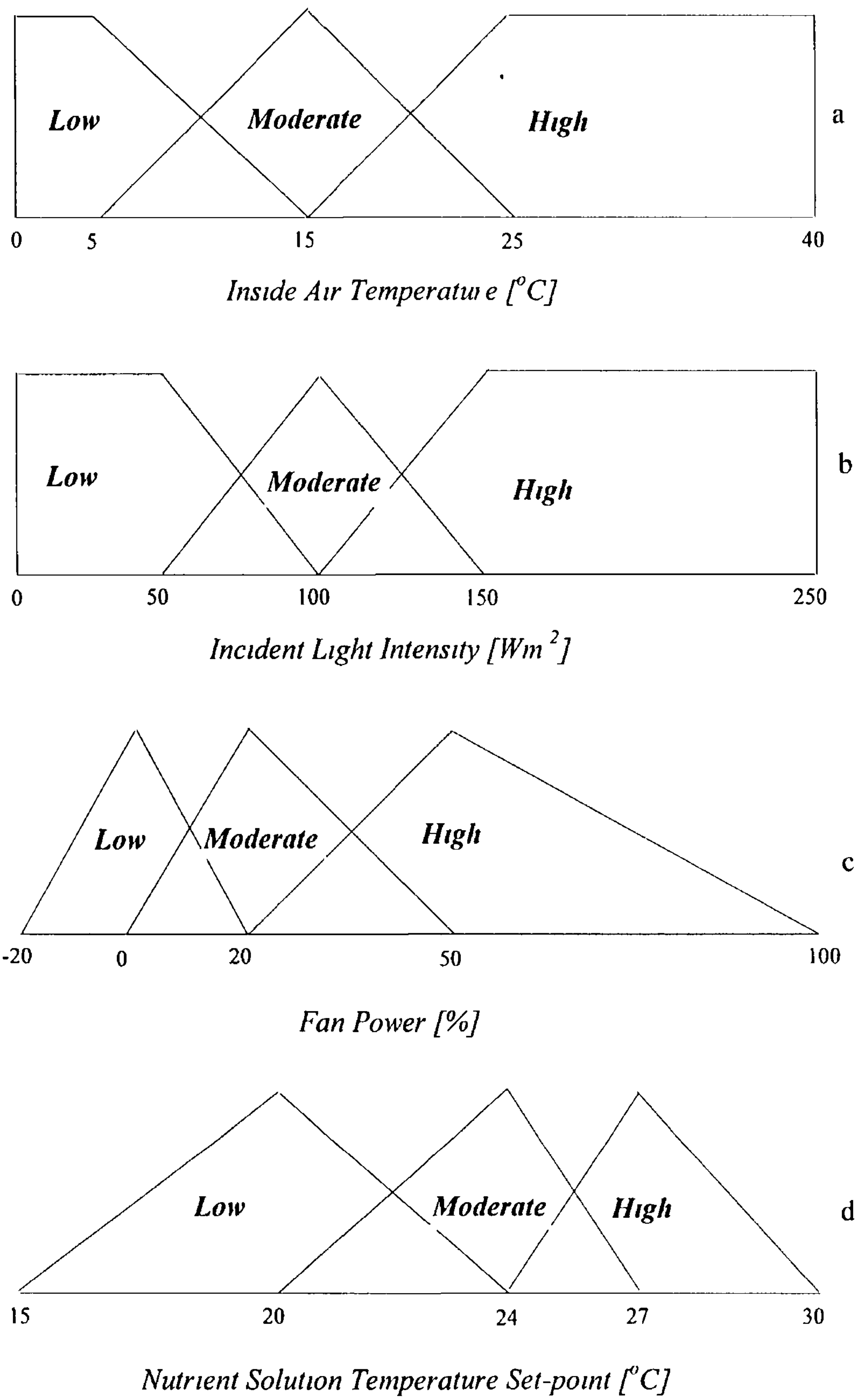


Figure 6 11. *Input and Output Universes of Discourse for Fuzzy Controller*

The rule-base for the fuzzy controller is shown below

If **Inside Air Temperature** is *low* and **Incident Light Intensity** is *low* then set **Nutrient Temperature Set-point** *high* and **Fan Power** *low*

If **Inside Air Temperature** is *low* and **Incident Light Intensity** is *moderate* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *low* and **Incident Light Intensity** is *high* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *moderate* and **Incident Light Intensity** is *low* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *moderate* and **Incident Light Intensity** is *moderate* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *moderate* and **Incident Light Intensity** is *high* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *high* and **Incident Light Intensity** is *low* then set Nutrient Temperature Set-point *moderate* and Fan Power *moderate*

If **Inside Air Temperature** is *high* and **Incident Light Intensity** is *moderate* then set **Nutrient Temperature Set-point** *moderate* and **Fan Power** *moderate*

If **Inside Air Temperature** is *high* and **Incident Light Intensity** is *high* then set **Nutrient Temperature Set-point** *low* and **Fan Power** *high*

The above set of fuzzy rules are presented in tabular form in table 6 2 below

Inside Air Temperature

Incident Light Intensity			*Low*	*Moderate*	*High*
	Low	*Nut Temp Set-point*	*High*	*Mod*	*Mod*
			Region 1		
		Fan Power	***Low***	***Mod.***	***Mod.***
	Moderate	*Nut Temp Set-point*	*Mod*	*Mod*	*Mod*
				Region 2	
		Fan Power	***Mod.***	***Mod.***	***Mod***
	High	*Nut Temp Set-point*	*Mod*	*Mod*	*Low*
					Region 3
		Fan Power	***Mod.***	***Mod***	***High***

Table 6 2 *Fuzzy Rule-base for Expert Fuzzy Climate Controller for Cropping House, in Tabular Form*

If you assume that higher temperatures are the result of high incident light intensities, then region 1 in the above table approximately corresponds to control rule 1 at the start of this section In the same way, region 3 corresponds to control rule 2 and region 2 corresponds to control rule 3

6.7 Simulation of the Complete Control System

The following two subsections describe the implementation of the simulated control system in the Matlab/simulink environment and the response of the simulated version of the control system to changes in the modelled environmental conditions outside the cropping house

6.7.1 Description of the Simulated Control System as Implemented in Matlab/Simulink

The fuzzy controller was tested in simulation by implementing it as a simulation in the MATLAB Simulink environment The following Simulink block diagram shows the simulation layout The three main elements in the simulation are three Simulink S-functions as listed below

- Mathematical Model describing the climate inside the cropping house written as an S-function
- S-function implementation of the digital PID controller
- S-function implementation of the expert fuzzy controller

One of the reasons for developing the model was to test the performance of the control system without having to perform tests on the real plant

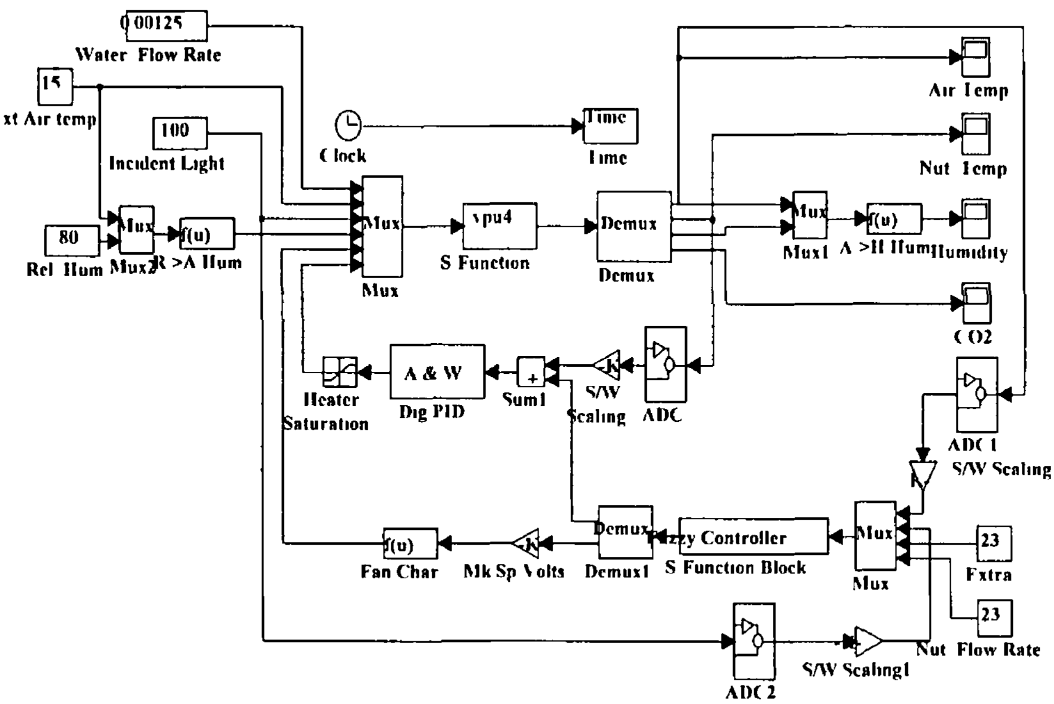


Figure 6.12 *Simulink Block Diagram Showing the Complete Control system for the Cropping House and Displaying Model Outputs*

The remote location of cropping houses makes them ill-suited to intensive experimental work such as system identification For this reason a model was developed to support any physical experiments and to permit efficient optimisation of any new control strategy A simulink block diagram of the controller is shown in figure 6 12 Consideration of the block diagram shows how the fuzzy controller forms an outer loop with the PID nutrient temperature controller forming the inner loop

In order to carry out tests on new control strategies or re-designs of the cropping house, the controller was implemented as MATLAB-Simulink ***S-Functions*** For this work, two S-functions were created to model the controller The first was a simulated version of the open loop fuzzy logic expert controller discussed earlier, which performs some of the tasks carried out by a grower in a conventional growing house This controller measures light intensity and air temperature and makes decisions about the heating and ventilation requirements of the house The decisions influence the two outputs of this simulated controller which are nutrient temperature set-point and fan power

The nutrient solution temperature set-point was taken as an input for the second S-function which simulated the digital PID controller introduced in the last section This controller measured the nutrient solution temperature and attempted to keep it at the desired set-point value which had been provided by the fuzzy logic expert controller block

The S-function implementation of the model of the system was incorporated into the simulation as the ***"Fuzzy Control"*** and ***"Dig PID"*** s-function blocks of figure 6 12 so that the two controllers controlled the model in simulation

Three ***"ADC"*** blocks simulated the eight bit analogue to digital converter feature of the Motorola 68HC11 micro-controller This was accomplished by using simulink's quantisation and saturation features as can be seen from figure 6 13

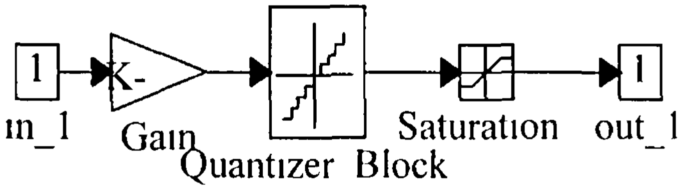


Figure 6 13: *Simulink Block Diagram representation of the Simulink group "ADC" which Models an Analogue to Digital Converter*

6.7.2 Response of the Simulated Controller to Step Changes in External Air Temperature

The present controller configuration should operate in three distinct regions as follows

- External air temperature much lower than that of heated air and nutrient solution inside the cropping house
- External air temperature above the optimum 22-25°C band
- External air temperature a few degrees less than the optimum air and nutrient temperature range

The first condition causes a heating problem for the controller The heater power should be sufficient to maintain acceptable air and nutrient temperatures even when the external air temperatures are low Excessively low heater power will result in the system going out of control at low to moderate external air temperatures

The second case occurs when outside air temperatures are high and the control system is unable cool the environment inside the cropping house The best that can be achieved by the controller with the existing controller outputs is to switch off the heating system

Finally, the last case corresponds to the system being in control when the air temperature and nutrient temperature inside the cropping house should be slightly less than optimum This means that only a slight temperature lift is required to bring the temperatures within the optimum range

Figure 6 14 below shows the simulated controller responses to step changes in external air temperature

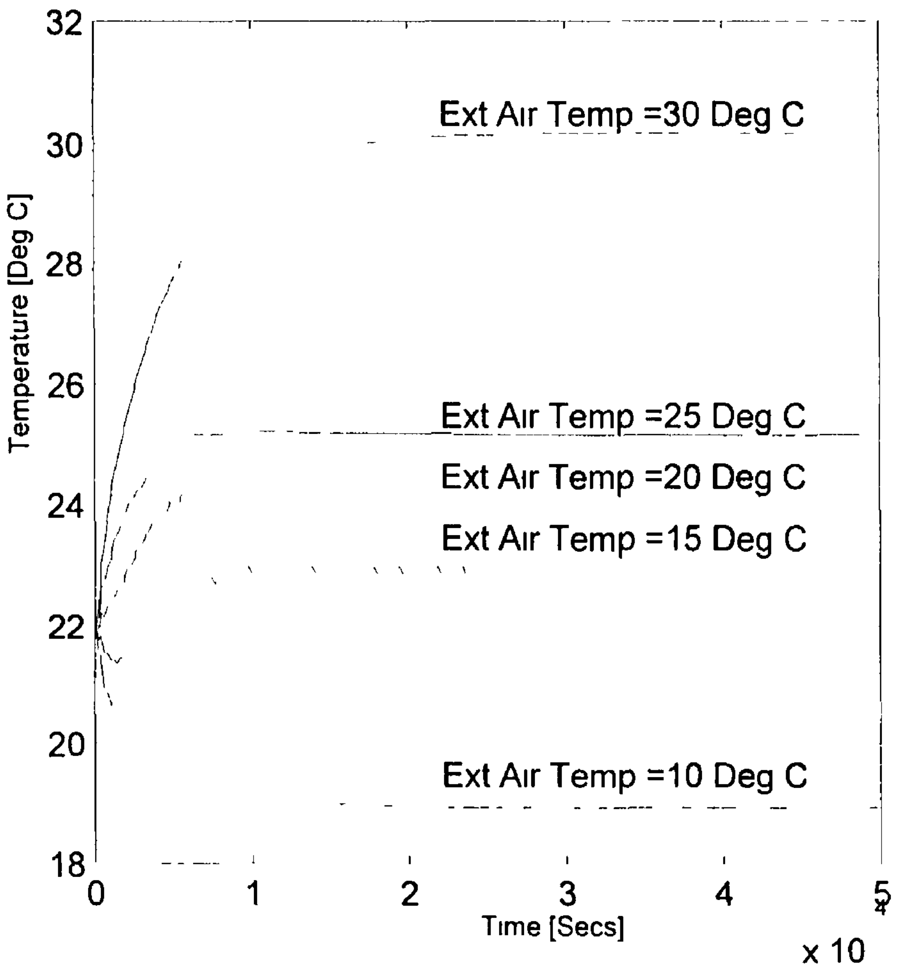


Fig 6 14 *Simulated Responses of Controlled Nutrient Temperature to Step Changes in External Air Temperature*

The water heater cannot provide enough power to heat the nutrient to the required temperature of 24°C when the external air temperature is below 15°C The curve showing the response to an external air temperature of 10°C is a typical example The heater can only provide a temperature lift of 9°C, which means that the water temperature cannot exceed 19°C and thus never reaches the set-point temperature This corresponds to case one above

The second case is represented by the curve where external air temperature is at 30°C This means that the air temperature outside the cropping house exceeds the optimum temperature range inside the cropping house Since there is no active cooling device such as a heat exchanger available to cool the incoming air, the nutrient temperature tends to rise towards the external air temperature of 30°C

The final class of curve represents external air temperatures in a range which allows the nutrient temperature to be controlled For a nutrient temperature set-point of 24°C, this occurs when the external air temperature is within the range 15°C- 24°C The curves representing external air temperatures of 15°C and 20°C are in this category It can be seen from these response curves that they are within 1°C of 24°C which is the set-point temperature

Since the present control configuration only operates correctly for external air temperatures above 15°C, it can be concluded that higher power heaters are required to ensure that the temperatures inside the cropping house are adequate Based on the fact that the present total heater power is 400 W, an additional 600-800 W of power would be needed However this amount of power is expensive to provide with electric heaters So based on recommendations resulting from this study, and for reasons of safety the electric heater system is to be replaced with a more powerful gas/oil burner-based water heating system

Figure 6 15 below shows the response of the simulated air temperature to step changes in the external air temperature from an initial temperature of 22°C As before, three types of response appear on the graph

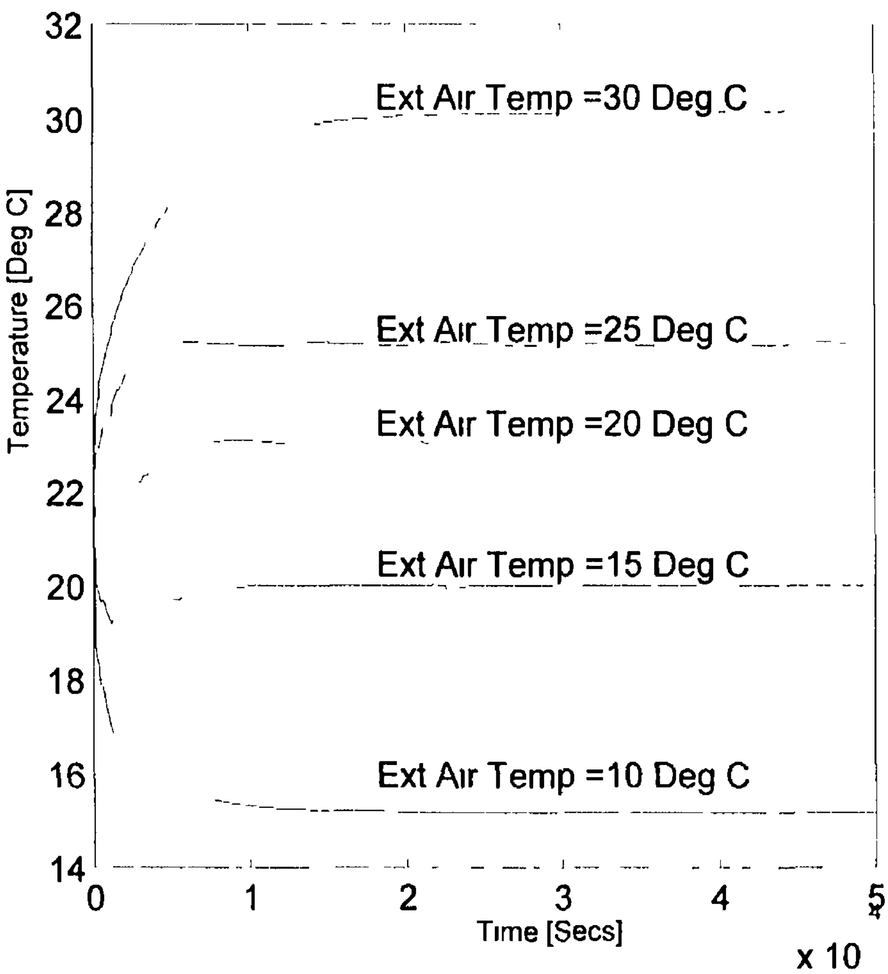


Fig 6 15 *Simulated Responses of Controlled Inside Air Temperature to Step Changes in External Air Temperature*

For final external air temperatures in the range 15°C to 25°C the simulated controller can keep the simulated inside air temperature in the desired range of 20°C to 25°C while allowing an acceptable ventilation rate Ventilation will rapidly decrease the air temperature in the cropping house Since air temperature is closely related to nutrient temperature, the nutrient temperature will also be affected

For satisfactory internal air temperatures when air temperatures outside the cropping house are low, it would be necessary to introduce some form of air heating device in addition to the proposed water heater Some possible air heating devices are described in the next chapter Using the existing control configuration, the air temperature must be above a threshold temperature before the air temperature stays within the desired range

For external air temperatures above 25°C, region 1 of the fuzzy controller rule-base ensures that the electric water heaters are switched off and the fan ventilation rate is set high This ensures that there is no temperature lift inside the cropping house as can be seen from the curve representing conditions when external air temperatures are at 30°C

6.8: Implementation of the Controller for the 68HC11 Micro-controller

To allow the controller code to be used on the real plant, the fuzzy controller and digital PID controller were implemented in the "C" programming language for the 68HC11 The controller code was written so that the PID controller settings and the control rules and fuzzy sets for the fuzzy controller would be identical to those used in the simulated controller written for Matlab The code was compiled, assembled and linked using the software development system described earlier in this chapter The first of the following three subsections describes the sequence of operation of the code The second subsection deals with execution time and memory requirements The final subsection briefly discusses how the code was tested in the development stage

6.8.1 Sequence of Operation of Controller Code

The sequence of operation of the code on the micro-controller is as follows Voltages corresponding to temperatures and light intensities are first sampled by the sampling service routines Sampled values from the ADC's are converted into floating point format after each sample instant All the internal calculations for the two controllers are performed by using floating point arithmetic Calculated control output values corresponding to PWM mark-space ratios, are converted back to integer format The PWM service routines then convert the integer to PWM signals for the fan and heater The sequence of execution of the various elements of the controller code is shown in figure 6 16 below

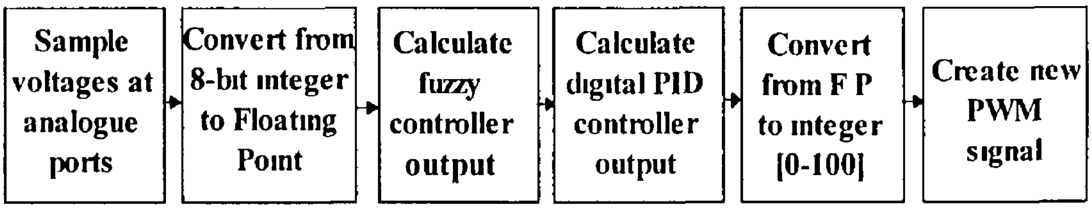


Figure 6.16 *Sequence of Execution of Controller code*

6.8.2 Execution time and Memory Requirements for the Controller

The software for the controller when actually resident on the micro-controller integrated circuit, occupies approximately 8 5 kBytes of EPROM This leaves 3 5 kBytes of EPROM for further development In addition, by using integer arithmetic in place of floating point arithmetic, the amount of memory required could be much reduced Extra inputs could easily be added to the fuzzy controller since the controller may need as little as four Bytes to store one fuzzy set and for *n* inputs and *m* outputs, needs only $2 + 2(n+m)$ Bytes per rule The

512 Bytes of RAM available on the 68HC11E9 are used for the stack and for storing variables This leaves the 512 Bytes of EEPROM free for other uses Typical examples would be as a data storage space in case of emergency shutdown or for data-logging In a later version of the controller it could be used to store modifications to the original rule-base This would allow the rule-base to be reprogrammed on-site via the serial link to a laptop computer for instance

The code takes milliseconds to go through one complete cycle This execution time is orders of magnitude less than the sample time of 200 s, so it is possible to add extra code for intelligent data-logging or more complex fuzzy control for instance, without timing constraints

6.8.3 Other Comments on the Implementation and Testing of the Controller

In the development stage of the project, low-level routines were tested by moving them to RAM where they could be single-stepped for debugging purposes Interrupt vectors were located as pseudo-vectors in RAM during the design stage and were finally moved to the last few Bytes of EPROM High level routines such as the PID controller and the fuzzy controller were tested by first compiling and run-time testing using Borland Turbo-C They were then re-compiled for the 68HC11 and tested with the assembly routines The full controller was then further tested by attempting to control the temperature in a tank of water, before being transferred to the real system This control was successful (Berry and Berrigan 1994)

Prior to testing the expert controller on the real system, the expert fuzzy controller was tested statically by changing the temperature measured by the two Pt100's and the light incident on the light sensor and observing the change in fan speed and the temperature of a water container in which the heaters were immersed (Berry and Berrigan 1994)

6.9 Performance Trials of the Expert Fuzzy Controller on the Real System and on the Simulated System

This section gives an assessment of the performance of the controller based on the results of a four day trial on the real system The first sub-section presents the result of the trial on the real system The second sub-section shows the output of the model which results from temperature data from the above trial being applied to the cropping house model

6.9.1 Controller Performance Trial on the Real System

In June 1995, the controller was set up to control the environment in the cropping house The remote location of the cropping house during the course of the trial meant that a personal computer could not be located sufficiently close to use the serial link capability For this reason, the data logger set-up identical to that described for the three day trial at the beginning of the previous chapter was used to monitor the performance of the controller Temperatures at four points in the nutrient circuit were monitored, as were external air temperature and air temperature inside the cropping house

Problems with humidity sensors and the CO_2 sensor meant that the humidity and CO_2 levels could not be measured reliably either inside or outside of the cropping house, These aspects of the control system model have therefore been ignored

Figure 6 17 above shows the response of the controlled nutrient solution temperature and the inside air temperature to changes in the external environment over four days in June 1995 The plots show how the controller responds when the external air temperature varies The controller keeps the nutrient temperature tightly regulated when the external air temperature is below the set-point value of 24°C

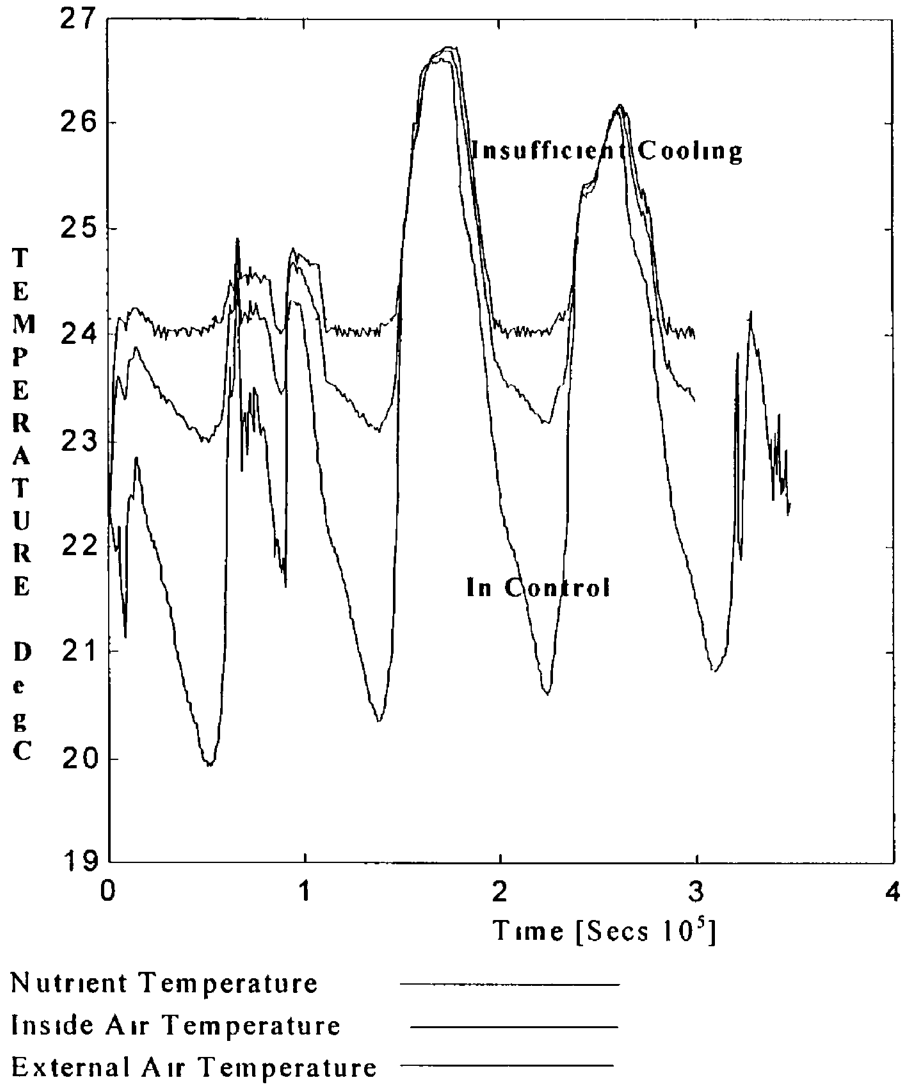


Figure 6 17 *Controller Performance Chart from a Controller Trial of the 3rd to the 7th June 1995 It Shows the Variation of Inside Air Temperature and Nutrient Solution Temperature over the Four Day Period In Response to Changes in the Air Temperature Outside the Cropping House*

If the external air temperature and hence the inside air temperature exceed this value, which happens when the fuzzy controller is operating in region 1, the controller cannot cool the air and this in turn heats the nutrient solution For external air temperatures below 24°C and above 15°C , the heater can provide enough temperature lift to heat the water This represents operating region 2 for the fuzzy controller As can be seen from the graph, external air temperature does not drop below 15°C at any point

The inside air temperature stays close to the optimum value of 24°C when the inside air temperature is below 24°C This is due to the action of the fuzzy controller, which ensures that the fan speed is low to keep the air temperature in the cropping house at acceptable levels When the inside air temperature exceeds the set-point temperature, the fuzzy expert controller sets the fan speed high, and the air temperature and nutrient temperatures are kept very close to the outside air temperature Again this shows the controller operating in region 1

Consideration of the nutrient temperature curve shows that the PID controller appears to be operating correctly When the external air temperature is low enough that no cooling is needed and high enough that the heater can provide enough power to heat the water sufficiently , the nutrient temperature is kept near 24°C, as can be seen from figure 6 17

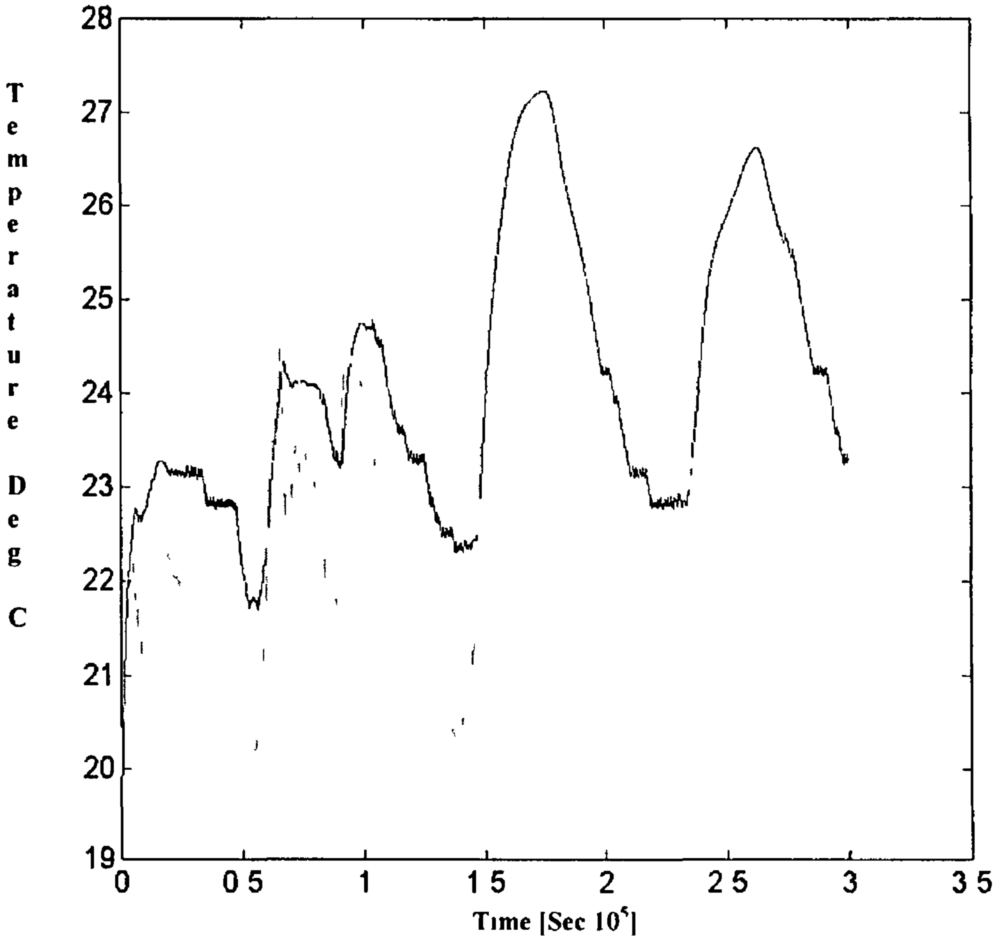
It appears from the above curve representing measured air temperature inside the cropping house, that the fuzzy controller is also performing satisfactorily in general The controller appears to be slightly deficient however, when low ventilation rates are required This is attributed to the non-linear effect of the threshold voltage of the fan, below which the fan will not function correctly It is also possible that by increasing the number of sets in the inside air temperature universe of discourse, the quality of control would improve A second suggestion is that the rate of change of external air temperature be taken as an additional input to the fuzzy controller subroutine Finally, to achieve full control of the inside air temperature, it would be desirable to have some form of heat exchange mechanism to heat or cool incoming air

The fuzzy controller produces an output control surface which is a non-linear function of the controller input variables A control surface is simpler to programme than a fuzzy controller However, control surfaces become more difficult to visualise as the number of inputs and outputs increases The rule-based nature of a fuzzy controller allows the controller designer to work on small portions of the control surface independently, which is why fuzzy controllers are suitable for controlling complex systems such as environmental systems

In retrospect, judging from the performance of the fuzzy expert controller, it may seem questionable whether at this level of sophistication the fuzzy expert controller is worth all the development effort It seems that, in order to justify the development of the controller, at least one extra interacting parameter would need to be included as part of the controlled system The expert knowledge which is encapsulated in the three control rules of sub-section 6 6 3 could be simply implemented as a three part *if* statement which would probably work quite satisfactorily, albeit without the influence of light However, it is envisaged that the controller will be extended eventually to include humidity control, which is a difficult control problem for a classical controller to handle Therefore the work on the fuzzy controller is quite valuable

6.9.2 Controller Performance Trial on Simulation of the Cropping House

In contrast to figure 6 17 above, the following figure shows the response of the model of the cropping house to the external air temperature data collected during the four day trial



Nutrient Temperature
Inside Air Temperature
Outside Air Temperature

Figure 6 18. *Response Inside Air Temperature and Nutrient Temperature in the Full Control System Model, to Changes in Air Temperature over a Four Day Period During June 1995, with Humidity Unmeasured and Set at 80%RH*

Unfortunately, since the humidity could not be measured directly, a constant value had to be applied to the model However despite this, the two graphs are quite similar The main difference between the plots is that the modelled nutrient temperature in figure 6 18 closely follows the modelled inside air temperature whereas the measured equivalent quantities of figure 6 17 do not This indicates that the model slightly over-emphasizes the interaction between the nutrient and inside air heat balance equations The model also under-estimates the heat loss through the cropping house cover, since the inside air temperature and nutrient temperature plots do not follow the outside air temperature plot as closely in the simulated graph as in the graph of data taken from the real system Apart from these slight inaccuracies, the model of the complete control system performs well

6.10 Summary

This chapter has discussed the elements of the control system for the vegetable propagation unit, which is a miniature hydroponic cropping house which is aimed at the amateur gardener In the next chapter, the elements of the project itself will be summarised and discussed with suggestions for future work

Chapter 7: Discussion

7.1 Introduction

This chapter may be broken up into two parts The first half of the chapter which includes sections 7 2 and 7 3, discusses the overall performance and suggests improvements to the deterministic model introduced in chapters four and five The second half of the chapter discusses issues relating to the implementation of the control system for the real system

7.2 Discussion of Performance of the Model of the Cropping House

The mathematical model presented in this work is an adaptation and extension of work by Hayes and Meath (1993) The main modifications to their equations are the inclusion of the equation describing nutrient temperature and selecting the original Penman formula, (Penman 1946) rather than the Penman formula as modified by Monteith (1973), to describe evapo-transpiration from the canopy This section will discuss the justification for these modifications, assess its performance and highlight areas where further modifications could be made to improve the model The next section will deal with issues relating to the digital controller

7.2 1 General Performance of the Deterministic Model

The reasons for the creation of the mathematical model of the cropping house were to gain an understanding of how the system functions and to provide a method by which modifications to the system could be tested The overall performance of the modified model was found to be sufficient to achieve these goals

It is questionable whether the approach of developing the model from first principles as used here, is superior to a system identification approach It seems that the main argument for using a deterministic model is the ease with which modifications to parameters such as water volume or fan power may be made This feature is advantageous when testing a new control strategy, or cropping house configuration This is acceptable if all that is required from the model are rough estimates of conditions inside the cropping house However researchers have found that the level of sophistication required to achieve accurate predictions from an altered model developed from first principles, would not justify further development in this direction (Young 1994) This is particularly true of models including equations describing humidity It would be far better to develop reliable empirical equations to describe the various elements of the system such as the heater and the transmission of light through the cover

7 2 2 The Heat Balance Equation for Nutrient Solution

Meath and Hayes in their original models of a mushroom growing tunnel ignored the influence of the soil on the temperature regime inside their mushroom tunnel This is acceptable with soil since soil has a large thermal capacity and hence the soil temperature changes really slowly in relation to the internal air temperature The nutrient temperature, which is equivalent to the soil temperature in the earlier works, has much faster dynamics which cannot be neglected It is also a controlled variable in the system so it is necessary to obtain a prediction of how water temperature varies over time

Consideration of figure 5 8 shows the response of the nutrient temperature to a step change in heater power It shows a response time which is of the same order as the air temperature The air temperature plots of figure 5 2 and 5 4 show dynamic responses which indicate a high level of interaction with the corresponding nutrient temperature dynamics of figures 5 3 and 5 5

The original model was modified to allow for the nutrient temperature gradient between the tanks and the trays The overall performance of the modified nutrient heat balance equation as seen in chapters four and five, is satisfactory for the purposes of this work The changes to the apparent volume of nutrient and to the apparent heater efficiency in the original model are therefore justified

A more satisfactory arrangement would be the inclusion of an additional first-order differential equation to describe the difference in temperature between nutrient in the tanks and in the trays This is relatively simple to model using thermal physics and would improve the performance of the model considerably

7 2.3 The Heat Balance Equation for the Air Inside the Cropping House

The inside air heat balance equation is perhaps the most satisfactory equation since it required little modification to achieve a satisfactory response The principal contributions to the heat balance in the air are ventilation Q_v and convection from the canopy and nutrient surface Q_{wa}

It appears from direct observation of the real system and of the model, that a less powerful fan is required for the cropping house Based on the results of simulations, it is estimated that a fan with a volumetric capacity of 20 ls^{-1} would be sufficient

It is possible that the convection term Q_{wa} could be reduced by improving the insulation between the nutrient flowing in the trays and the inside air However, this convection term serves the purpose of heating the air in the cropping house for low or zero ventilation rates

7.2 4 The Water Vapour Mass Balance Equation for the Air Inside the Cropping House

Two notable factors were found to influence the vapour mass balance equation These were the effect of the fan on the humidity inside the cropping house, and the equation used to describe evapo-transpiration from the crop canopy and the nutrient solution surface These two issues are discussed in the following two sub-sections

7 2 4 1 The Influence of the Fan on Humidity inside the Cropping House

The water vapour mass balance equation is greatly influenced by the fan power As an example of the power of the fan, consider a case where the air inside and outside the cropping house is at 23^{o}C, the inside relative humidity is 80% and outside humidity at 70% If the fan at full power, draws 73 1 of air per second through the cropping house, the cropping house loses 12 6 l of water vapour per day This is just a typical figure In the real system, losses of 30 l of water per day accompanied by severe water stress in the plants were observed Again, the conclusion is that the fan capacity is too high This is a demonstration of the usefulness of the model

7 2 3 2 Selection of the Equation Describing Evapo-transpiration

The most problematic element of the water vapour mass balance equation discussed above is the term describing evapo-transpiration A lot of work has been done by numerous researchers in this area over the last fifty years (see Rosenberg Blad and Verma 1983) There appears to be no simple deterministic approach to this problem which gives accurate results Many studies have relied on system identification approaches with some success (Seginer & Levav 1971), (Udink ten Cate 1983), (Kindelan 1980) In retrospect, with sufficiently accurate instruments, this would be the preferred technique for determining the heat lost due to evapo-transpiration, λE_c

The resistance to diffusion of heat from the surface of the crop and trays, r_H, is difficult to determine and is required by Monteiths version of the Penman formula This makes the Monteith version of the model less attractive for the purposes of this work The value of 577 sm^{-1} for r_H was arrived at by considering an air flow over a single leaf This figure is completely altered if a full tray of lettuce is considered

The most satisfactory method for determining r_H is by measurement This requires further instrumentation and is tending towards the empirical approach suggested in the last section The development of Penman-Monteith equation is left for further work However, as discussed in chapters four and five, it is recommended that a more empirical approach be taken with the moisture mass balance equations and this would preclude the use of Monteiths equation though the form of the equation could be used

7 2 4 The CO_2 Mass Balance Equation

The CO_2 mass balance equation appears to mimic the actual CO_2 concentration quite successfully This equation includes a term which describes the CO_2 concentration gradient within the mesophyll which accounts for photosynthesis This was not present in the models described by Hayes and Meath since they were modelling the mushroom growing environment The main problem with the photosynthesis term is apparent from consideration of figure 4 10 At zero

ventilation, the CO_2 concentration in the cropping house is not a function of light intensity To solve this problem it was suggested in section 4 7 8
that the CO_2 concentration in the mesophyll be modelled as a function of light intensity Of course the CO_2 concentration in the mesophyll would be difficult to measure directly without very specialised instruments It would be therefore necessary to use an estimation algorithm such as recursive least squares estimation to determine the best equation for describing this relationship This is again pointing towards an empirical technique

7 2 4 1 Modification of the Short-wave Radiation Equation to Allow a Position, Time and Month to be Selected

Meath (1993) used a half-wave rectified sinusoidal wave-form to mimic the change in short-wave radiation over a twenty four hour period The Q_{si} term in the model as presented in chapter four of this work depends on a measurement of light intensity being specified at the start of the simulation It would be preferable for the user to select a longitude, time of day, date, orientation, a measure of cloud cover and a description of structures likely to cast shadows This means the user of the model would be able to predict how the cropping house would behave under the wide range of environmental conditions encountered in a typical garden, without requiring historical data Jones (1992), developed an equation which would relate the above parameters to the incident short-wave radiation intensity It is suggested for further work that this equation be added to the model

7 2 5 Suggested Improvements to the Data-logging System

One of the prerequisites for a more empirical approach to modelling of the cropping house is a more comprehensive data-logging system For the trials which are shown above, some of the input data were obtained by referring to measurements taken in the Dublin area by the Meteorological Office While these data produced satisfactory results, they were only received twelve weeks after the trials took place This is not an ideal situation and it would be advisable for any future work to be independent of such restrictions The following instruments would be desirable additions to the instruments already available

- A pyrometer or other such instrument for measuring incident light intensity,
- A humidity sensor such as a wet and dry bulb thermometer which measures humidities up to 100%RH
- An instrument for measuring radiative heat losses from surfaces,
- A calibration system for the CO_2 sensor with samples of gases with different and known concentrations of CO_2

7.3 Assessment of the Performance of the Controller

The controller was seen in chapter 6 to fulfil its task of controlling the environment in the cropping house Figure 6 17 showed the performance of the controller controlling the environment in the cropping house

The most obvious problem with control arose from the control devices The fan was over-sized and had a threshold voltage below which it would not function correctly This problem could be overcome by resizing the fan and introducing a second smaller fan to supplement the first and allow low ventilation rates The total power of the nutrient heaters was slightly too low at 440 W It is recommended that the total heater power be increased to around 700 W

The digital PID controller which was used to control the nutrient temperature in the tanks and trays of the cropping house performed very well except where the heater power was insufficient to provide the temperature lift needed to keep temperature at acceptable levels

The selection of parameters for the digital PID controller was problematic however The volume of the nutrient in the tanks can vary in normal operation from 56 l down to 30 l, with a typical volume of 36 l as detailed in section 6 2 in the last chapter

Disconnection of the external water supply causes serious problems for the control system The cropping house with the fan on full has been known to lose in excess of 30 l in a day due to evaporation which could result in nutrient volumes as low as 20 l This would represent the minimum amount of water which the cropping house could reasonably be expected to hold It is not desirable for the cropping house to contain low quantities of the nutrient in the tanks as the recycling pumps, which had to be plastic welded onto the ends of the sump tanks, would then have to be on for a longer period of time and would eventually be uncovered, which would cause them to overheat In fact two sets of pumps were lost this way with an earlier prototype of the cropping house In addition, low volumes of nutrient would cause the nutrient heaters to become uncovered which could cause their fragile glass casings to crack which would in turn release oil into the nutrient supply For these reasons it was considered inadvisable to perform step responses to changes in heater power except with a volume of nutrient in excess of 35 l, since by the end of the trial the nutrient volume would be much reduced and would approach dangerously low levels

In 7 2 2 it was stated that the model required an extra equation to distinguish nutrient temperature in the trays from nutrient temperature in the tanks The performance of the model was found to deteriorate substantially when the nutrient volume was reduced to 20 l The nutrient capacity of the six trays totalled 10 l as noted in 5 3 1, which meant that a substantial quantity of water which was modelled as being heated in the model, was actually being cooled by heat transfer to the inside air in the real system The model was thus unsuitable for modelling the effects of low quantities of water on the real system

The result of the variation of nutrient volume was that both the apparent gain and apparent time constant of the real system changed unless the system was constantly monitored and the water supply to the tanks was regulated If the PID controller parameters were selected on the basis that the cropping house was always contained a full load of water while the controller was running then an interruption in the external water supply could cause the controller to lose control

Selection of the parameters of the controller based on robust control techniques would have required measurements with low time constants which was not possible for the reasons outlined above so to get the controller working on the real system, a trial and error technique was adopted which resulted in the parameters given in table 6 1

The PID controller was initially tested by controlling the temperature of a vessel containing 35 l of water at a constant air temperature of 22°C, thus producing estimate values for the controller coefficients This trial produced a favourable response except that the cooling characteristic in this trial was much slower than the heating characteristic since there was no active cooling and the exposed surface area of the water was much smaller than in the real system The dynamics of the vessel and water were quite different from those of the real system however This is probably due to the absence of the substantial heat transfer between the nutrient solution and the surrounding air which occurs in the real system The coefficients derived from the above tests were refined in set of tests on the real system which produced the coefficients given in table 6 1

The expert fuzzy controller kept air temperature within 5°C of the optimum inside air temperature of 24°C while keeping CO_2 levels and humidity at acceptable levels by constantly ventilating Recommended changes to the fuzzy controller are as follows

- Extend the controller to control humidity
- Add extra sets to the air temperature input universe of discourse
- Add an input which accounts for rate of change of air temperature

These improvements would improve the performance and effectiveness of the controller, especially if a heating/cooling device is incorporated into the control system This will be discussed in the next section

7.4 Recommended Improvements to Controller

This section will outline a set of improvements which could be applied to the existing controller as well as recommendations for extending the complete control system The comments will be split into three sections as follows,

- Controller inputs
- Controller outputs
- Improvements to the configuration of the Micro-controller unit

7.4.1 Extra Sensors as Inputs for the Digital Controller.

Additional inputs which were also considered for the controller were an electric psychrometer in the form of wet and dry bulb thermometers and a CO_2 sensor

The following subsections will explain why these inputs were rejected and suggest which inputs might be added in later versions of the controller

7 4 1 1 Humidity Sensor

Since one Pt100 was already set up to measure dry bulb temperature within the cropping house it would be relatively simple to connect a second thermometer covered in gauze This was considered to be unnecessary however, without a method for controlling the humidity directly It is suggested that any attempt to control humidity in the future would incorporate a wet and dry bulb thermometer since it allows humidities in excess of 95%RH to be measured High humidities can occur inside an enclosed space such as the cropping house where plants are transpiring

7 4 1 2 CO_2 Sensor

The CO_2 levels within a cropping house are of great concern to growers High CO_2 levels generally mean higher yields To control CO_2 levels a device for measuring CO_2 levels accurately is required Unfortunately any of the commercial CO_2 sensors encountered are too expensive for a simple control system such as the one presented here and were difficult to calibrate Consequently, no CO_2 sensor was included in the controller The sensor used in this work was only connected to the data-logger for data acquisition It is possible to construct inexpensive hand-made CO_2 transducers but the accuracy of such sensors is questionable The light sensor in the existing controller will at least give a good indication of when the demand for CO_2 is likely to be high

7.4.1.3 Control of Nutrient Levels using Conductivity and pH Sensors

For fully automatic control of the nutrient levels in the hydroponic cropping house it is necessary to regulate the pH and the conductivity of the nutrient This was outside the original specification of the project but it is desirable to have control of the nutrient levels since it will mean less work for growers who would otherwise have to constantly monitor the nutrient levels A relatively inexpensive and reliable analogue control circuit for monitoring and controlling conductivity has been developed independently for the cropping house (Berry and Ryan 1995) Trials have shown that this circuit would be sufficient for controlling the nutrient levels in the tanks if the nutrient supply is flushed and replaced every fortnight This circuit could easily be modified and incorporated into the controller

The addition of a pH measuring circuit with small reservoirs of acid and base would ensure that the controller kept the pH of the nutrient solution balanced and this in turn would allow the solution to be used for an extended period without replacing it It is doubtful however whether this extra feature would be economic in temperate climates such as those found in northern Europe

7 4 2 Suggestions for Additional Control Outputs

This section describes suggested improvements or modifications which could be made to the environmental controller to improve performance or flexibility The following subsections deal with three such additions

7 4 2.1 Peltier-Effect Heat Pump

The inclusion of a Peltier Effect heat pump as a device for heating /cooling incoming air in the greenhouse would greatly enhance the effectiveness of the controller These devices are quite inexpensive for low power applications such as this The heat pump could then form the basis for a humidifier/dehumidifier Commercial humidity control systems tend to be relatively expensive

7.4.2.2 Bi-directional Fan System with Low Speed Capability

A bi-directional d c fan in place of the existing one would allow the proposed humidifier to be a simple wet pad This could be achieved by allowing the controller to decide whether to draw incoming air or outgoing air over the pad, thus controlling the humidity and allowing a certain amount of evaporative cooling to take place

One problem which was encountered with the control of fan speed in the real system involved the threshold voltage of the fan The fan would not operate with an applied voltage of less than 2 V Starting from a standstill, a voltage of not less than 4 V had to be applied to the fan to ensure that it began to rotate It is possible that a pair of fans of different sizes could be used to overcome this problem

7 4 2 3 Gas Heater in Place of the Electric Water Heater

The electric water heaters used in this study are expensive to run and are not well suited to remote locations An alternative would be to use an oil or gas heater to heat the air and the nutrient in the cropping house This would be more energy efficient and less expensive to run However, full control of nutrient temperature and/or air temperature may involve expensive hardware such as valves and positioners This suggestion is being investigated by the manufacturer of the cropping house

7 4 3 Other Additions to the Controller Hardware and Software

In addition to the changes to the controller input and output devices, the following changes to the controller structure should be considered

7 4 3 1 Duplex Serial Communications between the Controller and the Personal Computer

The serial communications feature of the controller is potentially a very powerful addition to the controller The present version of the controller only allows data to be transmitted from the controller to the personal computer An enhanced version of the controller could allow the user to alter the control settings for the PID controller, change rules and sets in the fuzzy controller or decide which parameters were sent down the serial line to be logged The P C could also be replaced by a palm-top computer which would be portable and could be used to down load data in blocks from battery backed RAM on the controller

7 4 3 2 User Interface for the Controller

The present version of the controller does not allow the user to alter the controller settings A simple and inexpensive method for allowing more advanced users to do this would be to use Radionics supplied LCD display and a keypad, which could be interfaced to the serial peripheral interface output of the micro-controller

7 4 3 3 Modifications to the Code for the Direct Digital Controller of Nutrient Temperature

The direct digital controller described in chapter 6 had no protection against the phenomenon known as derivative kick In extreme condtions the equation for the digital PID controller could be susceptible to sudden changes in required nutrient temperature set-point which would result in a sudden large and unnecessary change in output from the derivative term of the controller This can be rectified by making the derivative term of the digital controller proportional to the rate of change of the negation of the nutrient temperature, instead of the rate of change of nutrient temperature error as in equation 6 1 This leads to the following equation

$$m_n = m_{n-1} + K_p\left\{(e_n - e_{n-1}) + \frac{Te_n}{T_i} - \frac{T_d(y_n - 2y_{n-1} + y_{n-2})}{T}\right\} \qquad \textbf{\textit{Eqn 7.1}}$$

where K_p is the proportional gain

T is the sampling interval

T_i the integral action time

T_d derivative action time

m_k control output value at the k^{th} instant

y_k measured value at the k^{th} instant

A more correct procedure for selection of sampling time has been discovered since this work was completed Rather than making the sample time 4 to 20 times smaller than the shortest time constant in the system, it is suggested that the sampling be selected as one fifth of the dead time (Bennett 1994)

7 4 3 4 Modifications to the Code for the Expert Fuzzy Controller

It is advised that in future implementations, some account be taken of what should happen when nutrient levels in the cropping house get very low Low volumes of nutrient in the cropping house may lead to loss of the crop or damage to the control system In this case it must be decided whether the crop or the cropping house should be protected first It might seem that the controller should always come first, but this might not be the case if the cropping house contains a particularly valuable crop This information could then be coded as fuzzy rules for the controller

A final notable point is that evaporation of water from the nutrient solution causes concentration of the nutrient which may adversely affect the growth of the crop during excessive evaporation This effect should also be considered when designing future controllers

Chapter 8: Conclusion

8.1 Introduction

This work described a deterministic model and a control system for a miniature cropping house Most of the model was developed from principles of environmental physics The remainder of the model was determined empirically The issues regarding the model is dealt with in the next section The controller for the cropping house was developed using the Motorola 68HC11 micro-controller unit (MCU) and this controller is dealt with in the last section

8.2 The Deterministic Model of the Cropping House

A deterministic model of a miniature cropping house was developed in the Matlab/Simulink environment The following main conclusion has been reached about this model

- The altered form of the cropping house model was found to produce accurate results It has been shown that the behaviour of the model is sufficiently similar to the behaviour of the real system, that the model can be used to pinpoint potential weaknesses in the control system

In addition, the following important points have been made about the model

- A more empirical approach to modelling, with improved instrumentation and more system identification would allow easier and more accurate estimation of the coefficients in the model The first principles approach which was followed here may be used instead at an early stage to determine the significant mass and heat transfers in the model

- By treating the heat balance in the trays and the tanks as ***separate*** homogeneous regions, by introducing an additional differential equation, the modelled dynamic responses of the nutrient temperature and the air temperature would be much improved

8.3 The Climate Controller for the Cropping House

The control system for the cropping house was simulated in the Matlab/Simulink environment By combining the simulation of the controller with the plant simulation, a simulation of the entire control system was created in Matlab The real control system was designed around the 68HC11 MPU The control strategy for the real controller was tested on the simulated model by monitoring step responses The following three main weaknesses were identified in the real control system by modelling the cropping house and by observation of the real and the modelled control system

- The original 100 ls^{-1} fan was found to be too powerful for the actual system Since it tended to expel heated air rapidly the air temperature and the nutrient temperatures in the unit dropped to unacceptable levels when the fan was on full power

- The heater power was insufficient to keep the water temperature at acceptable temperatures if external air temperatures dropped below 10^oC, even if the ventilation rate was very low

- The fuzzy expert controller was found to operate successfully, but to gain full benefit from the expert controller it would be desirable to include extra inputs and outputs as detailed in chapter 7

In addition to the above points, it is suggested that an extended form of the cropping house control system would benefit greatly from a cooling system There is still some work to be done on the control system before the miniature cropping house will be capable of operating all through the year

Appendix A: Additional Experimental Results

A.1: Fan Characteristics

An experiment was conducted to discover the relationship between voltage applied to the fan and the resulting wind-speed at the crop canopy Applied voltage was varied in steps of 0 5 V from 5 V to 11 V The resulting fan speed, air speed at the fan and air speed at the canopy are shown in figure A 1 below

The data for air speed at the canopy were fitted using a second order regression model and least squares estimation in the system identification toolbox in MATLAB The resulting equation relating fan voltage V_{fan}, and air speed at the canopy vel_{canopy} is as follows

$$vel_{canopy} = 4\ 0\ 10^{4} V_{fan}^{2} + 2\ 4\ 10^{3} V_{fan} + 3\ 63\ 10^{3} [ms^{1}] \qquad \textbf{Eqn. A1}$$

The equation fits data for Applied voltage between 5 V and 11 V Turbulence at the point of measurement caused fluctuation in the airspeed measurements but it is assumed that the equation holds reasonably well up to an applied d c voltage of 12 V The fan manufacturers recommend that the applied voltage not drop below 5 V d c so equation A1 will be taken to be valid between 5 V and 12 V

The voltage to be applied to the fan is pulse width modulated 12 V d c The fan due to its low pass nature, filters out high frequency PWM signals The duty cycle is therefore proportional to the equivalent d c voltage The volumetric flow rate at the canopy can by calculated by multiplying by the air speed by the area through which it passes, which is the area of the cover A_c =1 53 m^2 So equation A1 now becomes

$$q_v = 6\ 1\ 10^{4} V_{fan}^{2} + 3\ 7\ 10^{3} V_{fan} + 5\ 6\ 10^{3} [m^3 s^{-1}] \qquad \textbf{Eqn. A2}$$

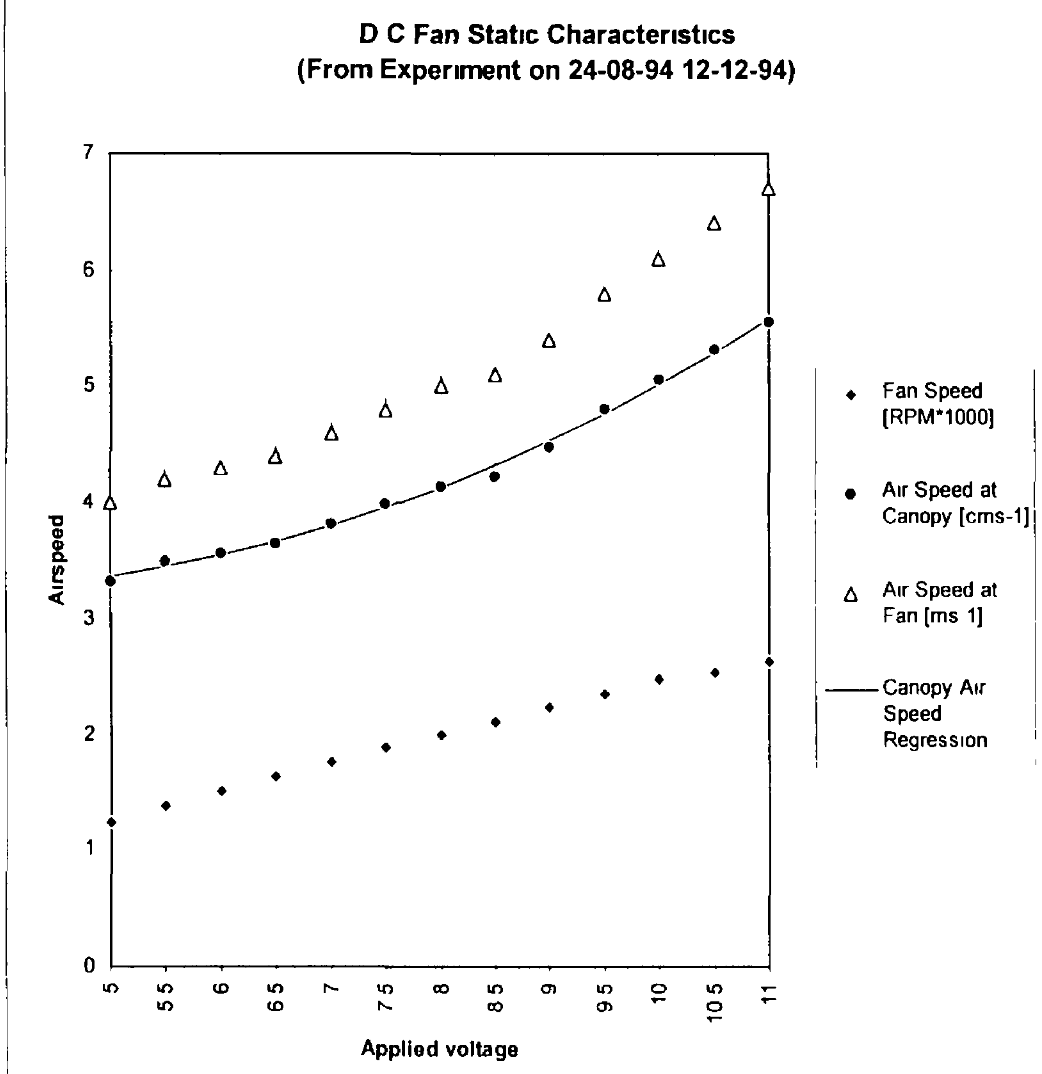


Figure A.1 *Static Characteristics of the Papst D C Fan*

Appendix B: Software Listings and Flowcharts

B.1 68HC11 Memory Map

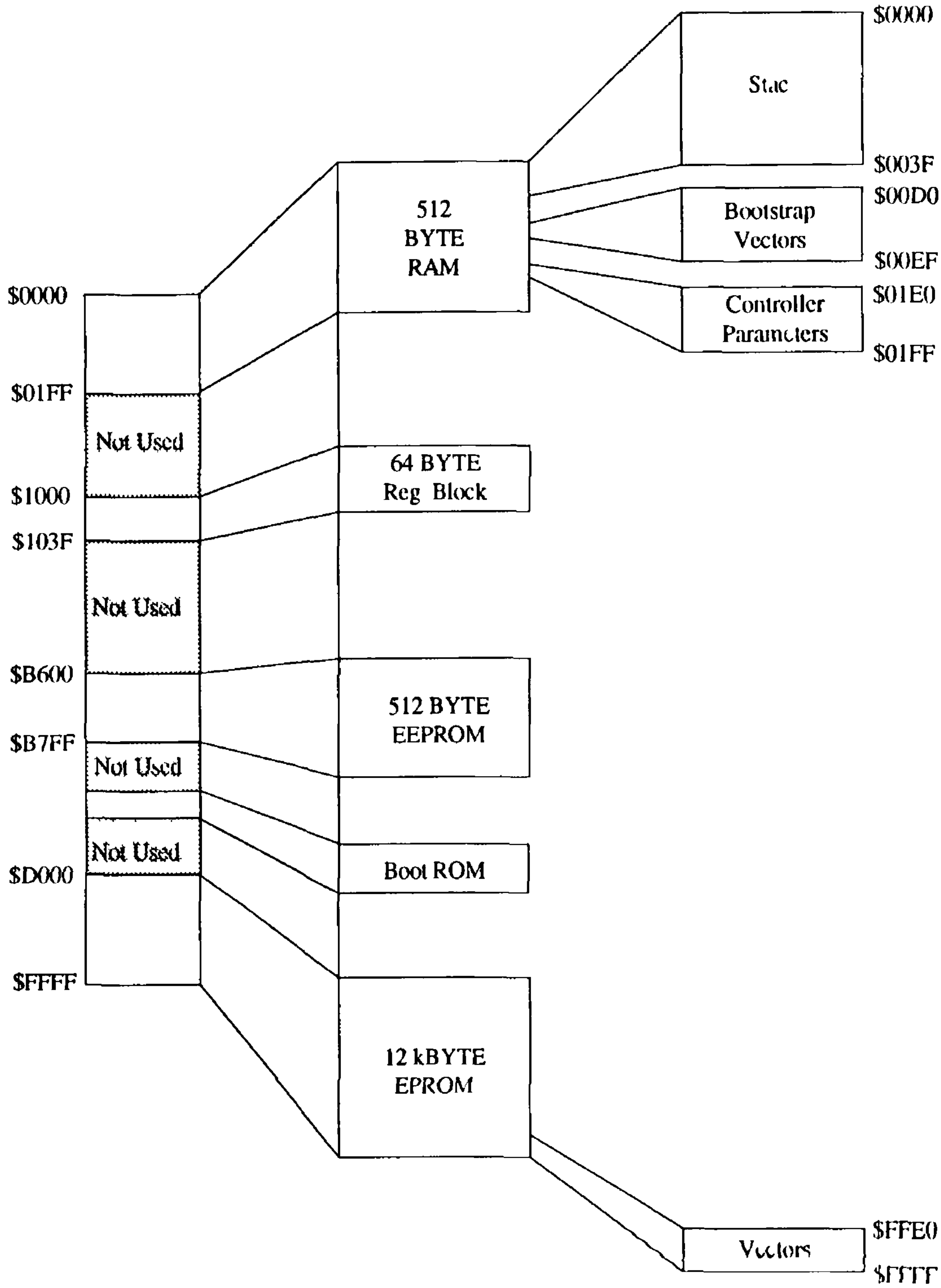


Fig. B1 *Memory Map of the 68HC711E9 as Used in this Work*

The memory map of the 68HC11E9 micro-controller is shown in fig B 1 above The map shows the parts of memory in use by the controller Parts of memory denoted as 'Not Used', are available for external addressing

Fig B 2 below gives a closer view of the controller parameters block These parameters provide the link between the assembly code and C source Most of the addresses shown here are used by both The C Code and the 68HC11 assembly code The first ten parameters shown here are sent down the serial lead to the P C for data logging

$01E0	ADR1	A/D Register #1 (Nutrient Temperature ANAIN0 [0-255])
$01E1	ADR2	A/D Register #2 (Air Temperature ANAIN1 [0-255])
$01E2	ADR3	A/D Register #3 (Light Intensity ANAIN2 [0-255])
$01E3	ADR4	A/D Register #4 (Conductivity ANAIN3 [0-255])
$01E4	PWMDC1	PWM O/P #1 (Heater Current Output m_char [0-100])
$01E5	PWMDC2	PWM O/P #2 (Fan Speed Output m_char1 [0-100])
$01E6	OP3	ANALOG O/P #1 (Not Connected)
$01E7	OP4	ANALOG O/P #2 (Not Connected)
$01E8	SCNTR	8 Bit Sample Counter [0-255]
$01E9 $01EA	TS	Sample Time (In Increments of 4.096ms) [0-65536]
$01EB $01EC	RTICTR	16-Bit Counter for Real Time Interrupt Used for Sampling [0-65536]
$01ED	Not Used	
$01EE	CONFLG	"Ready for Control" Flag [0-1]
$01EF	Not Used	

$01F0 $01F1	Not Used	
$01F2	PWMP1P	1% of PWM Period in Increments of 1uS
$01F3 $01F4	PWMPER	PWM Period in Increments of 1uS[0-65536]
$01F5 $01F6	OC2OFF	Offset Between OC1 Interrupt and OC2 Toggle (Not Used)
$01F7 $01F8	OC3OFF	Offset Between OC1 Interrupt and OC3 Toggle [0-65536]
$01F9	PWMCTR	Counter for Slow PWM for Fan, to Set Mark Space Ratio [0-100]
$01FA ⋮ $01FF	Not Used	

Fig. B.2 *Memory Map of Controller Parameters*

B.2 Flowcharts for Low level Routines

The following section contains a set of flow-charts representing the low-level service routines which were described in chapter 5

Fig B.3: *Flowchart showing Relationship Between Low-level Routines and Controller Code*

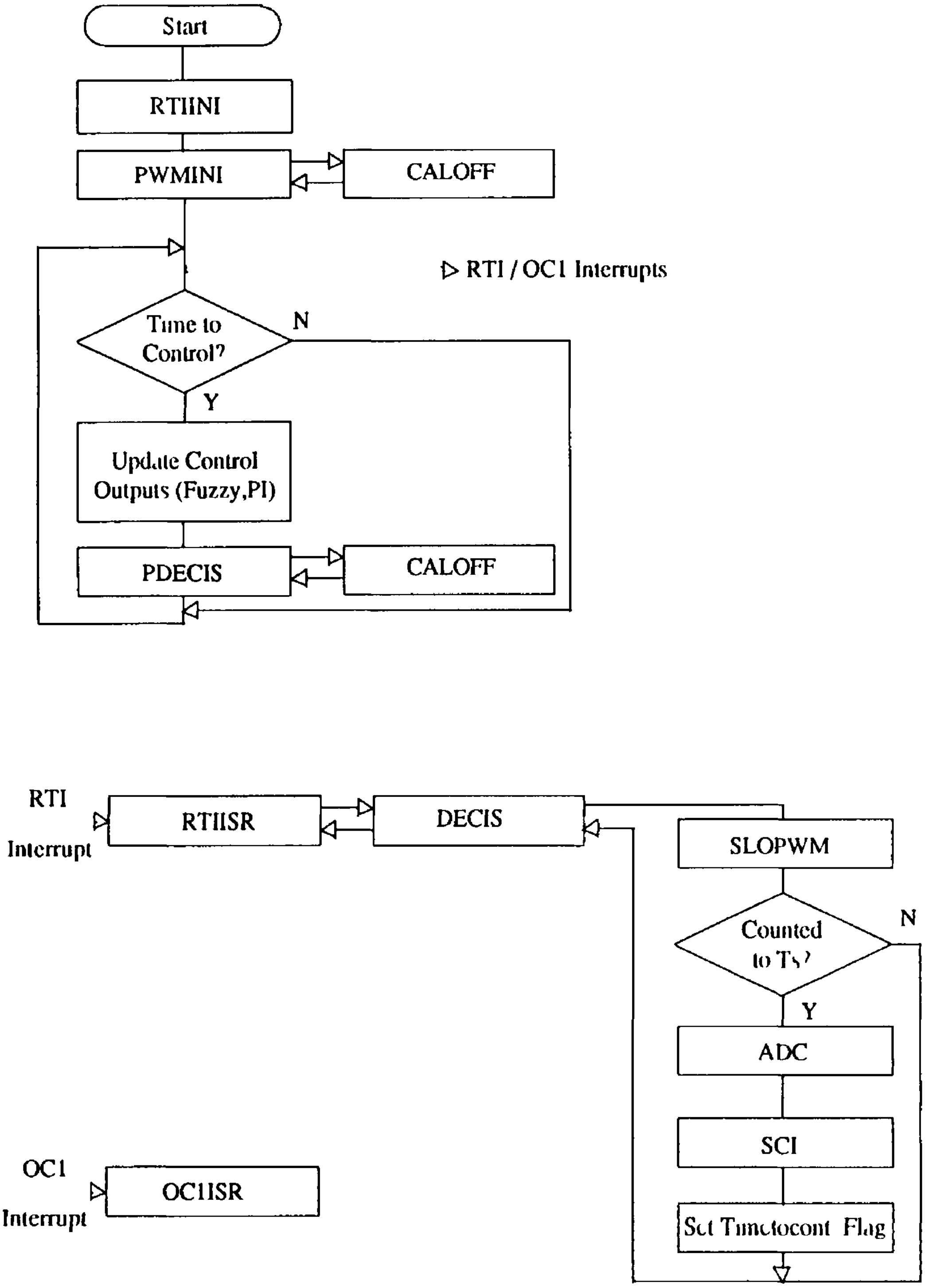


Fig B.4: *Flowchart for Subroutine RTIINI*

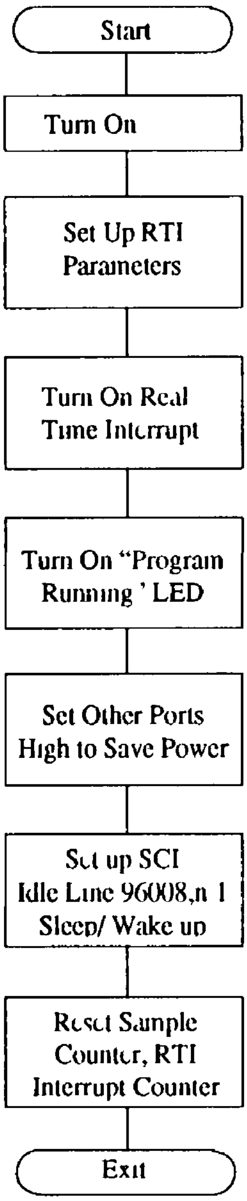


Fig B.5: *Flowchart for Subroutine DECIS*

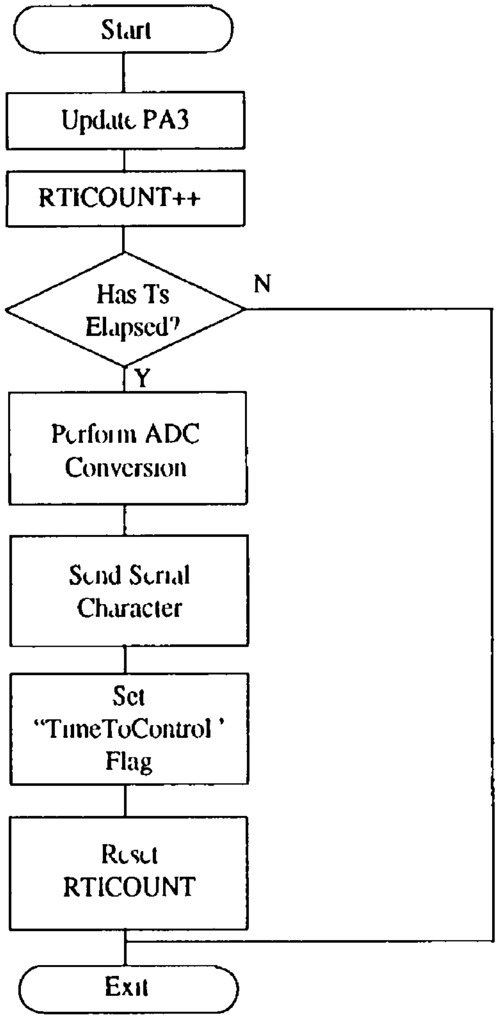


Fig B.6: *Flowchart for Subroutine ADC*

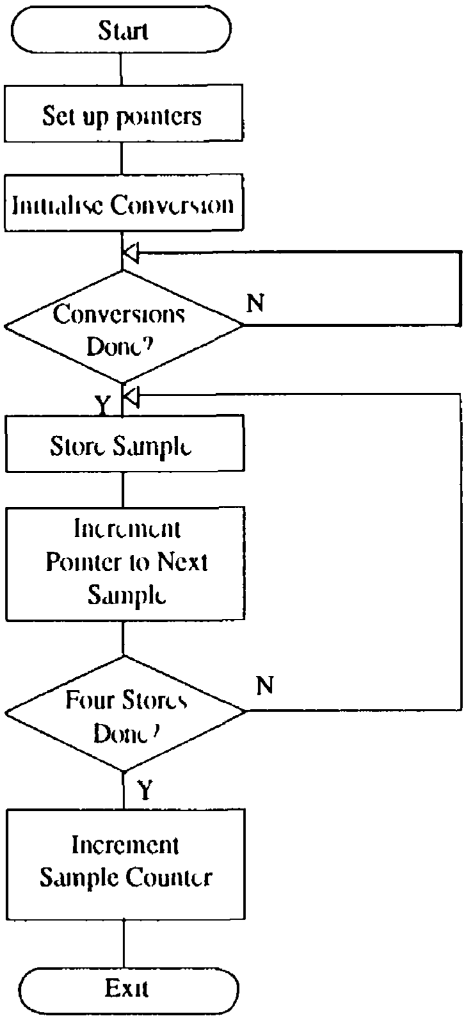


Fig B.7: *Flowchart for the Subroutine SCI*

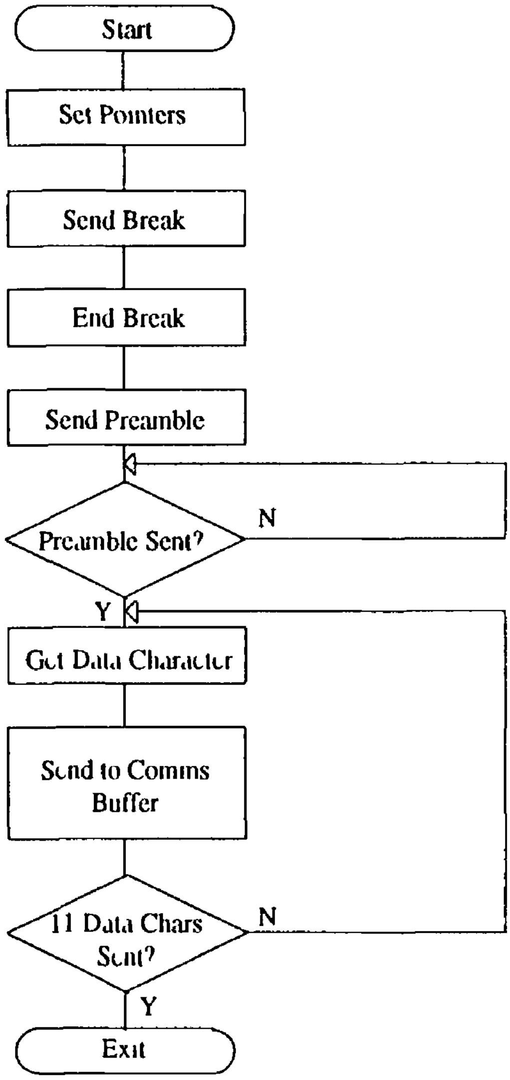


Fig B.8: *Flowchart for Subroutine PWMINI*

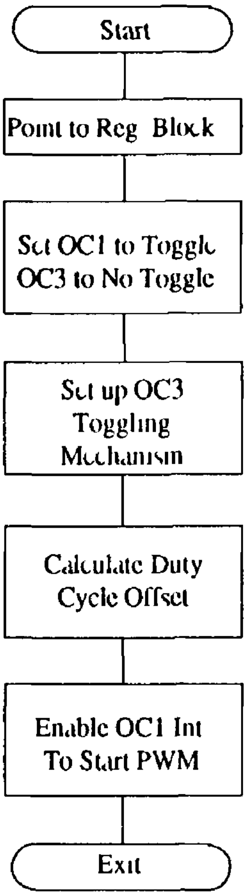


Fig B.9 *Flowchart for Subroutine PDECIS*

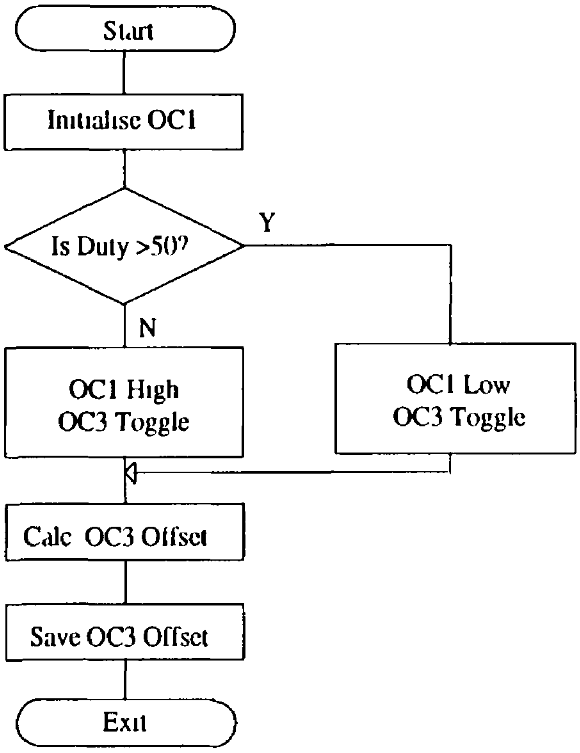
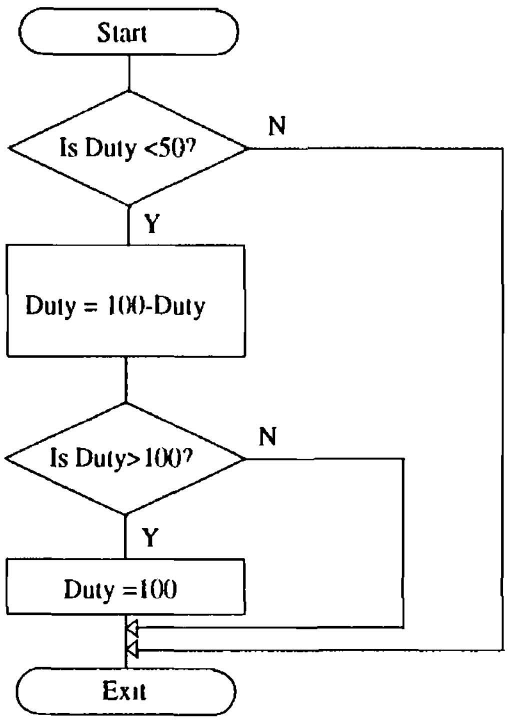


Fig B.10: *Flowchart for Subroutine CALOFF*



Appendix C: Parameters used in Model of Cropping House

C.1: Variables in Model and Values of Parameters for Original Model

A_c	Surface area of cover $[1.53\,m^2]$
A_t	Surface area of trays $[2.5\ 10^{-1}\,m^2]$
A_w	Surface area of water $[m^2]$
c_{pa}	Specific heat capacity of air $[1010\,Jkg^{-1}K^{-1}]$
c_{pw}	Specific heat capacity of water $[4200\,Jkg^{-1}K^{-1}]$
e	Current vapour pressure $[mbar]$
e_s	Saturation vapour pressure $[mbar]$
E	Evaporation from crop canopy $[kgs^{-1}]$
I_h	Current through heater $[2A]$
L_{ai}	Leaf area index $[6]$
q_v	Volumetric flow rate of air in cropping house $[ms^{-1}]$
Q_c	Heat lost through conduction to outside $[W]$
Q_{cv}	Heat lost by convection $[W]$
Q_{iv}	Heat in by ventilation $[W]$
Q_{ov}	Heat out by ventilation $[W]$
Q_{si}	Short – wave radiation flux inside $[W]$
Q_{si}	Short – wave radiation flux outside $[W]$
M_{iv}	CO_2 in due to ventilation $[kgs^{-1}]$
M_{ov}	CO_2 out due to ventilation $[kgs^{-1}]$

Q_{lw}	Heat transferred due to LW radiation $[W]$
Q_{v}	Heat out due to ventilation $[W]$
Q_{si}	Heat gained due to SW radiation in cropping house $[W]$
Q_{so}	Heat gained due to SW radiation outside cropping house $[W]$
r_{H}	Resistance to sensible heat diffusion at boundary layer $[577 sm^{-1}]$
r_{v}	Resistance to diffusion of water vapour boundary layer $[sm^{-1}]$
r_{s}	Stomatal diffusion resistance $[sm^{-1}]$
W_{iv}	Water vapour in due to ventilation $[kgs^{-1}]$
W_{ov}	Water vapour out due to ventilation $[kgs^{-1}]$
v_{a}	Volume of air in unit $[1\ 39m^{3}]$
v_{w}	Volume of water in unit $[54l]$
V_{h}	RMS voltage applied to water heater $[220V]$

α Albedo of canopy and water surface $[0.6]$

Δ Change of saturation vapour pressure with temperature $[mbarK^{-1}]$

ε Emissivity of a "black body" $[\ ]$

Φ_a CO_2 concentration of inside air $[kgm^{-3}]$

Φ_c CO_2 concentration in chlorophyll $[kgm^{-3}]$

Φ_e CO_2 concentration of outside air $[kgm^{-3}]$

Φ_{meso} CO_2 concentration at mesophyll $[kgm^{-3}]$

Γ_a Absolute humidity of inside air $[kgm^{-3}]$

Γ_e Absolute humidity of outside air $[kgm^{-3}]$

γ^* Penman's modified psychrometer constant $[66Pa]$

η Efficiency of heater $[0.95]$

λ Latent heat of vapourisation $[2.454\ MJkg^{-1}]$

θ_a Temperature of inside air $[K]$

θ_e Temperature of outside air $[K]$

θ_{cold} Temperature on cold side of conducting material $[K]$

θ_{hot} Temperature on hot side of conducting material $[K]$

θ_w Temperature of water $[K]$

ρ_a Density of air $[1.2kgm^{-3}]$

ρ_w Density of water $[1000kgm^{-3}]$

σ Stefan – Boltzmann constant $[5.76\ 10^{8}\ WK^{-4}]$

τ_c Optical transmission co – efficient of cover material $[0.85]$

C.2: Values of Parameters which were Changed for Modified Model

v_w $[12l]$

η $[0.25]$

r_d $[10]$

Appendix D: Extra Calculations

E1: Calculation of the Linear Approximation of the Rate of Net Long Wave Radiation Emissions from the Crop Canopy and Nutrient Surface.

The incident long wave radiation at the surface is given by

$$Q_{lwi} = \sigma\theta_a^4 \qquad \textit{Eqn D1}$$

where θ_a is the temperature of the surrounding air expressed in Kelvin and σ is the Stefan-Boltzmann constant

The long wave radiation emitted by the crop canopy and nutrient solution surface can be expressed by

$$Q_{lwo} = \sigma\theta_w^4 \qquad \textit{Eqn D2}$$

Where θ_w is the temperature at the crop canopy and nutrient solution surface which is slightly greater than θ_a and is also expressed in Kelvin

The temperature of the crop canopy and nutrient solution surface may be expressed as

$$\theta_w = \theta_a + \Delta\theta \qquad \textit{Eqn D3}$$

where $\Delta\theta$ is the difference in temperature between the nutrient solution surface and the air inside the cropping house

The net heat loss from the crop canopy and nutrient solution surface is then

$$Q_{lw} = \sigma(\theta_a + \Delta\theta)^4 - \sigma\theta_a^4 \qquad \textit{Eqn D4}$$

By expanding this equation, we arrive at the following

$$Q_{lw} = \sigma\left(4\theta_a^3\Delta\theta + 6\theta_a^2\Delta\theta^2 + 4\theta_a\Delta\theta^3 + \Delta\theta^4\right) \qquad \textit{Eqn D5}$$

Since $\Delta\theta$, the difference between the two temperatures θ_a and θ_w, is typically in the range 0°C -10°C, it is insignificant when compared to their absolute values when expressed in Kelvin By ignoring the terms involving $\Delta\theta^2$ and higher orders we get

$$Q_{lw} = 4\sigma\theta_a^3\Delta\theta \qquad \textit{Eqn D6}$$

Note This is the long wave radiation exchange per unit area of the interface between the two media To allow for any area of interface it is necessary to multiply the above equation by A_s, the area of the interface

If we assume that θ_a is 22 5^{0}C = (22 5+273)K which is roughly the average of the temperature range used in this study, then the product

$4\sigma\theta_a^3$ = **(4)(5 67x10^{-8})(273+22 5)^3** = **5 852** which is approximately equal to **5.9**

Since equation D6 represents a difference in heat exchange, there is no offset term in the equation to account for that conversion to Kelvin So equation D4 may be approximated by the following linear equation

$$Q_{lw} = 5\,9(\theta_w - \theta_a) \qquad \textit{Eqn. D7}$$

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