University of Zimbabwe

Research project

A flexible computer based irrigation control system

By

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ABSTRACT

The project seeks to investigate the possibility of efficient water use in irrigation scheduling systems through the use of a designed flexible computer based irrigation control system. One of the specific objectives of the project was, to develop an irrigation control software program for a drip irrigation system, which will monitor and manage irrigation in the greenhouse. The other specific objectives of the project are to experimental determine the control parameter such as leaf area index, thermal conductance constant *Ksh*, which are inputs to the developed control program. The final objective of the project was to test the designed control system in a greenhouse. The designed irrigation control system consisted of a combination of hardware, software and electric devices that monitored the plant sap flow variations in a plant via a sap flow gauge, data logger and an interface card. Four voltage signals from the sap flow gauge were sent to the computer via the interface board for computations and control purposes. The processed signals were sent back to the relay card via the same interface board for the actual control of irrigation scheduling. In the control program development phase a software program flowchart was developed followed by the development of actual irrigation control program using Visual Basic 6 enterprise edition (VB6.0) complier. The control program parameters were determined with relative errors as follows, average stem diameter of the rose plant (11.37 $\pm$ 0.04mm), the averaged total leaf area ($29.25 \pm 0.06 \times 10^{-3} m^2$), leaf area index (2.58 $\pm$ *0.19)*, thermal conductance constant (0.846 $\pm$ 0.002). The peak stem sap flow rate during the field testing (implementation) period was found to be in the range of 16 - 18 g h^{-1}, corresponding to crop transpiration rates of 0.01-0.03 kg s^{-1}. The current grower system applied 337.4 litres of water for 24 minutes each day of the two field testing days. It was also observed that the designed control system applied less water on both days of implementation, supplying 323.8 and 326.7 litres respectively. The project also reviews the relative suitability of different plant water deficit indicators for specific crop and climatic situations.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Irrigated agriculture uses about 70% of the available fresh water resources on a global scale[1]. As the world population expands and economies grow, the competition for fresh water increases, while water resources get more polluted and limited due to recurrent droughts and high cost of production. Water-saving agricultural practices and sound water management strategies are therefore urgently required to ensure the long-term viability of the agriculture industry[2]. Water management is very important in irrigated areas since it determines the amount of water used, energy consumption and labour costs. It also has implications on the soil characteristics, such as water logging, salinity and leaching. Irrigation is the artificial application of water to the soil in crop production, this is done as a way to replace water used by the plant, or to supplement rainfall. A good irrigation control system maximizes irrigation efficiency by applying the exact amount of water needed to replenish the soil moisture to the desired level through the use of proper irrigation scheduling techniques.

An approach to irrigation scheduling with considerable promise for efficient water management is to base irrigation on measurements of the actual crop water consumption by the plant, such as monitoring sap flow or a property of the plant that responds to water stress such as leaf turgor pressure and trunk diameter[3]. These systems can be manual or automated. However, recent developments have focused on automated scheduling using plant water status monitoring (the speaking plant concept). Measurements of plant-water use in comparison to rainfall, soil moisture, and irrigation water supplied can enable calculation of the water balance or water deficit in the plant, which then determines the amount of water to be applied to replenish the water loss at a predetermined interval. A good irrigation control system can inform the grower to manually apply a specific volume of water for the area intended, or may automatically open irrigation valves until the water balance is replenished or water deficit in the plant is satisfied.

The advent of precision irrigation methods such as trickle irrigation has played a major role in reducing the water required in agricultural and horticultural crops, but has highlighted the need for improved accurate irrigation scheduling and control methods. The choice of irrigation scheduling method depends to a large extent on the objectives of the irrigator and the irrigation system available. The more sophisticated scheduling methods generally require higher-precision application systems.

1.1 Problem formulation and justification

Roses are one of the most important cash-crop flowers in Zimbabwe. These crops are typically grown under drip irrigation systems in greenhouses, where optimal conditions can be achieved for maximum production and optimization time of harvest in order to satisfy specific market needs**.** The current irrigation control systems in Zimbabwe use measurements of soil water content or use weather data to calculate evapotranspiration rates or establish irrigation thresholds for irrigation management. The major problems associated with these control systems are that they are not accurate and may lead to over or under-irrigation, especially when the plant demand increases or declines temporarily under changing environmental conditions. In addition, the current control systems do not respond rapidly enough to meet the demand of the plant. Automated irrigation control systems require the use of soil, crop, or environmental sensors to determine the need for irrigation and then either a controller or a computer to control the irrigation sequence. The common problem with existing irrigation controllers is that they are typically factory set with a designated group of features that may not be modified.

1.2 Aim and objectives of the project

This project seeks to investigate the possibility of efficient water use in an irrigation scheduling system through the use of a flexible computer-based irrigation control system

The specific objectives of the project are to:

i) Design a flexible computer-based irrigation control system using real time sap flow measurements;

ii) Program, interface and test the designed control system;

iii) Implement the sap flow based control system in a greenhouse and evaluate its performance by comparing it against an existing operational system.

1. 3 Anticipated benefits/results

The benefit expected from this research project is to introduce a relatively cheap and flexible computer-based automated irrigation control system that provides efficient water management, low energy consumption and low labour requirements in irrigated agriculture.

1.4 Structure of the project

Chapter 1 is devoted to introducing the scope and justification of the research project. The relative suitability of different plant water deficit indicators for specific crop and climatic situations are reviewed in Chapter 2. This review is aimed at indicating the strengths and weaknesses of different irrigation scheduling approaches, highlighting their suitability over different spatial and temporal scales. Some sections of chapter 2, familiarizes the reader with the fundamental energy balance method used to measure heat flux and sap flow in the stem in determining the plant's water consumption. The last section of chapter 2 is devoted to the theory of automated irrigation systems. Chapter 3 reviews the details of materials and methods used in the development of this research project, outlining the developmental phases sequentially. The developmental phases discussed are the computer and electronic interfacing, control program development, and implementation/field-testing of the designed irrigation system. Chapter 4 presents experimental results and discussion of measurements of quantities required for the development of the control program, and implementation. The field testing results and evaluation of data/discussions are also presented in this chapter and forms the fundamental findings of this research project. Chapter 5 provides a brief summary, and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

There is a growing need to provide a diverse range of agricultural products to feed the increasing world population in the face of a decreasing supply of fresh water. Consumers are demanding food products that are safe to eat and that have been produced in such a way as to minimise the environmental footprint (natural production). This entails effective management of water and agrochemicals. Worldwide there are increasing concerns about the availability and quality of fresh water for agriculture, which must also be shared with other water-user sectors. The problem becomes severe especially in arid and semi-arid areas, where water for irrigation is becoming more scarce due to recurrent droughts. In the last decades, the reaction of the scientific community to this problem has been to invest a substantial amount of research into new irrigation technologies, focusing on more efficient scheduling approaches[3]. Plant-based methods are considered to have the greatest potential for efficient irrigation scheduling method, though with limitations. Improved scientific and practical knowledge on plant responses together with advances in electronic sensors and automated equipment for monitoring and data acquisition are helping to overcome some of these limitations[4]

2.1 Water conservation and management in agriculture

Water conservation refers to the reduction of the use of fresh water, through technological or social methods. It can be defined as improved water management practices that reduce or enhance the efficient use of water. A water conservation measure is an action, device, technology, or improved design or process implemented to reduce water loss, waste, or use[5]. The goals of water conservation efforts include: 1) sustainability, which refers to ensuring availability of water for future generations: the withdrawal of fresh water from an ecosystem should not exceed its natural replacement rate; 2) energy conservation resulting from water pumping, delivery, and waste water treatment facilities, which consume a significant amount of energy; and 3) efficiency of the water management system. For crop irrigation, optimal water efficiency means minimizing losses due to deep percolation, evaporation or runoff.

2.1.1 Crop water requirement

Crop water requirement is defined as the amount of water required to compensate the water loss from a cropped field.[2] Water is lost in a cropped field from the soil surface by evaporation and by the transpiration process of the plants (evapotranspiration). The two processes of evaporation and transpiration occur simultaneously in the field and hence the term evapotranspiration. Transpiration consists of the vaporization of water contained in plant tissues and the removal of the vapour to the atmosphere. Crops predominately lose their water small openings on the plant leaves known as stomata. Evaporation is the process whereby water is converted to water vapour and removed from the soil surface. The process is highest for a young crop and reduces as the crop develops and shades the soil. Evaporation can be reduced to as little as 5% of the total evapotranspiration at full canopy when the soil surface is completely shaded[5]. The factors that affect evapotranspiration include weather parameters, crop characteristics, soil management and environmental aspects. Weather parameters include solar radiation, air temperature and humidity and wind speed. The crop characteristics comprise of the resistance to the transfer process, crop height, crop roughness, reflection, ground cover and crop rooting. Management and environmental aspects of interest are soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases, pests and poor soil management. A number of methods are used to determine the crop water requirements, and can be classified as direct and indirect methods. The direct methods entail that the measurement of the soil water or plant water status is done directly by sensing the water deficit in a plant or soil moisture content. Plant water status can be measured using different techniques, which include monitoring sap flow and telemetry. Soil moisture measurements include hand feel and appearance of the soil, lysimeters, electric resistance blocks, gravimetric soil moisture sampling, tensiometers, and neutron probes. The indirect methods may vary from calculation by simple empirical formulae of the water balance approach to sophisticated mass and energy balance models. The crop water requirement is used as the basic irrigation indicator in an efficient irrigation scheduling method.

2.1.2 Water Efficiency

Water efficiency can be defined as the accomplishment of a function, task or process that results in the minimal amount of water feasible or an indication of the relationship between the amount of water required for a particular purpose and the amount of water used or delivered. The value and cost-effectiveness of a water use efficiency measure must be evaluated in relation to its effects on the use and cost of other natural resources (e.g. energy or chemicals). In irrigated agriculture water- use- efficiency (WUE) is defined by equation (2.1).

$$\text{Water use efficiency (WUE)} = \frac{\text{Yield per unit area}}{\text{Water used to produce yield}} * 100 \qquad (2.1)$$

Yield can be the total above-ground biomass of the plant or the total grain or fruit weight and in the denominator there is the total water input into the system (i.e. irrigation and rainfall) is taken into account Improved WUE can come about by either crop improvement that increases transpiration efficiency (defined as dry matter accumulated per unit water used) or by agronomic and/or technical management that maximize transpiration by reducing the other irrigation water losses i.e. runoff, soil evaporation, and deep percolation.

2.2 Irrigation methods and techniques

In general, the goal of an efficient irrigation system is to supply the entire field uniformly with water, so that each plant has the amount of

water it needs, neither too much nor too little, thus avoiding runoff and deep percolation. Runoff can be defined as the water that leaves the boundaries of a field as stream flow over the surface. This is usually of no beneficial use in irrigated agriculture and is considered a loss, even though, in some instances it can be recollected for use either downstream or on the same field. Runoff picks up sediments and agrochemicals, especially fertilizers, and becomes contaminated. It also reduces the soil productivity. Deep percolation is the fraction of the water that moves through the soil to below the root zone, at which it is unavailable to the crop. It can result from over irrigation or the non-uniformity of irrigation over a field area. It has the potential to be reused downstream although it is of much poorer quality than the original irrigated water. Both runoff and deep percolation can be reduced considerably by use of appropriate irrigation scheduling technique. Various types of irrigation techniques are available, and these differ in how the water is obtained from the source and distributed within the field.

2.2.1 Irrigation methods

Irrigation methods vary low sophisticated such as surface irrigation, overhead irrigation, to highly sophisticated ones such as micro-sprinkler irrigation, drip irrigation and centre pivot irrigation

2.2.1.1 Surface irrigation

In surface irrigation systems water moves over and across the land by simple gravity flow in order to wet it and to infiltrate into the soil.

2.2.1.2 Manual irrigation using buckets or watering cans

These systems have low requirements for infrastructure and technical equipment but need high labor inputs. Irrigation using watering cans is to be found for example in peri-urban and rural agriculture areas in most African countries.

2.2.1.3 Overhead irrigation

Water is piped to one or more central locations within the field and distributed by overhead high-pressure sprayers or lower-pressure sprinklers. The sprayers can be hidden below ground level, if esthetics is a concern, and pop up in response to increased water pressure. Individual sprayers can be designed to rotate in a full or partial circle. At the high-tech end, computerized, automatically moving wheeled setups may irrigate large areas unattended. At the low end, a person may water each plant individually with a watering can. Much water can be lost because of high winds or evaporation, and irrigating the entire field uniformly can be difficult or tedious.

2.2.1.4 Lateral move irrigation

A series of pipes, each with a wheel of about 1.5m diameter permanently affixed to its midpoint and sprinklers along its length, are coupled together at one edge of a field. Water is supplied at one end using a large hose. After sufficient water has been applied, the hose is removed and the remaining assembly rotated either by hand or with a purpose-built mechanism, so that the sprinklers move 10m across the field. The hose is reconnected. The process is repeated until the opposite edge of the field is reached. This system is less expensive to install than center pivot and is most often used for small or oddly-shaped fields, such as those found in hilly or mountainous regions.

2.2.1.5 Centre pivot irrigation

The centre pivot system is propelled by electric motors or hydraulic motors located on each wheel of the drive system. Centre pivot irrigation is a form of sprinkler irrigation consisting of several segments of pipe (usually galvanized steel or aluminum) joined and supported by trusses, mounted on wheeled towers with sprinklers positioned along its length. The system movement can be circular or lateral. The system is fed with water from the pivot point at the center of the arc. Most center pivot systems now have drops hanging from a u-shaped pipe called a gooseneck attached at the top of the pipe with sprinkler heads that are positioned a few meters (at most) above the crop, thus limiting evaporative losses.

2.2.1.6 Localized irrigation

In localized irrigation the water is distributed under low pressure through a piped network, in a pre-determined pattern, and applied as a small discharge to each plant or adjacent to it. Drip irrigation, spray or micro-sprinkler irrigation and bubbler irrigation belong to this category of irrigation methods.

2.2.1.6.1 Micro-sprinkler irrigation

Here water is applied as to the soil surface as spray droplets or tiny streams through miniature spray heads placed along a water delivery line called a lateral or feeder line. The typical wetted diameter is 0.6 to 2.2 m with discharge rates less than 4.5 litres per hour.

2.2.1.6.2 Drip Irrigation

In drip irrigation, water is delivered drop by drop through an emitter to or near the root zone of plants. If managed properly, this method can be the most water-efficient method of irrigation, resulting in minimized evaporation and runoff. In modern agriculture, drip irrigation is often combined with plastic mulch to further reduce evaporation, and can also be a means of delivering fertilizer and agrochemicals. The process is known as fertigation. Drip irrigation methods range from very high-tech and computerized to low-tech and relatively labor-intensive. In some instances the irrigation tape can be buried at depth range of 10.2 to 12.7 cm below the surface.

2.2.2 Irrigation efficiency

The term irrigation efficiency is used to express the ratio of the percentage of water used efficiently and the percentage of the water lost in irrigation. The scheme irrigation efficiency (ε - %) is that part of the water pumped or diverted through the scheme inlet, which is used effectively by the plants. The scheme irrigation efficiency can be sub-divided into: the conveyance efficiency (ε_c), which represents the efficiency of water transport, and the field application efficiency (ε_a), which represents the efficiency of water application in the field. The conveyance efficiency (ε_c) mainly depends on the characteristics of the water delivery system (eg. the length of the canals, the soil type or permeability of the canal banks and the condition of the canals). The field application efficiency mainly depends on the irrigation method and the level of the farmer discipline. Once the conveyance and field application efficiency have been determined, the scheme irrigation efficiency can be calculated, using equation (2.2):

$$\varepsilon = \frac{\varepsilon_c \times \varepsilon_a}{100} \tag{2.2}$$

A scheme irrigation efficiency of 50-60 % is good; 40 % is reasonable, while a scheme irrigation efficiency of 20-30 % is poor. In large irrigation schemes there is a greater percentage loss of water than in small schemes, this is due to the larger water delivery system of the former. The pressures to improve irrigation efficiency and to use irrigation for precise control of vegetative growth both imply a requirement for increased precision in irrigation control. Such objectives can only be met by precision irrigation systems such as drip irrigation that can apply precise amounts of water at frequent intervals (often several times per day). The effective operation of such systems equally requires a sensing system that determines the irrigation need in real time or at least at frequent intervals.

This rules out large-scale manual monitoring programs for such purposes and indicates a need for automated irrigation monitoring and control systems

2.2.3 Irrigation scheduling techniques

Irrigation scheduling is the technical procedure of determining when an irrigation event should occur and how much water should be applied. Several irrigation-scheduling methods have been developed to assist farmers and irrigators to apply water more efficiently based on soil water measurement, meteorological data or monitoring plant water stress. Irrigation scheduling has conventionally aimed to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity. However, increased need for enhanced water use efficiency and for greater precision in irrigation systems are likely to provide a real impetus for the development of new precision irrigation scheduling systems that take account of the irrigation need of individual plants, and may well involve greater use of plant-based sensing systems. There are potential opportunities for use of weather based (meteorological) methods, simulation models and plant-based stress sensing as the basis for irrigation scheduling and control. Although plant-based sensing has several potential advantages, including a greater relevance to plant functioning than soil-based measures, these may be offset by a number of practical difficulties of implementation that have thus far limited the development of commercially successful systems. Both water balance and meteorological methods can provide estimates of evapotranspiration, which includes soil evaporation and plant water use while plant based techniques measure transpiration alone. Thus sap flow techniques have the advantage that it can be used to portion or split evapotranspiration between plant and soil.

2.2.3.1 Weather based approaches

Most of automated irrigation control systems are based on measurement of environmental parameters as inputs for feedback control. Reference evapotranspiration is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water [2]. An evaporation pan, eddy currents correlation, The Bowen ratio method [5], or models that use the evaporative demand of the atmosphere, such as the modified Penman-Monteith equation, can be used to determine the reference evapotranspiration [2]. The evapotranspiration from a cropped field is calculated from reference evapotranspiration using crop factors. Crop evapotranspiration (ET_c) under standard conditions is related to the reference evapotranspiration (ET_0), using experimentally determined crop coefficients (K_c). The relationship is in the following form shown in equation (2.3):

$$ET_c = K_c \times ET_0 \tag{2.3}$$

Due to variations in the crop characteristics throughout its growing season, K_c changes according to stage of growth. The daily reference evapotranspiration, ET_0, can be determined by models that use the evaporative demand of the atmosphere, such as the modified Penman-Monteith equation (2.5) [6].

$$ET_o = \frac{0.408\Delta(R_a - G) + \gamma(900/(T+273))u_i VPD}{\Delta + \gamma(1+0.34u_i)} \tag{2.5}$$

Where R_a is the net radiation at the crop surface (MJ m^{-2} per day), G the soil heat flux density (MJ m^{-2} per day), T the air temperature at 2 m height(°C), u_1 the wind speed at 2 m height (m s^{-1}), VPD the vapour pressure deficit (kPa), Δ the slope of the vapour pressure curve at T (kPa °C^{-1}) and γ the psychrometric constant (kPa °C^{-1}).

2.2.3.1.1 Evaporation pan

The evaporation pan is a simple device that has been used for a long time to provide estimates of crop water requirements while integrating all the evaporative components of the environment. It is used to hold water during observations for the determination of the quantity of evaporation at a given location. Such pans are of varying sizes and shapes, the most commonly used being circular or square.

Evaporation is measured daily as the depth of water (in mm) of the evaporated quantity from the pan. The measurement day begins with the pan filled to a marked initial level of the pan. At the end of 24 hours, the amount of water evaporated, E_{pan}, is determined from the remaining depth of the water. If precipitation occurs within the measuring period, it is taken into account in calculating the evaporation. Often the evaporation pans are automated with water level sensors and a small weather station located nearby. The reference evatranspiration (ET_0) is then calculated from the pan readings using the relation in equation (2.4):

$$ET_0 = K_p \times E_{pan} \tag{2.4}$$

Where ET_o is the daily reference evapotranspiration (mm); K_p is a monthly pan factor and E_{pan} is daily pan evaporation (mm) measured on site by the class A-pan.

2.2.3.2 Soil-water based approaches

The soil water balance method is the most commonly used method in planning and management of irrigated agriculture, it monitors the change in the water stored in the root zone [7] . The soil water balance method is achieved by tracking the incoming and outgoing water fluxes at the root zone. The water inputs to the soil are rainfall (P), irrigation (I) and capillary rise (CR) from a shallow groundwater table as shown in Fig 2.1. The loss of water from the soil is through processes of soil evaporation and evapotranspiration (*ET*), runoff (*RO*), subsurface outflow (*SF*) and deep percolation (*DP*).

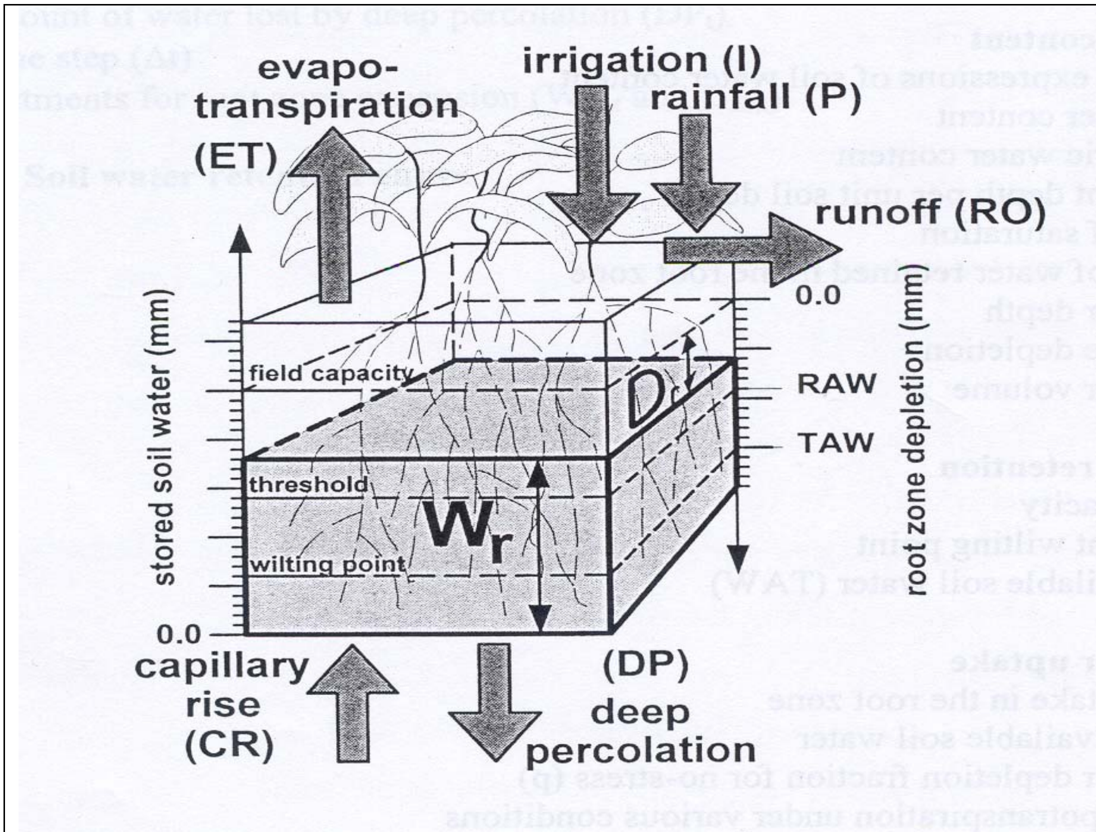

Figure 2.1: Water balance of a cropped soil [7]

The object of this irrigation technique is to obtain a balance of incoming and outgoing water fluxes so that adequate water is maintained and available for the plant[3]. The soil water balance can be calculated either as soil water content or crop water requirements. Crop water requirement is defined as the amount of water required to compensate the evapotranspiration loss from a cropped field. The general equation is as given in equation (2.6):

$$ET_c = I + P - RO - DP + CR \pm \Delta SF \quad (2.6)$$

Irrigation scheduling can then be based on a water balance algorithm of the form given by equation (2.7):

$$SW_i = SW_{(i-1)} + I + R - ET_c - DP - RO \quad (2.7)$$

Where SW_i is soil water content on day i, $SW_{(i\text{-}1)}$ is soil water content on day (i-1), I is irrigation (mm), R is rainfall (mm), ET is evapotranspiration (mm), DP is deep percolation losses and RO is run-off. Rainfall is measured using a manual rain gauge and is considered dependable when it is greater than 20 mm. DP and RO are assumed to be zero since drip irrigation water was applied to artificial culture, such that the soil water balance between dates (i-1 and i) is defined as can be seen in equation (2.8):

$$SW_i = SW_{(i-1)} - (ET_c) + (I + R) \quad (2.8)$$

A potential problem with all soil-water based approaches is that, many features of the plant's physiology respond directly to changes in water status in the plant tissues, whether in the roots or in other tissues, rather than to changes in the bulk soil water content (or potential). The actual tissue water potential at any time depends both on the soil moisture status and on the rate of water flow through the plant and the corresponding hydraulic flow resistances between the bulk soil and the appropriate plant tissues. The plant response to a given amount of soil moisture therefore varies as a complex function of evaporative demand. As a result it has been suggested in theory that greater precision in the application of irrigation can be obtained by a third approach, the use of plant need for water "stress" sensing’ [3].

2.2.3.3 Plant based approaches

A number of plant physiological processes are known to respond sensitively to water deficits in a plant, and can be used as an effective irrigation indicator. Specific plant based methods include dendrometry or micromorphometry, leaf turgor pressure, sap flow, stomatal conductance, infrared thermometry and thermography. It can be expected that a direct measure of plant water status should be the most rigorous and hence the most useful indicator of irrigation requirement. In general, the use of any plant-based indicator for irrigation scheduling requires the definition of reference or threshold values, beyond which irrigation is necessary. Such reference values are commonly determined for plants growing under non-limiting soil water supply [8]. The choice of which plant-based measure to use depends on their relative sensitivity to water deficits and cost, as shown in Table 2.1.

Table 2.1. Relative sensitivity, cost and commercial application potential of selected plant indicators of water stress for irrigation scheduling

Indicators	**Sensitivity**	**Capital cost**	**Commercial applications**
Direct indicators			
Leaf water potential	Moderate	Low	Poor
Stomatal conductance	Moderate	High	Poor
Stem water potential	High	Low	Poor
Sap flow	High	Moderate	Good
Indirect indicators			
Canopy temperature	Moderate	Low	Good
Thermal imaging	High	High	Good
Fruit and stem diameter	High	Low	Good

In practice, as has been argued strongly in theory that most plants exercise some measure of autonomous control over their shoot or leaf water status, tending to minimize changes in shoot water status as the soil dries or as evaporative demand increases[8] . In the long term, this control is achieved through changes in leaf area and root extension, and in the shorter term through changes in leaf angle, stomatal conductance, and hydraulic properties of the transport system (sap flow)

2.2.3.3.1 Sap flow based approach

There are two main types of liquid that flows along the plant stem, these are the upward sap flow, which consists of water with dissolved nutrients from roots up to the crown through the xylem, and the downward flow of photosynthesis products through the phloem. Phloem is a living tissue forming a thin layer (about 1 mm) located between the bark and the woody xylem tissues. Sap flow takes place in the conductive xylem tissues known as sapwood, located in the outer part of the stem cross-sectional area. Sapwood is usually more than one order thicker than phloem. Whereas the linear velocities of the phloem and the xylem flows may be comparable[9]. The volumetric flow in the phloem is negligible relative to the volume transported via the xylem conductive area. The sap flow pattern is usually not homogeneous across the stem, its radial profile is generally asymmetric with one maximum in the outer part of the sapwood[9]. Only over long time periods, such as 24 hours or 12 daytime hours, will transpiration and sap flow be substantially equal. The possible difference over shorter periods of time is caused by changes in the water content of the plant above the gauge and on larger gauges it may be caused by a time lag in the measurement of sap flows. The size or duration of this difference depends on the plant species, size, and the environmental conditions. Appropriate sap-flow rates to use as ‘control thresholds’ may be derived by means of regular calibration measurements, especially for larger trees. Alternatively, it is at least feasible in principle to derive an irrigation-scheduling algorithm that is based on an analysis of the diurnal patterns of sap flow, with midday reductions being indicative of the developing water deficits

2. 3 Measurement of sap flow in plant stems

Water requirements of individual plants can be determined using sap flow sensors. These sensors are capable of adapting easily to visible or exposed stems, which makes them appropriate for agricultural irrigation research, particularly in row crops[10]. The changes in transpiration rate that sap flow indicates are largely determined by the changes in stomata aperture. Transpiration is also influenced by other environmental conditions such as humidity. Therefore, the changes in sap flow can occur without changes in stomatal opening. Even though rates of sap flow may vary markedly between trees as a result of differences in tree size and exposure, the general patterns of the change in response to both environmental conditions and to water status are similar[11] Transpiration rates for whole plants, individual branches or tillers can be determined by measuring the rate at which the sap ascends stems. All of the available techniques for triggering irrigation use heat as a tracer for sap movement, but they are fundamentally different in their operating principles. Two methods which commonly employed are the stem heat balance and the heat-pulse method. In the former, the stem is heated electrically and the heat balance is solved for the amount of heat taken up by the moving sap stream, which is then used to calculate the mass flow of sap in the stem. In the heat-pulse method, rather than using continuous heating, short pulses of heat are applied and the mass flow of sap is determined from the velocity of the heat pulses moving along the stem. In addition, rates of sap flow can be determined empirically, using the thermal dissipation technique, from the temperature of sapwood near a continuously powered heater implanted in the stem. When attempting to estimate transpiration by stands of vegetation from measurements of sap flow in individual plants, it is important to select an appropriate sampling strategy and scaling method. Sap flow methods are easily automated, so continuous records of plant water use with high resolution can be obtained.

2.3.1 Thermal dissipation method

It is an empirical method for measuring sap flow in plants.[12] Two cylindrical probes of 2 mm diameter are inserted radially into the stem, with one probe placed approximately 100 mm above the other, as shown in Fig. 2.2.

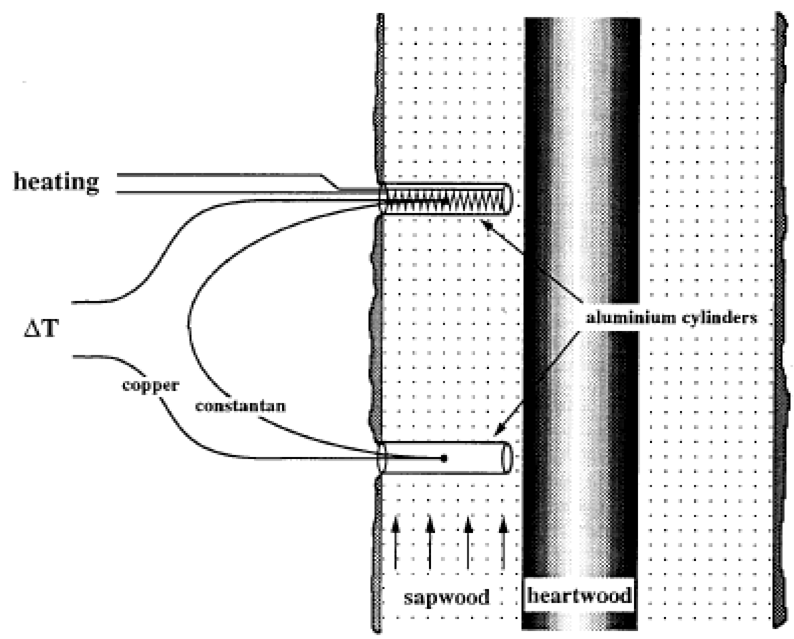

Figure 2.2: Thermal dissipation set-up[12]

The upper probe contains a heater element and a thermocouple junction that is referenced to another junction in the lower probe[12]. Constant power is applied to the heater and the difference in temperature between the two probes (ΔT) is then dependent on the rate of sap flow around the probes; as sap flow rates increase, heat is dissipated more rapidly and so ΔT decreases. Granier (1985) found experimentally that for Pseudotsuga menziesii (Mirb.) Franco, Pinus nigra Arnold and Quercus pedunculata Ehrh, volumetric sap flux density (U_v in $m^3m^{-2}s^{-1}$) is related to ΔT [12] by equation (2.8)

$$U_v = 0.000119Z^{1.231} \tag{2.8}$$

With Z defined as in equation (2.9)

$$Z = \frac{(\Delta T_o - \Delta T)}{\Delta T} \tag{2.9}$$

Where ΔT_o is the value of ΔT when there is no sap flow, and ΔT is the instantaneous change in temperature. The mass flow rate of sap is then calculated using equation (2.10)

$$F_m = \rho_s U_v A_{sw} \tag{2.10}$$

Where p, is the density of sap and A_{sw} is the cross-sectional area of sapwood. The major advantages of the thermal dissipation method appear to be easy installation, simple requirements for recording sensor outputs, simple sap flow calculations and lower costs. The disadvantage of method is the need to scale for the whole field.

2.3.2 The heat-pulse method

In the heat-pulse method, the rates of sap flow are measured by determining the velocity of a short pulse of heat carried by the moving sap stream, rather than the heat balance of a heated stem. Short pulses of heat are periodically released from the heater probe and the sensor probes are monitored continuously to measure the velocity of each pulse as it moves with the sap stream. This method is suitable only for use on woody stems. Heater and sensor probes are installed by drilling holes into the sapwood, hence its use is limited to stems that are large enough to accommodate these, but not so large that the full depth of sapwood cannot be accessed. Each set of heat-pulse probes comprises one heater probe and two sensor probes containing miniature thermistors approximately 1 mm in diameter. It houses a resistance wire in a stainless steel cylinder, while sensor probes are constructed by mounting thermistors in either Teflon or stainless steel tubing. Figure 2.3 shows a single installation.

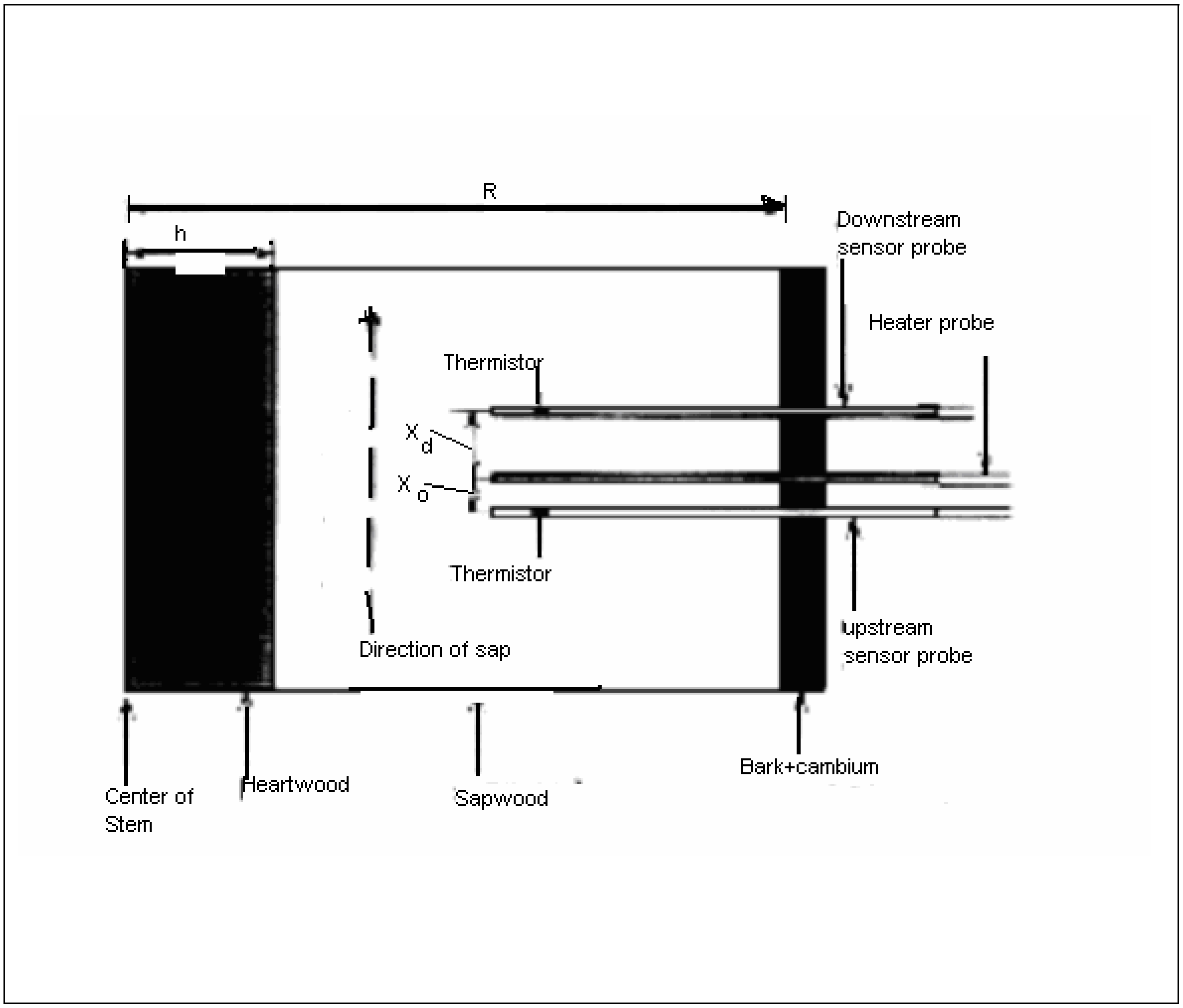

Figure 2.3: Configuration of a single set of heat-pulse probes implanted radially into a stem of radius R at the cambium and H at the heartwood boundary[12]

The upstream temperature sensor is installed at a distance x_o below the heater and the down stream sensor at a distance x_d above the heater. In practice, four sets of heat-pulse probes are typically used to measure sap flow, one installed in each quadrant of the stem. The probes are implanted in parallel holes drilled radially into the stem, with one sensor probe (the upstream probe) placed 5 mm below the heater and the other (the downstream probe) placed 10 mm above the heater

The heat-pulse technique is based on the compensation principle. The velocity of the sap ascending a stem is determined by compensation of the measured velocity of a heat pulse for the dissipation of heat by conduction through the matrix of wood fibres, water and gas within the stem. With modern instrumentation, this is accomplished by deploying the sensor probe at unequal distances upstream and downstream of the heater probe, with the upstream sensor placed nearer to the heater than the down stream sensor[12]. Immediately after the release of a pulse of heat of 1-2 s duration, the temperature becomes higher at the closer, upstream sensor than at the downstream sensor because of conduction. The heat carried by the moving sap then quickly warms the downstream sensor, such that the temperature of the two sensors is again equal after a time, $t_c = 60$ s, as shown in Fig 2.4.

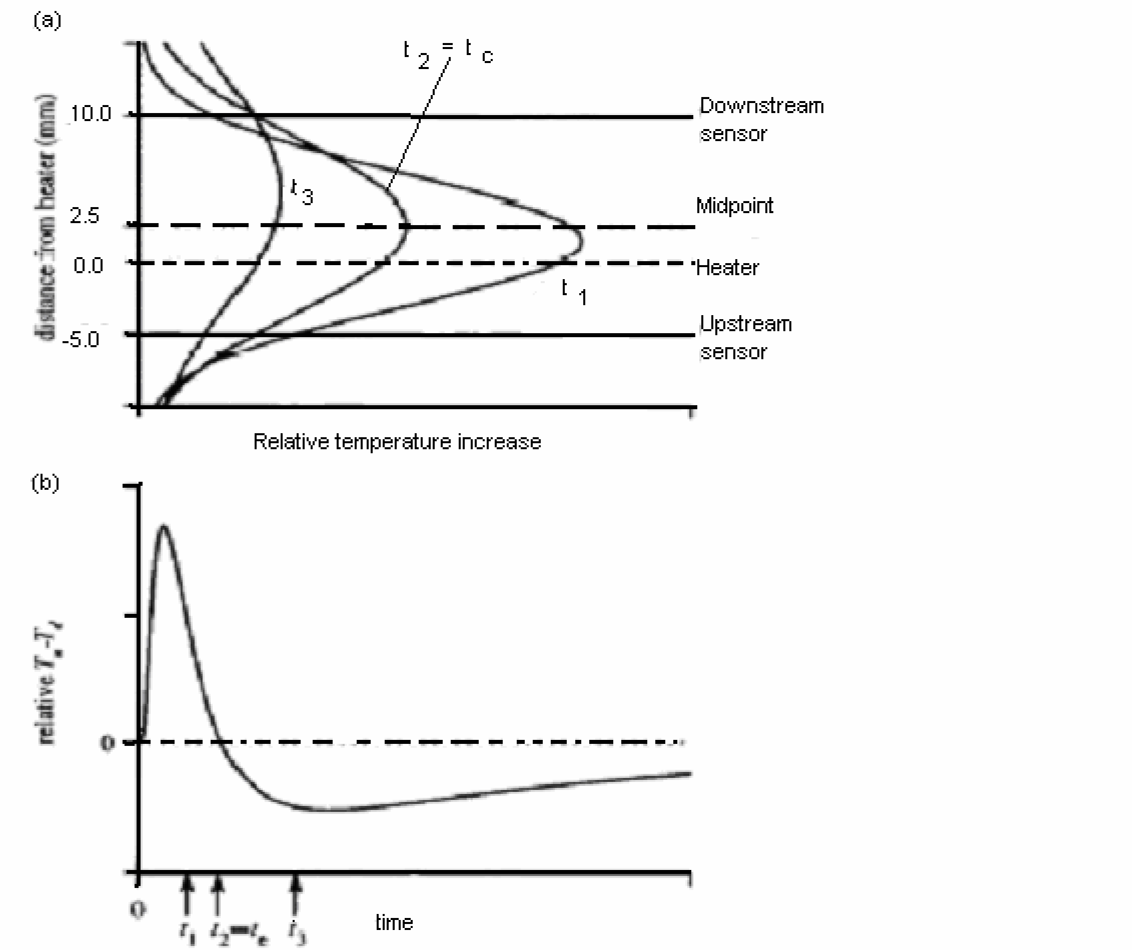

Figure 2.4: Dissipation of a heat pulse released from a line heater into a stem containing moving sap and upstream sensor probes. (a) The distribution of relative temperature at times t_1, t_2 and t_3 after the release of the heat pulse; the temperature of the upstream and downstream sensors probes are equal at t_c. (b) Change with time in the temperature difference between the upstream and downstream temperature sensors (T_u -T_d) after the release of the heat pulse[13]

In Fig. 2.4, t_c is the time required for convection in the moving sap stream to move the peak of the heat pulse from the heater to the point midway between the two temperature sensors, so that t_c decreases as sap velocity increases. The velocity of the heat pulse (V_b) is given by the Swanson and Whitfield equation (2.11)[14].

$$V_b = \frac{(x_d - x_o)}{2t_c} \tag{2.11}$$

Where x_o and x_d are the distances between the heater and the upstream and downstream sensors respectively. It was demonstrated analytically that V_b in woody stems is not identical to sap velocity[13]. The analysis of the diffusion of heat in wood containing moving sap showed that heat ascends the stem more slowly than sap because of the transfer of heat between the moving sap and the stationary, interstitial tissue between the xylem vessels or the tracheas[13]. For thermally homogeneous wood, where conducting elements are uniformly spaced and interstitial thickness is sufficiently small that the time required for equilibration of sap and woody matrix is negligible, it was found that the velocity of sap (V_s) is related to V_b by equation (2.12).

$$aV_s = \frac{\rho_{am} C_{am}}{\rho_s C_s} \times V_h \tag{2.12}$$

Where a is the fraction of the cross-sectional area of conducting sapwood occupied by moving sap streams and, ρ and C are density and specific heat capacity, with the subscripts s and am referring to sap and sap plus woody matrix (including gas), respectively. The volumetric sap flux density per meter squared of sapwood (U_v) is then given by equation (2.13)

$$U_v = a\ V_s \qquad (2.13)$$

So that, theoretically, sap flux densities can be determined from measured values of V_b using equations 2.11 and 2.12 without having to quantify *a*, provided the condition of thermal homogeneity is satisfied and values of ρ_s, ρ_{am}, C_s, C_{am} are known.

2. 3. 3 The stem heat balance method

The stem heat balance method is used to measure the sap flow in both the hollow and the herbaceous stems. It has been used on stems as small as 4 mm in diameter, as well as on tree branches and the trunks of small trees. Heat is applied to the entire circumference of the stem encircled by the heater. The mass flow of sap is obtained from the balance of the fluxes of heat into and out of the heated section of the stem as shown in Fig 2.5. +

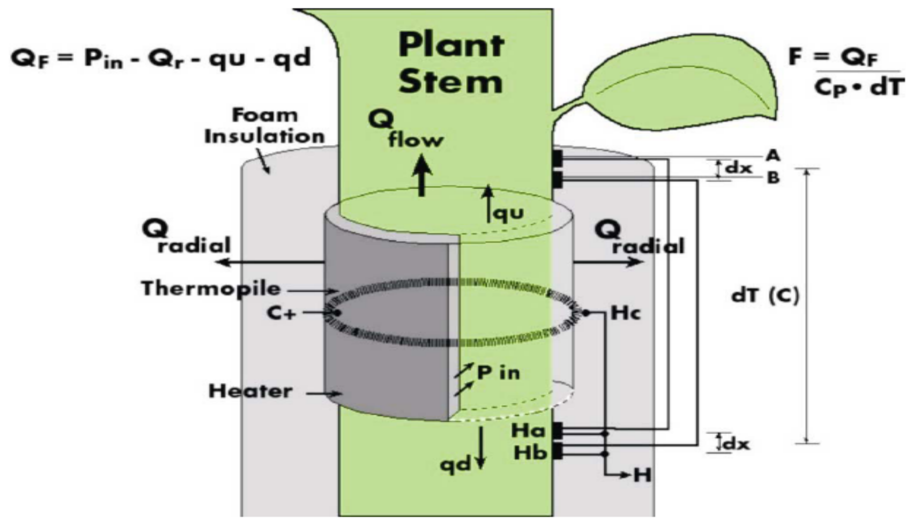

Figure 2.5: Stem section and the possible components of heat flux, assuming no heat storage. The foam insulation and weather shield surrounding the stem extend above and below the heater sufficiently to minimize erroneous thermal gradients across the heated section of stem and reduce solar heating of the stem to a negligible level

The heater surrounds the stem under test and is powered by a DC supply with a fixed amount of heat, which is proportional to the power input to the stem, P_{in}. This heat is dissipated as q_r, the radial heat conducted through the gauge to the ambient, qv, the vertical, or axial heat conduction through the stem, and q_f, the heat uptake by the moving sap stream (as shown in Fig. 2.6). The vertical component, q_v has two components, heat that ascends the stem $q_{u,}$ and heat that descends the stem q_d.

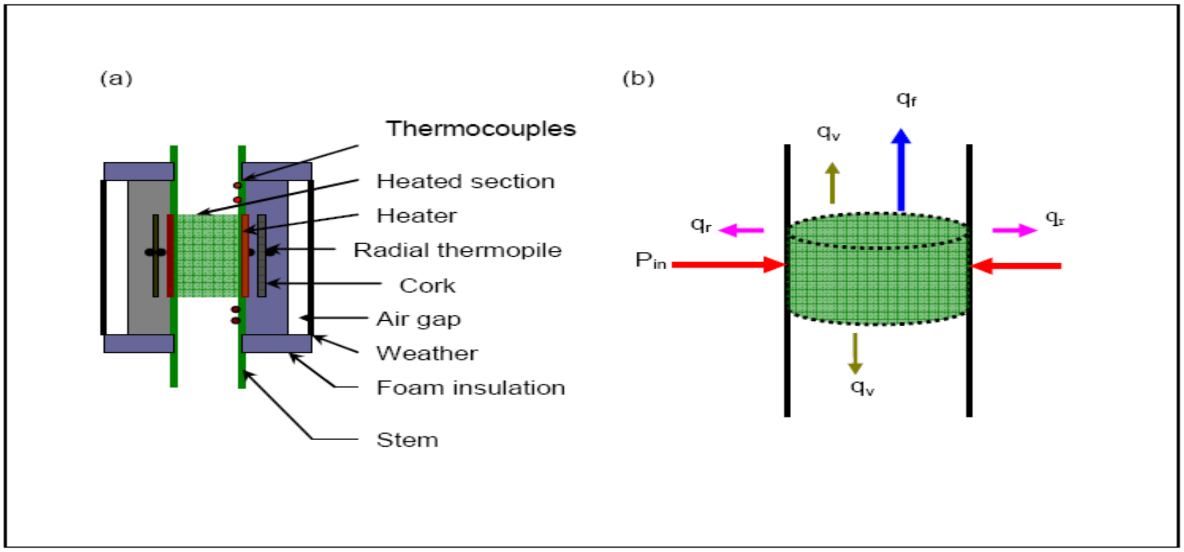

Figure 2.6: Stem gauge set, showing thermocouple junction and thermopile positions and the heat flux components[12]

The heat balance of the stem (assuming no heat storage) is defined as shown in equation (2.14). [12]

$$Pin = q_v + q_r + q_f \tag{2.14}$$

By measuring P_{in}, q_v and q_r, the remainder, q_f can be calculated. The heat input to the stem section is limited to the electrical power supplied to the heater (P_{in}) as can be seen in fig 2.6, so that:

$$P_{in} = \frac{V^2}{R} \tag{2.15}$$

Where V is the input voltage to the heater element, and R is the resistance of a given gauge. The vertical and radial components, q_v and q_r, respectively, are determined from measurements of temperature differences at two-thermocouple junctions and a thermopile junction, ΔT_a, ΔT_b and ΔT_r respectively. The value of q_v is calculated using Fourier's Law for one-dimensional heat flow from the upward and downward gradients in temperature (ΔT_b and ΔT_a) away from the heater[12]. The sum of these gradients is algebraically equivalent to measurement of sap flow ($\Delta T_b + \Delta T_a$), so that q_v is obtained from equation (2.16)

$$q_v = K_{st} A_{st} \left(\frac{\Delta T}{dx} \right) \tag{2.16}$$

Where A_{st} is the cross-sectional area of the heated section of stem, K_{st} is the thermal conductivity of sapwood, $\Delta T \left(= \frac{\Delta T_b + \Delta T_a}{2} \right)$, is the temperature increase of the sap and dx is the distance between two thermocouple junctions on each side of the heater. The value of K_{st} is generally taken from the literature as 0.42 W $m^{-1}K^{-1}$ for woody stems and 0.54 W $m^{-1}K^{-1}$ for hollow stems[15]. The radial component of the stem heat balance, q_r is determined from ΔT_r(temperature difference at a thermopile junction) using equation (2.17)

$$q_r = K_{sh} \Delta T_r \tag{2.17}$$

Where K_{sh} is the effective thermal conductance of the sheath of materials surrounding the heater. The value of K_{sh} depends on the thermal conductivity of the insulating sheath and stem diameter. It usually changes for each new installation, so it must be calculated from ΔT_r and the other components of the stem heat balance during periods when there is no sap flow, and therefore q_f, is zero. Once all other components of the stem heat balance are known and q_f is determined, finally, q_f is converted to the mass flow rate of sap (F_s) calculated using equation (2.18)[16].

$$F_s = \frac{q_f}{C_p\left(\frac{\Delta T_a + \Delta Tb}{2}\right)} \tag{2.18}$$

Where C_p is the specific heat capacity of sap flow which is taken to be the same as that of water, assuming that heating of the sap is radially uniform. It has been found that errors in sap flow rates measured using stem heat balance gauges can arise if changes in the storage of heat in the heated section of stem is neglected[9]. The size of these errors increases with the diameter of the stem, but they are less important when daily rates of transpiration are determined, as the change in heat storage over a day is usually zero[14]. A term which accounts for changes in heat storage, q_s, can be added to the heat balance in equation 2.14 and quantified by measuring the change in temperature of the stem (ΔT_{st}) over a time interval, Δt as can be seen in equation (2.19)[9] .

$$q_s = C_{st}^{v} V_{st} \frac{\Delta T_{st}}{\Delta t} \tag{2.19}$$

The coefficient C_{st}^{v} is the volumetric heat capacity of stem tissue, which can be taken from values in the literature, and V_{st} is the volume of stem affected by heating, which can be reasonably approximated as the volume of stem enclosed by the heater[17]. ΔT_{st} is evaluated from measurements of the absolute temperature of the stem, made by placing a thermocouple between the heater and the surface of a small stem or by implanting a thermocouple beneath the surface of a larger stem.

2.3.3.1 Stem gauge (sensor)

There are two differentially wired thermocouples both measuring the rise in sap temperature as shown in fig 2.7. Channel AH measures the difference in temperature A-H_a (mV). Channel BH measures the difference in temperature B-H_b (mV), and channel CH measures the difference in temperature C-H_c

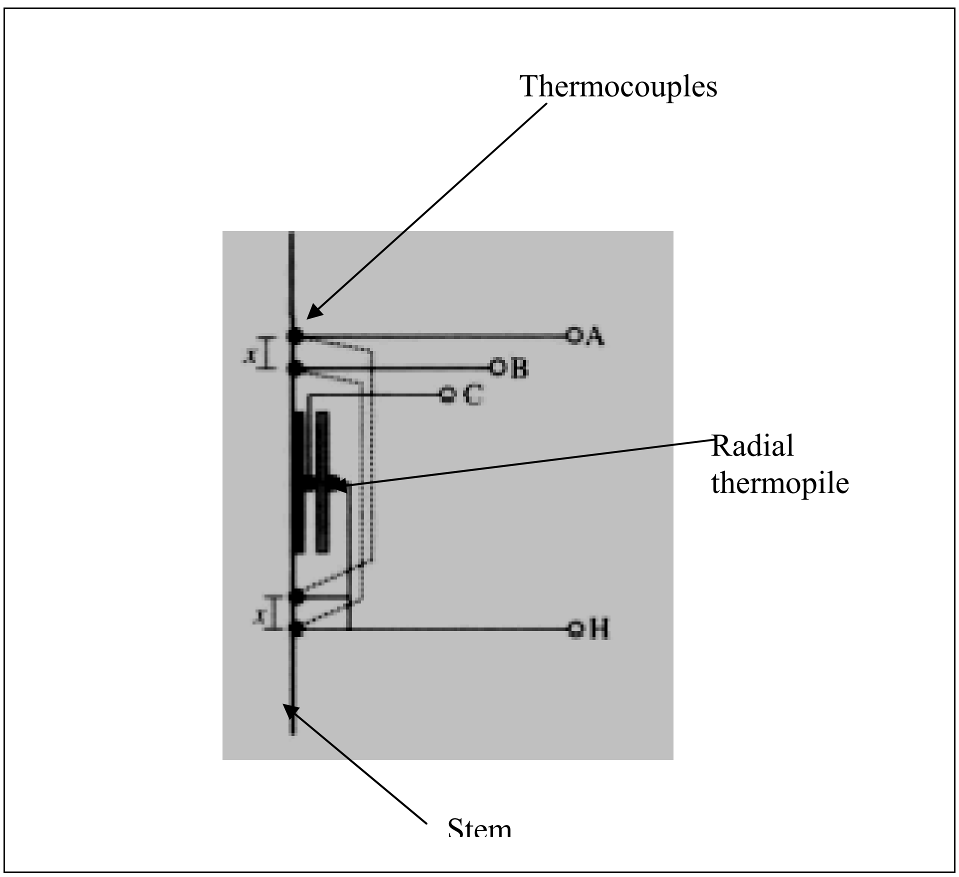

Figure 2.7: Schematic diagram of a stem gauge[17].

The channels AH and BH yields the two components of axial heat conduction out of the stem section, q_u and q_d. Since the distances separating the upper TC pair and lower TC pair are fixed by design for each particular gauge to the same value, the components of q_v are combined with a common denominator as in equation (2.20)

$$q_v = K_{st} A \frac{(BH - AH)}{dX} \times 0.040 mVC^{-1} \tag{2.20}$$

The factor 0.040 mVC^{-1} converts the thermocouple differential signals to degree celcius. The radial heat flux of sap flow is derived from equation of thermodynamics of a heated fluid in an insulated cylindrical section, at a constant temperature as in equation (2.21). The other quantises in equation 2.21 indicate the source of the K_{sh} computation and the effects of the radius of the cylinder's thermal conduction is given by equation (2.21).

$$q_r = 2(pi) K_{co} L \frac{(T_i - T_o)}{In(r_i / r_o)} \tag{2.21}$$

Where K_{co} is the thermal conductivity of the cork substrate surrounding the heater. This is where the thermopile junctions measure the temperature adjacent to the heater and on the outside of the cork. L is the length of the cylinder, T_i and T_o are the inner and outer temperatures of the insulating cylinder respectively, r_i is the inner radius, and r_o is the outer radius. For an installation of a fixed diameter, the K_{sh} represents all of the parameters and constants in equation (2.21), and relates the radial heat flux to the thermopile output CH by a constant factor as shown in equation (2.22):

$$q_r = K_{sh}\,(C\text{-}H_c) \tag{2.22}$$

The signal $C\text{-}H_c$ is directly proportional to the temperature difference between inner and outer layers of the cork substrate and therefore the heat transferred radially.

2.3.3.2 Sampling and scaling from plant to stand

After measuring the sap flow, it is often necessary to extrapolate the water use by sampled plants to an entire stand or greenhouse. The mass or volume flow rates for individual plants are converted to estimates of transpiration per unit area of land. The measurements of stem sap flow can be scaled up to crop transpiration rate by assuming that the stem sap flow is uniform throughout the crop[14]. In uniform stands, such as monoculture crops or forest plantations with closed canopies, this is relatively simple because most plants in the stand are of similar size, thus the supply of radiant energy and soil water is uniform. Transpiration is unlikely to vary strongly among the members of such stands, so that sap flow can be measured in a number of individual plants and stand transpiration calculated from plant density[18]. In thinned forest plantations with a closed canopy, where variation in plant size is low but spacing between plants is not uniform. It was found that stand transpiration could be estimated by scaling-up water use on the basis of the ground area occupied by individual plants as shown in equation (2.23)[18].

$$T_r(t) = \frac{1000}{3600} \times P_v \times A_g \times \frac{F_S(t)}{A_L} \times LAI \tag{2.23}$$

Where $T_r(t)$ is the greenhouse crop transpiration rate (kg s^{-1}), P_V is the fraction of the total greenhouse floor area covered by the crop, A_g is the total greenhouse floor area (m^2), $F_s(t)$ is the stem sap flow (g h^{-1}), A_L is the total leaf area of the plant on which the gauge is installed (m^2) and LAI is the leaf are index. Equation 2.23 forms the basis for estimating the rate of water loss by the plants in a greenhouse or stand. Many algorithms and techniques were developed to replace the water lost in a specified interval as shown in equations (2.24), (2.25) and (2.26). The volumetric rate of the water lost by the plant is given by equation (2.24).

$$V_t = \frac{T_r(acc)}{\rho} \tag{2.24}$$

Where $T_r(acc)$ is the accumulated transpiration in a time interval t_{oset}, which is set by the user, and ρ is the density of the sap, which is taken to be the same as that of water. The volume of the water lost by the plant is given by equation (2.25)

$$Vol = t_{0set}\ (V_t) \tag{2.25}$$

Time required to replace the water lost by the plants is estimated from equation (2.26)

$$t_R = \frac{Vol}{E_R \times N} \tag{2.26}$$

Where E_R is the rate at which water is lost at each emitting point along the piped and N is the total number of emitters in the entire green house or stand.

2.4 Irrigation control systems

An irrigation controller is a device used to control, electrically or otherwise, operated valves, which control the flow of water to sprinkler heads and drip lines in an irrigation system. A single irrigation valve typically controls the flow of water to a specific area of a landscape. A controller is an integral part of an irrigation system. It is an essential tool to apply water in the necessary quantity and at the right time to sustain agricultural production and to achieve high levels of efficiency in water, energy and chemical uses. An irrigation controller is responsible for selectively turning on and off a set of sprinkler valve stations [2] .

In recent years, a variety of sophisticated features has been incorporated into irrigation controllers, such as microcontrollers and microprocessors. When properly utilized some of these features can contribute to an irrigation system that makes more efficient use of the available water resources. A computer-based control system consists of a combination of hardware and software that acts as a supervisor with the purpose of managing irrigation and other related practices such as fertigation. This is done by the use of a closed control loop. A closed control loop performs the following tasks :

1) Monitoring the state variables;

2) Comparing the state variables with their desired or target state;

3) Deciding on what actions are necessary to change the state of the system

4) Carrying out the necessary actions.

Performing these functions requires a combination of hardware and software that must be implemented for each specific application.

2.4.1 Microcontroller- based systems

The micro-controller based system includes a control processor. The control processor consists of a Central Processing Unit (CPU), an input port, an output port, a memory element for storing a control program and control parameters. The control program is responsible for implementing a plurality of functionalities that are selectively enabled. The processing unit executes the control program, and there are buses which connect the processing unit to the memory element and to the input and output ports. An input device (sensor) is interfaced to the input port, and the output port provides an interface with the sprinkler valve stations for controlling the turning on and off. The operation of a microcontroller depends entirely on a series of fetching, and execution of the program instructions from the memory. The instruction decoder in the control unit decodes the instruction. Two or more instructions can be fetched from different memory locations within the microcontroller, and certain arithmetic or logic operations are performed on them in the ALU contained in the CPU. The result of which can be stored in a different register. An instruction thus fetched from program memory must be decoded to determine the assigned or user defined task that has to be executed. The major disadvantage of microcontrollers over microprocessor in that they are designed to perform specific tacks only and have restricted real-time operations.

2.4.2 Microprocessor based systems

Microprocessors have found great application in instrumentation, industrial control and aerospace. Microprocessors are used to handle a set of tasks that control one or more external events or systems. Microprocessors substitute programmed logic for hard-wired logics. The programmed logic can be placed into a semiconductor read only memories (ROMs), which have a very regular structure and hence offers even greater functionality per chip. It has been shown that a ROM can replace a large number of standard logic gates. Once the basic microprocessor module is built, a large number of logics can be added with only a few additional integrated circuits. The other or older technique of implementing the logic product in the inter-connection of the standard hardware is to have the logic stored in a ROM. This has permitted the designer to place nearly all of his product logic in a very small portion of the design tool. That is, the logic is in a few integrated circuits rather than diffused throughout the design in wiring. With the logic concentrated in only a few components, a high degree of design flexibility is possible. Applications, problem-oriented architectures with an optimum instruction set for each use are in great demand to improve system performance and efficiencies. The Central Processing Unit (CPU) usually contains an execution core with two or more pipelines, a data and address bus, a dedicated arithmetic logic unit (ALU, also called the math co-processor), and in some cases special high-speed memory for caching program instructions from RAM as shown in Fig 2.8.

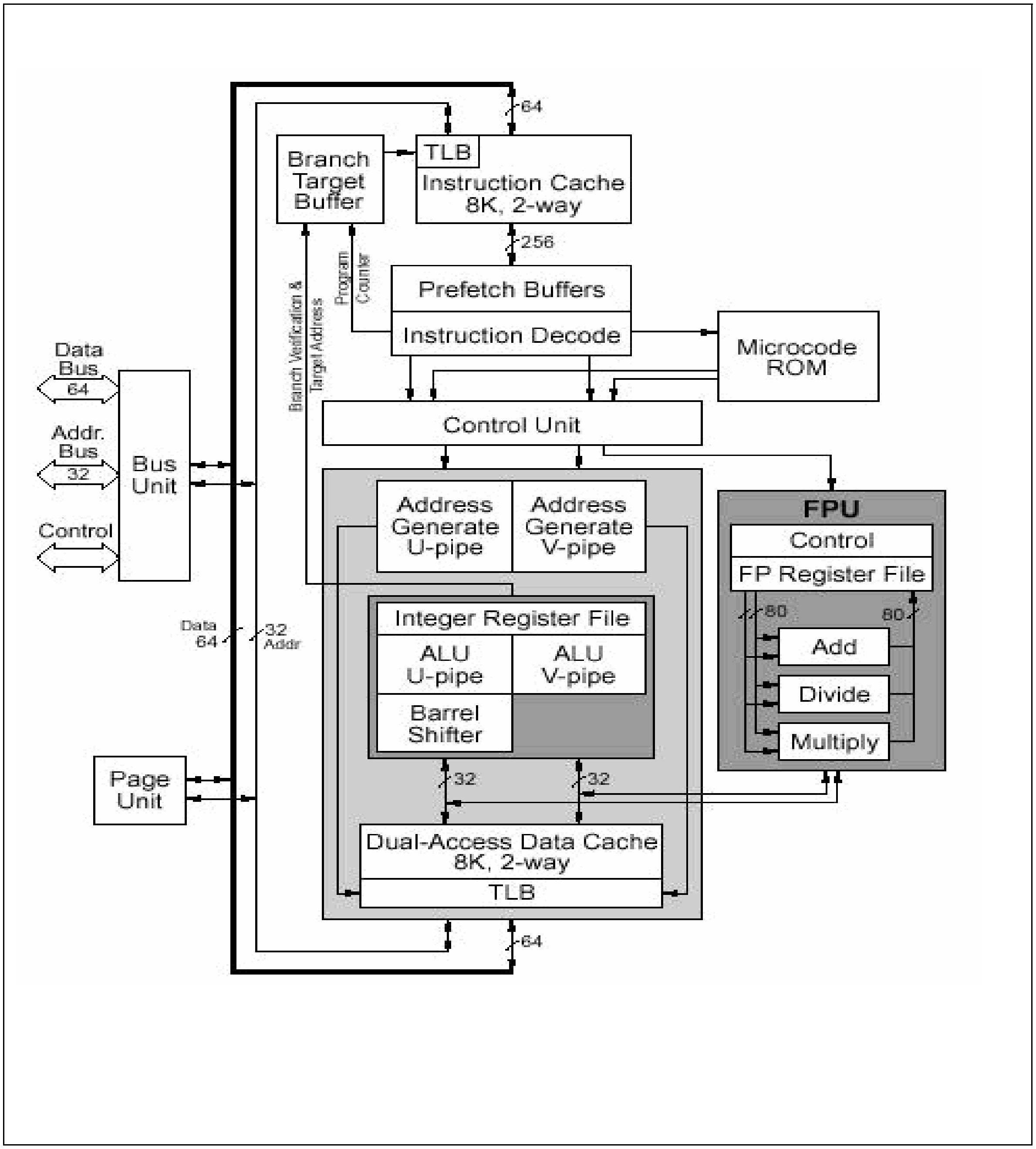

Figure 2.8: Pentium block diagram

These microprocessors are used in either reactive or embedded systems. Reactive systems are those that have an ongoing interaction with their environment and embedded systems are those used to control specialized hardware in which a computer system is installed.

Embedded system software is completely encapsulated by the hardware that it controls. The introduction of digital computers in the control loop has allowed development of more flexible control systems including higher-level functions and advanced algorithms. Furthermore, most current complex control systems could not be implemented without the application of digital hardware. However, the simple sequence sensing–control–actuation for the classical feedback control becomes more complex as well [3]. Nowadays, this sequence can be supplemented by the use of sensing–data and acquisition–control law, coupled with calculation–actuation–data base update. Thus, the control system now contains not only wired components but also algorithms, which must be programmed, i.e. software is now included in the control loop. This leads to new aspects to take into account when designing and interfacing control systems, such as real time systems.

2.4.3 Interfacing techniques

Serial data communication is the most common means of transmitting data from one point to another. In serial communication systems, the data or characters are sent bit by bit over some kind of transmission path. The receiving device recognizes the bits and resembles them back into the original data word. Serial data communication systems can be divided into binary and character oriented systems. Binary systems are generally used to send high-speed data between computers and external devices. Binary transmission systems often include data, clock and sync or frame signals. Character oriented serial systems encode characters into bit patterns that can be read on a wide variety of computer terminals, teletypes, and printers, as shown in Fig 2.9. Clocking and syncing are part of the data character design as shown in fig 2.10.

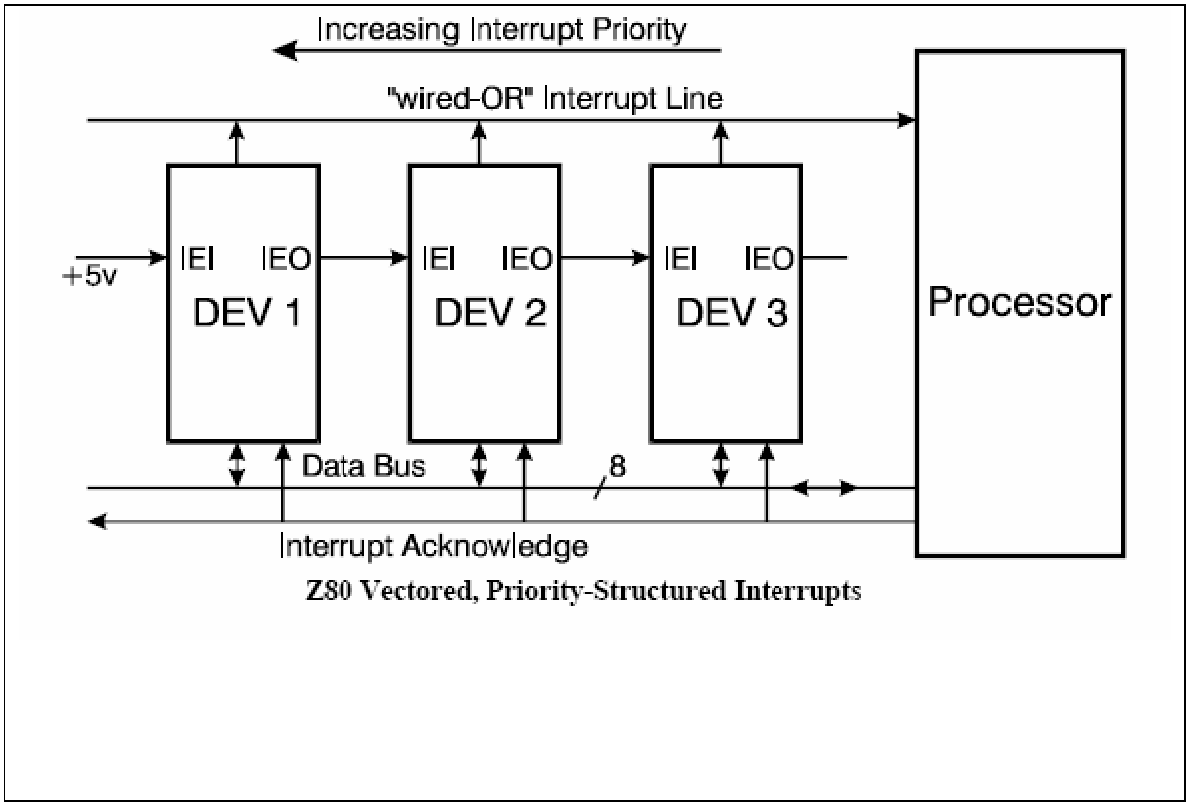

Figure 2.9: Priority-structured Interrupts

The I^2C-bus is used for 2-way, 2-line communication between different ICs or modules. The two lines are a serial data line (SDA) and a serial clock line (SCL). Both lines must be connected to a positive supply via a pull-up resistor when connected to the output stages of a device. Data transfer may be initiated only when the bus is not busy, and one data bit is transferred during each clock pulse as shown in fig 2.10.

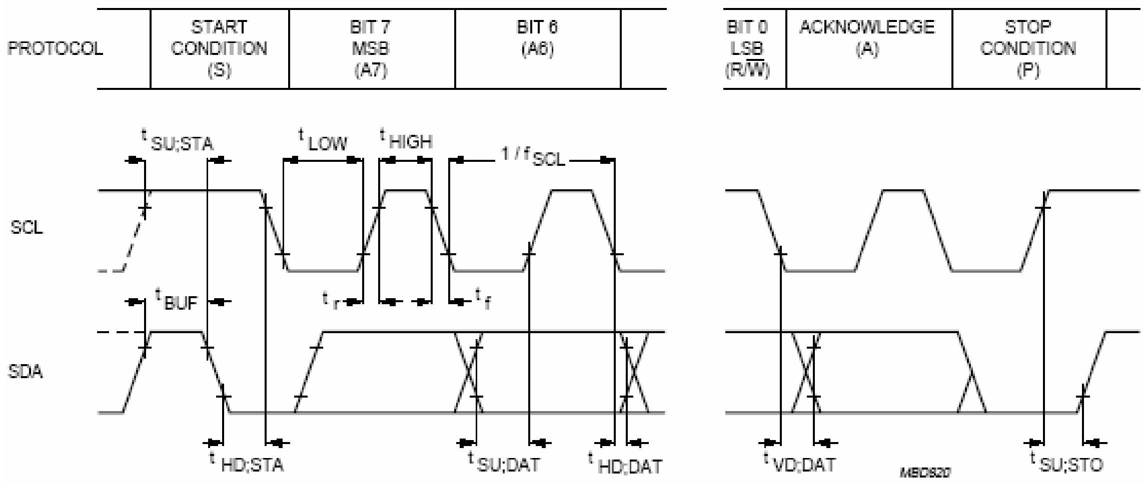

Figure 2.10: Clock pulsing, signal transmission from external device to the computer

The data on the SDA line must remain stable during the HIGH period of the clock pulse, as changes in the data line at this time will be interpreted as control signals. In start and stop conditions both data and clock lines remain high when the bus is not busy. A high-to-low transition of the data line, while the clock is HIGH is defined as the start condition (S). A LOW-to-HIGH transition of the data line while the clock is HIGH is defined as the stop condition. The number of data bytes transferred between the start and the stop conditions from transmitter to receiver is not limited. One follows each byte of eight bits is an acknowledgement bit. The acknowledge bit is a HIGH level put on the bus by the transmitter whereas the master generates an extra acknowledge related clock pulse. A slave receiver, which is addressed, must generate an acknowledgement after the reception of each byte. Also a master must generate an acknowledgement after the reception of each byte that has been clocked out of the slave acknowledges has to pull down the SDA line during the acknowledge clock pulse, so that the SDA line is stable LOW during the HIGH period of the acknowledgement related clock pulse, set-up and hold times must be taken into account. A master receiver must signal an end of data to the transmitter by not generating an acknowledgement on the last byte that has been clocked out of the slave. In this event the transmitter must leave the data line HIGH to enable the master to generate a stop condition. In I^2C-bus protocol, after a start condition a valid hardware address has to be sent to a sensing device. The read/write bit defines the direction of the following single or multiple byte data transfer. For the format and the timing of the start condition (S), the stop condition (P) and the acknowledge bit (A) refer to the I2C-bus characteristics. In the write mode sending either a stop condition or the start condition of the next data transfer terminates a data transfer.

CHAPTER 3

MATERIALS AND METHODS

3.0 Introduction

The research project was conducted in three stages: (1) computer and electronic interfacing, (2) control program development, and (3) implementation. This chapter presents a detailed description of the materials, methods and data analysis techniques used in this project. In computer and electronic interfacing a review of equipment and instruments used in this research project is done, focusing mainly on the K800 interface board, relay card. An integrity test was conducted to test the basic connection and interface between the computer, interface board, and relay card. In the control program development phase a program flowchart was developed followed by the development of actual irrigation control program using Visual Basic 6 enterprise edition (VB6.0) software. Before the designed system can be implemented several measurements and experiments were carried out to determine the necessary irrigation control parameters such as thermal conductance constant (*Ksh*), leaf area index, leaf area. In the implementation phase, the designed irrigation control system was tested and evaluated in a greenhouse by comparing it against an existing control system (weather based system).

3. 1 Computer and electronic interfacing

Equipment and instruments used in this research project include an interface board (model K8000, Velleman Components N.V., Gavere, Belgium), electronic relay card (model K6714, Velleman Components N.V., Gavere, Belgium), and an IBM Pentium 4 computer with 128RAM, 1.7GHz microprocessor. The irrigation control system designed consists of a combination of hardware and software that monitored the plant sap flow variations via an interface card and managed irrigation scheduling as shown in Fig. 3.1.

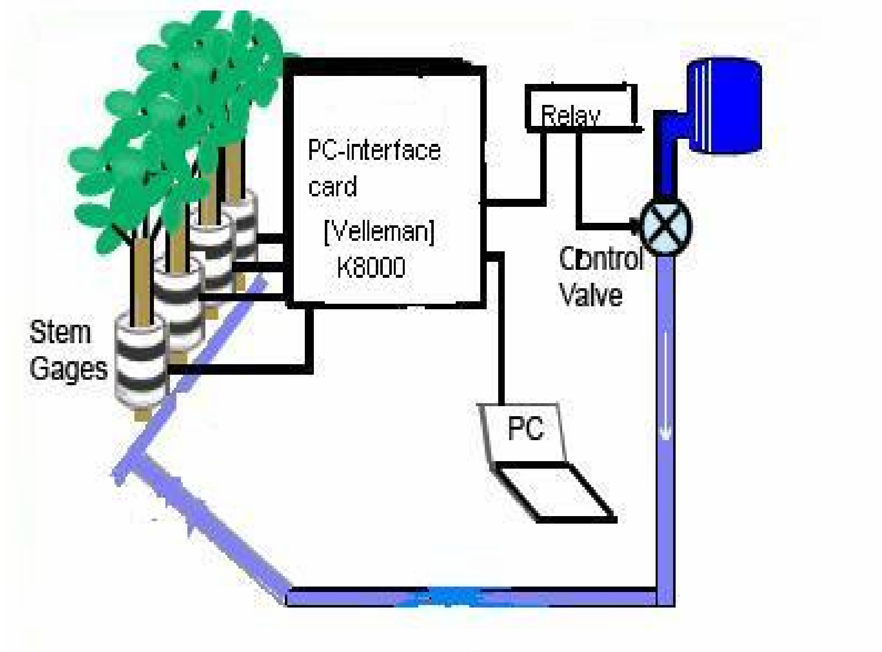

Figure 3.1: Designed computer based irrigation control system

Four voltage signals from the sap flow gauge (thermocouple voltages AH , BH, CH and input voltage V) were sent to the computer via the interface board for processing and control purposes. If the decision to switch on or off the valves is reached after computation and data processing by the developed irrigation control program, it sent to the system actuator via the same interface board and relay card. The interface board could not drive an electric device, so a relay card was used between the interface board and the valve switch (electric device). The relay card was piloted directly through open collector outputs. The electronic setup of the designed system consists of a computer, interface board, relay card and sap flow gauges as shown in the block diagram in Fig. 3.2.

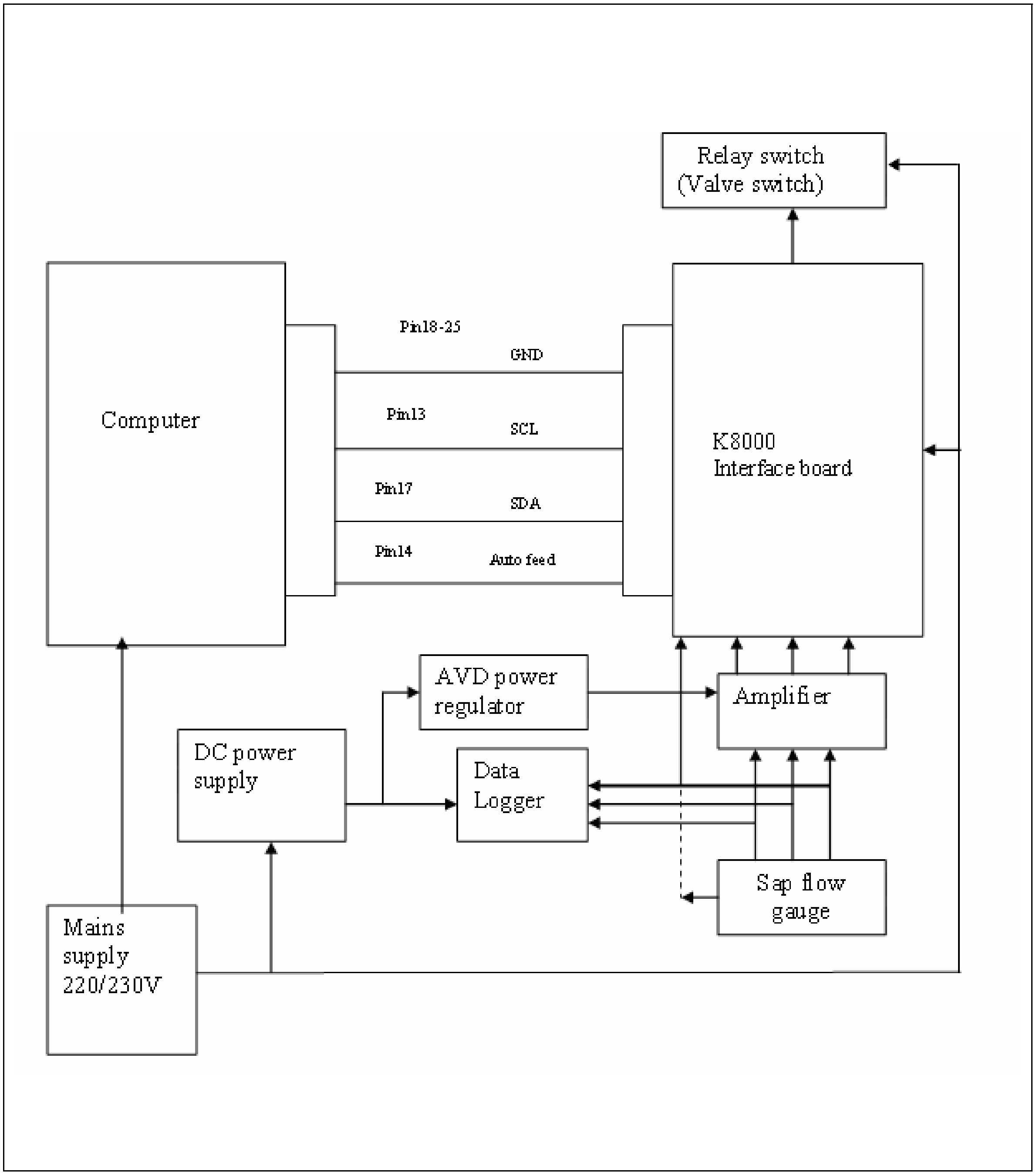

Figure 3.2: Electronic set-up of the designed system

The testing and irrigation control program was written in Visual Basic 6 enterprise edition (VB6.0). The VB6.0 program sent and received feedback commands from the interface board through a LPT1 port. The irrigation control program and the interface board communicated indirectly through the k8000 interface board's dynamic link libraries (K8D.DLL). These dynamic link libraries are a set of software functions and procedures, which allow the written computer program to exchange information and instructions with the firmware, embedded software in the IC chips constituting the interface board. The major functions of the k8000 interface board was to provide power, external clock, input/output connectors, signal conditioning components, and circuit for communicating with the computer.

3.1.1 K8000 Interface board

The K8000 Interface board has sixteen digital input/output channels, which can be used as either input or output as desired. In addition, it also has eight analogue outputs with 6-bit resolution, one analogue output with 8-bit resolution, and four analogue inputs of 8-bit resolution. The card is connected to the computer via a LPT1 printer port. Three lines from this port are used, namely, "Select" (pin 13), "Auto feed" (pin 14) and "Select in" (pin 17). The two lines are a serial data line (SDA) and a serial clock line (SCL). Both lines must be connected to a positive supply via a pull-up resistor when connected to the output stages of a device.

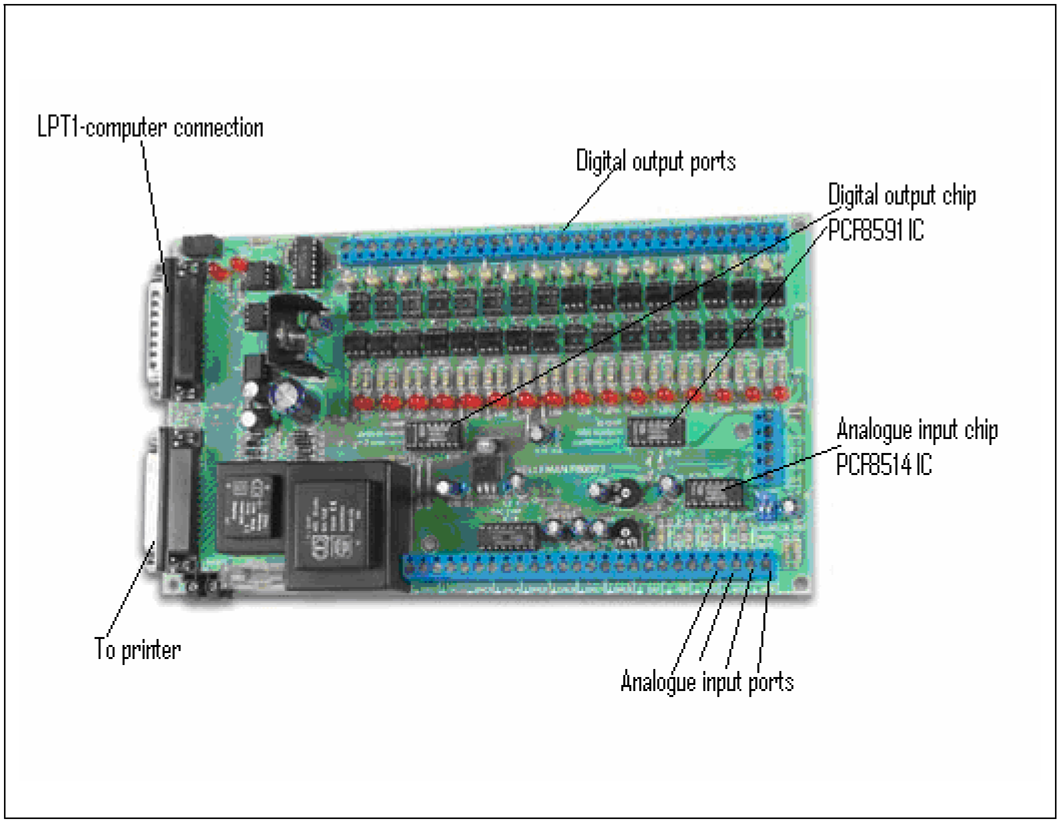

Figure 3.3: The K8000 interface board

Up to a maximum of four K8000 interface cards can be connected to a single computer, thus expanding the number of inputs/outputs. Each card is given its own identification by means of a two pole DIP-switch SW1. The K8000 board can be connected to a stand-alone microcontroller. In this project only two important ICs were utilised from the K8000 interface board, namely the input ADC chip (PCF8591) and the digital output port (PCF8574 IC), representing 70% utilization of the K8000 interface card

3.1.1.1 Input chip (ADC: PCF8591 IC)

The PCF8591 is a single-chip, single-supply low power 8-bit CMOS data acquisition device with four analogue inputs connected to a serial I^2 C-bus interface. Three address pins A0, A1 and A2 are used for programming the hardware address, allowing the use of all devices connected to a I^2 C-bus system without additional hardware. Address, control and data to and from the device are transferred serially via the two-line bi-directional I^2 C-bus. The functions of this device include analogue input multiplexing, on-chip track and hold function, 8-bit analogue-to-digital conversion and an 8-bit digital-to-analogue conversion. The maximum conversion rate is given by the maximum speed of the I^2 C-bus. Sending a valid address to the device activates addressing each PCF8591 device in the I^2 C-bus system. The address consists of a fixed part and a programmable part. The programmable part must be set according to the address pins A0, A1, A3 and A4. The address always has to be sent as the first byte after the start condition in the I^2 C-bus protocol. The last bit of the address byte is the read/write-bit, which sets the direction of the following data transfer. The second byte sent to a PCF8591 device will be stored in its control register and is required to control the device function. The upper nibble of the control register is used for enabling the analogue output, and for programming the analogue inputs as single-ended or differential inputs. The lower nibble selects one of the analogue input channels defined by the upper nibble. After the signal has been converted to digital form, it is sent to the computer for computations, and the irrigation control program' decision is communicated to the irrigation control devices through the digital output chip (PCF8574).

3.1.1.2 Digital output chip (PF8574 IC)

This device consists of an 8-bit quasi bi-directional port and the I^2C-bus interface. The PCF8574 has a low current consumption and includes latched outputs with high current drive capability for directly driving external circuits. In this project the output was used to drive the universal relay card (K6714)

3.1.2 The universal relay card

The universal relay card can operate 8 relays contacts. It is capable of switching high currents and at the same time offering isolation between the controller and the controlled devices. The relay can be controlled in different ways, direct from open-collector outputs, TTL or CMOS level or trough. It also has dipswitches to allow manual activation of the relay in the case of maintenance work. The maximum switch over contact current is 5A at 220V. This relay card was used both during the integrity test when conducting the computer and electronic interfacing tests, and during the implementation stages of the project.

3.1.3 Integrity test

The integrity test included testing resolution, input and output characteristics, and I^2C bus transmission protocol. During testing, a variable power supply was used to mimic the sensors as shown in the set up in fig 3.4. The testing program was developed using visual basic 6 enterprise edition. The program developed could read all four analogue inputs and display the results in an excel program.

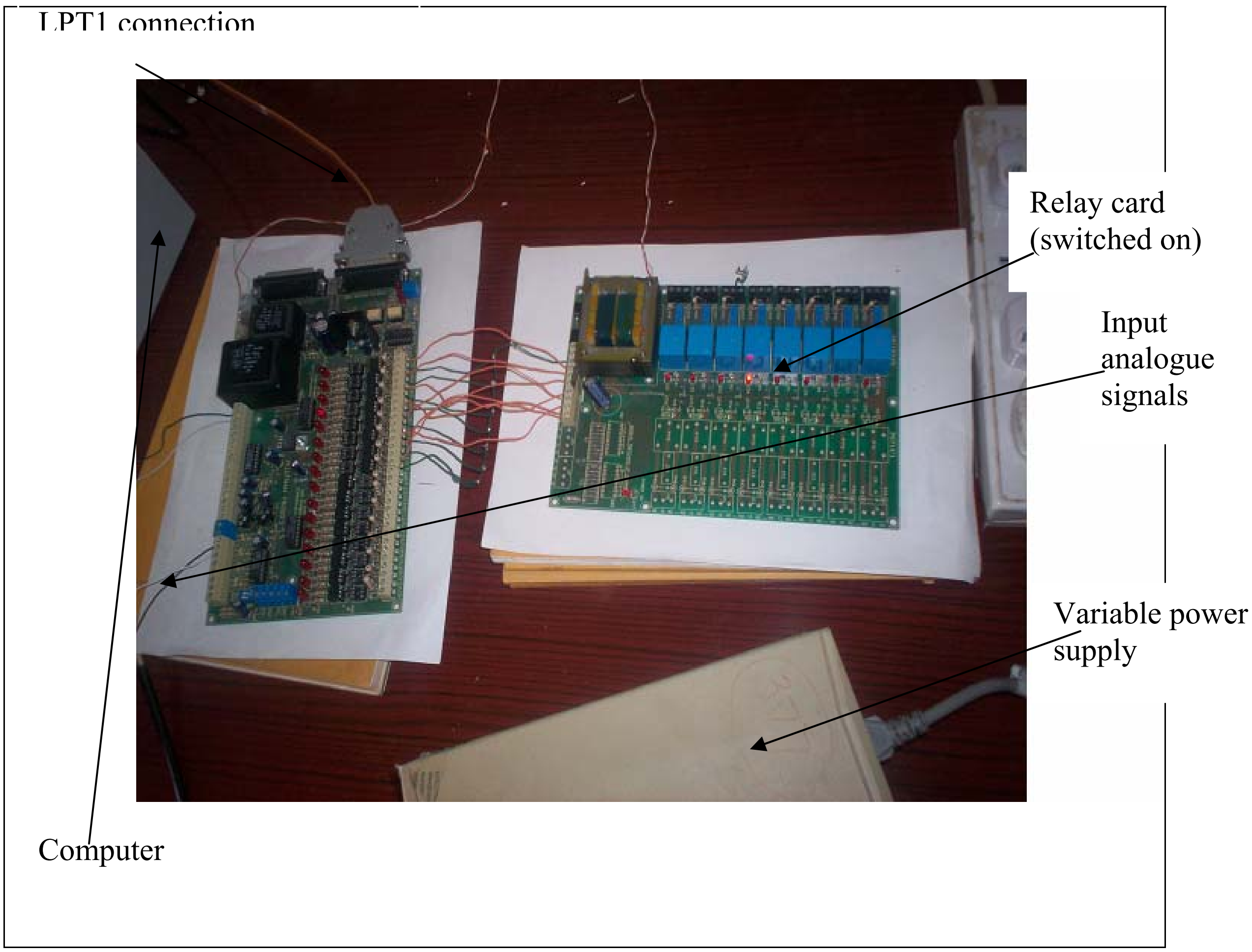

Figure 3.4: Integrity set up [ref: personal digital camera photo]

Initially a 20 mV analogue signal from a variable power supply was fed to the interface board and the resulting step value was recorded. The above procedure was repeated with input voltage incremented from 1mV to 5V (the maximum analogue voltage permitted for the interface board). The results were used to plot a graph, which was used to determine the resolution of the interface board. The experimental value was compared with the one supplied by the manufacturer. The above process was repeated using a modified program, which converted the steps into a voltage, this was done to determine possible errors in real time application. This data was used to test the functionality and integrity of the software – hardware protocols of the designed system.

3.2 Irrigation control program development

A computer was programmed such that the input voltage signals from the sap flow gauges were used to compute the accumulated transpiration according to equation 2.23 (§2.3.3.3). At time intervals that can be preset by the user, in this case, it was set to 30 minutes, the accumulated transpiration values were then used to compute the volume of water presumably lost by the plants. A corresponding variable time, t_v (computed from sap flow measurements) depending on the value calculated by the control program was used to switch on the relay card. After a time t_v has elapsed the relay switches the relay off and waits for the next switching command. In other words if a decision to switch on or off was reached, it was sent to the switching relay via the K8000 interface card. The schematic flow chart of the developed program is as shown in fig 3.5, and actual software program used is as shown in appendix 4.

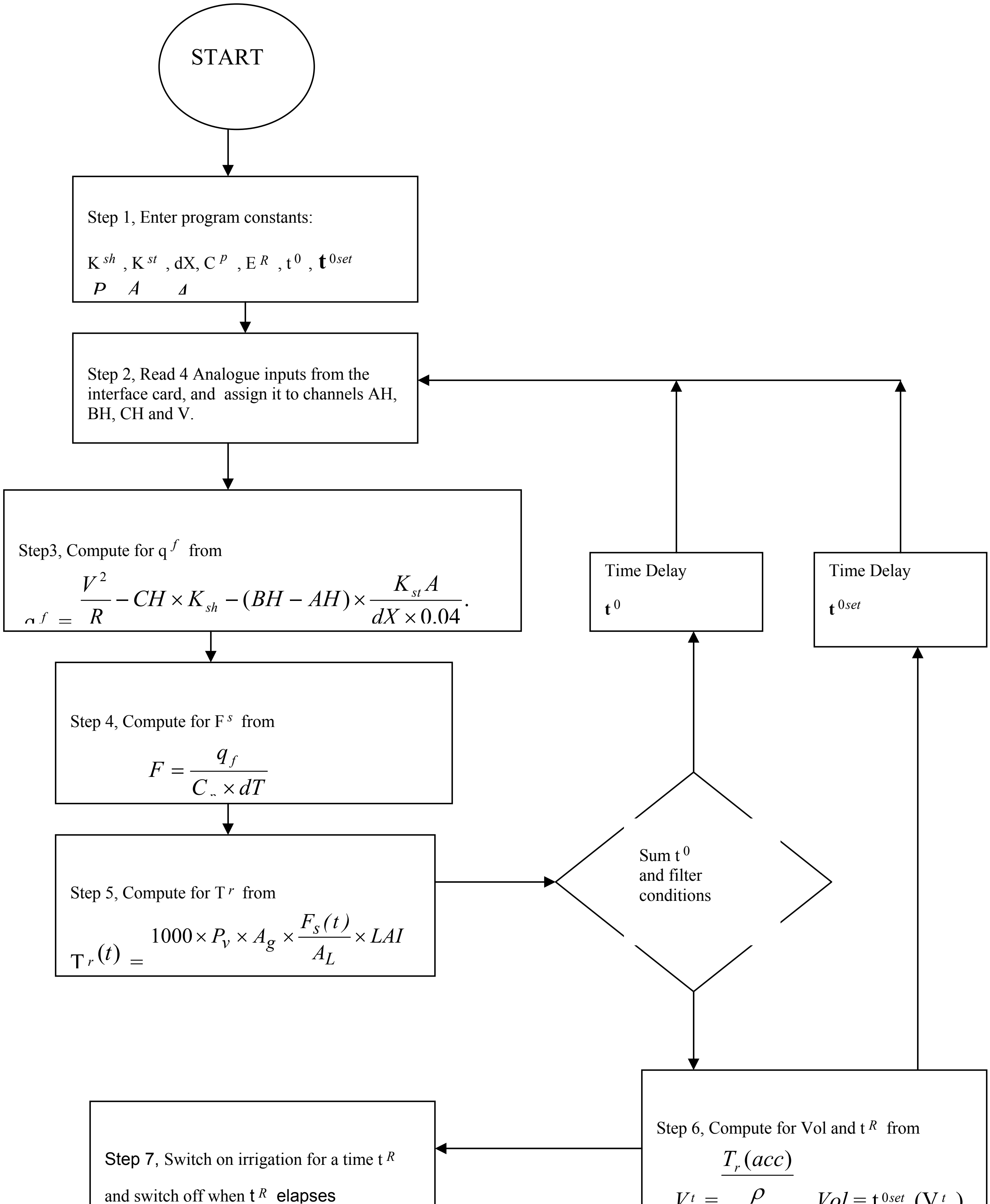
START
Step 1, Enter program constants:
K_{sh}, K_{st}, dX, C_p, E_R, t_0, t_{0set}
Step 2, Read 4 Analogue inputs from the interface card, and assign it to channels AH, BH, CH and V.
Step3, Compute for q_f from
$q_f = \frac{V^2}{R} - CH \times K_{sh} - (BH - AH) \times \frac{K_{st} A}{dX \times 0.04}$.
Step 4, Compute for F_s from
$F = \frac{q_f}{C_p \times dT}$
Step 5, Compute for T_r from
$T_r(t) = 1000 \times P_v \times A_g \times \frac{F_s(t)}{A_L} \times LAI$
Sum t_0 and filter conditions
Time Delay
t_0
Time Delay
t_{0set}
Step 6, Compute for Vol and t_R from
$V_t = \frac{T_r(acc)}{\rho}$
$Vol = t_{0set}$ (V_t)
Step 7, Switch on irrigation for a time t_R and switch off when t_R elapses

Fig 3.5: The flow chart for the designed irrigation control program, the control program is in appendix 5

The program was designed to perform three major tasks: task 1 was to read the sensor output voltages from the interface card; task 2 was to use preset formulas to compute the heat conversion carried by the sap (q_f), sap flow rate $F_s(t)$ and crop transpiration rate ($T_r(t)$) at specified time interval (t_0), accumulated transpiration ($T_r(acc)$) in a time interval $\mathbf{t}_{0set}$; and task 3 was to use ($T_r(acc)$), drip emitter rate (E_R), volumetric rate (V_t) of water lost in a time interval $\mathbf{t}_{0set}$ to determine (t_v) the time required to replace the volume of water lost (*Vol*) by the plant. The quantity ρ is the density of the sap, which is taken to be that of pure water. The control command to switch on or off the irrigation for a time (t_v) was based on equations (2.24, 2.25, and 2.26) in §2.3.3.3

3.3 Implementation/ field testing

This phase of the project was characterised by determination of irrigation control program parameters, and the physical/ practical testing of the designed system. Control program parameters determined includes the thermal conductance constant (*Ksh*), leaf area index and leaf area. Two treatments were set up in one flower bed near the centre of the greenhouse: treatment A (the current grower practice), in which irrigation was based on measurements of outside weather conditions such as temperature, solar radiation and humidity. In treatment B (the sap flow computer-based system), the accumulated transpiration rates were determined at preset intervals. The time needed to replace the water lost by the plants was computed by the developed irrigation control program. In order to full implement the treatments in the green house, the voltage signal from the stem gauge were branched into two, with one set going to the data logger and the other set going to the K800 interface board via a quad- input operational amplifier.

3.3.1 The greenhouse and crop description

The field-testing was conducted in a commercial 1250 m^2 greenhouse (Fig 3.6) at Floraline Pvt Ltd. in Harare, Zimbabwe (17.8 °S, 31.1 °E, and altitude 1500 m) from 20 July 2008 to 27 July 2008.

Figure 3.6: The greenhouse at Floraline Pvt Ltd, where the measurements and the field testing was conducted

Each span of the greenhouse was 9.6 m wide and 44 m long, with ridge and gutter heights of 6.5 m and 4.1 m, respectively. The ridges were oriented north-south direction, The greenhouse had a total floor area of 1267 m^2 and the roof sloped at about 26° to the horizontal. The cladding material was 200 μm polyethylene film with terrestrial infrared and UV absorbing additives (Ganeigar Co., Israel). The roof vents (one in each span on the west side of the roof) were located along the whole length of the ridge and were 1.4 m wide, with a maximum opening angle of about 34° to the roof. The polyethylene side vents could be rolled up from 2 m above the floor to 3.35 m on the south wall and to 3.45 m on the north wall. Plastic insect proof nets (50 mesh) covered the openings of the side vents. The side and roof vents positions were controlled by an automated climate control system (NETAFIM NETAGROW Version 718.3, Priva, Israel) in response to ventilation temperatures (temperature at which ventilation is initiated) which were calculated on the basis of the set ventilation temperatures and a number of influences, including the measured inside air relative humidity and outside conditions.

The crop included several cultivars of roses (Rosa x Hybrida), grown in vermiculite in slightly raised 20 m × 0.45 m × 0.2 m (length × width × depth) containers and watered through an automated drip system. The total crop cover represented about 40 % of the total greenhouse floor area. The containers were laid parallel to the gutters in twelve 20 m rows in each span. Generally the crop (average height of about 1.2 m) was well watered, with an average of 10.8 m^3 (33.3 mm) of water applied per day, usually divided into about ten to fourteen applications during the day depending on the climate conditions (air temperature, total solar radiation and wind speed) measured outside the greenhouse. The cultivars in the greenhouse included commercial ones like Myrthe, Nectarine, Respect, Orchestra, Bonfire, and Romeo and several trial cultivars. All the cultivars were grafted onto Natal Brier rootstocks.

Relevant climatic data (air temperature and humidity, wind speed, and global solar radiation) were measured by two automatic weather stations (AWS), outside the greenhouse. Air temperature and humidity were measured at 1.5 m above soil level for inside measurements, by means of temperature and humidity probes equipped with capacitive chips and platinum thermistors (model RHT2nl, Delta T Devices Cambridge, UK), to measure relative humidity and resistance respectively. The probes were shielded from radiation by a 12-plate Gill radiation shield. The total solar radiation and PAR were measured at 2 m above soil level, by means of a tube solarimeter (model TSL, Delta T Devices Cambridge, UK) and PAR sensor (model PAR-LITE, Kipp and Zonen, Delft, Netherlands). The outside wind speed and direction were measured at 2 m above the ground by means of a cup anemometer (model A100L2) and a wind vane (model WD1, Delta T Devices Cambridge, UK), respectively, while inside air velocity was measured at three positions at an above-soil level of 2 m by means of air velocity transducers (model TSI 8475, TSI Inc., Shoreview, U.S.A.). The leaf temperatures were measured with fine thermocouple wires (Type K), 80 μm in diameter, attached to the lower side of the leaf by plastic paper clips. The measurements were performed at six different positions along the flowerbed, within the canopy: two thermocouples were attached on the leaves of the bent shots (lower part of the canopy), and four on the leaves of the flower stem. The canopy temperature (T_v) was taken as the mean value of the six leaf temperatures. All measurements were automatically recorded by a data logger (model DL2e, Delta T Devices, Cambridge, UK) every 5 seconds and averaged over 30 minutes. The recorded data was used to plot graph showing the diurnal variation of the greenhouse to external air temperature difference and greenhouse to canopy temperature difference as shown in fig 4.2, and the whole plant transpiration as shown in fig 4.3

3.3.2 Determination of control program parameters

The accumulated transpiration values were used to compute the volume of water presumable lost by the plants according to equations 2.24 and 2.25 in (§2.3.3.3). Control program parameters determined includes the thermal conductance constant (Ksh), leaf area index and leaf area.

3.3.2.1 Leaf area index determination

Leaf area index (LAI) was determined using a SunScan canopy analysis system (model SS1-TM, Delta T Devices, Cambridge, UK), as shown in Fig 3.7. LAI is the ratio of the total upper leaf surface of vegetation divided by the surface area of the land on which vegetation grows and it is a dimensionless value.

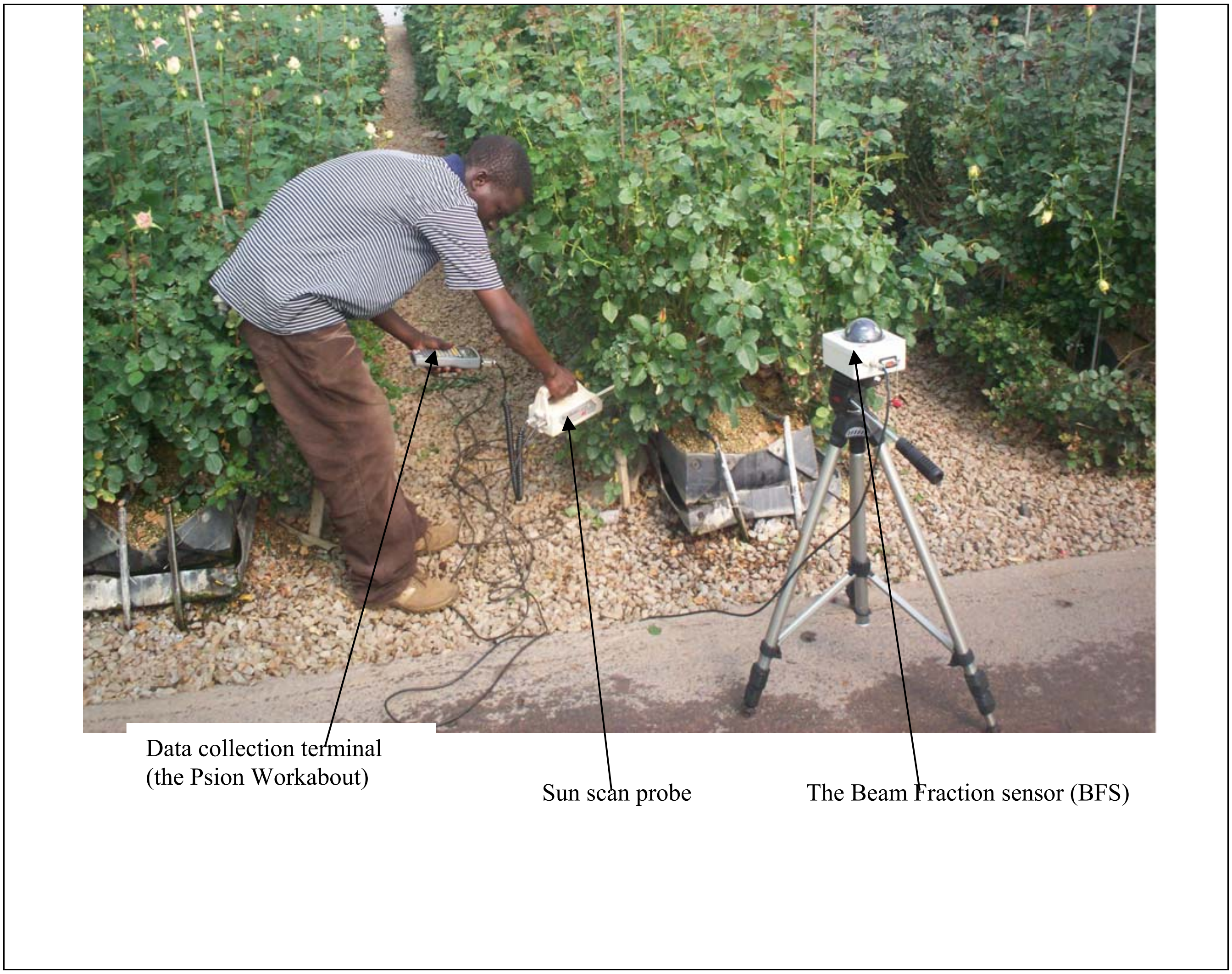

Figure 3.7: Determination of LAI using a sun scan canopy analysis system [ref: personal digital camera]

The measurement points were taken at eight different positions across the flowerbed by moving the sun scan probe at equidistant positions. The SunScan canopy analysis system is a portable instrument for measuring the light levels of photosynthetically active radiation (PAR) in plant canopies. With it, the interception of solar radiation by the canopy is measured, enabling estimates of canopy leaf area index (LAI) to be found. The sunscan canopy analysis system consists of a beam fraction sensor (BFS) for measuring the light incident on the canopy, and a sun scan probe for measuring the light transmitted through the canopy and a data collection terminal (the Psion Workabout) to observe and store readings from the BFS and SunScan probe. The light sensitive probe is 1 metre long, containing 64 photodiodes equally spaced along its length. The probe handle contains batteries and electronics for converting the photodiode voltage output into digital PAR readings, which get sent to the data collection terminal via a RS232 link. The Beam Fraction sensor (BFS) is used to monitor the light incident on the canopy at the same time as measurements are being taken beneath it. The BFS incorporates two photodiodes, one of which can be shaded from the direct solar beam by the shading ring. This allows the direct and diffuse components of PAR to be separated, which is necessary for the computation of LAI.

The LAI is calculated from measurements of the incident and transmitted light using Beer's Law in equation (3.1), which gives the relationship between the transmitted light I, incident light I_0 and the LAI:

$$I = I_0 \cdot e^{-kLAI} \tag{3.1}$$

Where k is an extinction coefficient which depends on the leaf angle distribution and the direction of the beam. In this project k was taken to be 1, and is equal to 0 for a vertical leaf.

3.3.2.2 Leaf area determination

The total leaf area, A_L, of the plant where the gauge was installed, was determined destructively by means a WinDIAS colour image analysis system (Delta T Devices, Cambridge, UK) connected to a personal computer, as shown in Fig 3.8

Sampled leaves

Figure 3.8: The WINDIAS and PC used to measure leaf area

The total leaf area was determined to establish relevant irrigation control parameters.

3.3.2.3 Thermal conductance constant (K_{sh}) Zero set calculation

As explained in §2.3.3.1, the thermal conductance constant, K_{sh}, needed for calculating the radial component of the stem heat balance, q depends on the thermal conductivity of the insulating sheath and stem diameter. As such, it usually changes for each new installation and so must be calculated for each new installation. It is evaluated during periods when there is no sap flow ($q_f = 0$). The K_{sh} zero set value was evaluated using the set up shown in Fig 3.9, by enclosing the entire canopy of the plant above the stem gauge with a plastic bag.

Figure 3.9: The set up to determine the K_{sh} zero set value, a plastic covers the whole plant where the stem gauge is installed.

The bag was secured airtight and kept in place overnight (21 July to 22 July 2009) until the gauge signals showed stability. In this time, the plant, the pot, the gauge and soil would have come to a thermal equilibrium. The assumption is that the humidity will rise to the highest possible level, and that the plant is shielded from radiation and wind. At this time K_{sh} can be established with 1 to 5 % accuracy and the gauge will provide good sap-flow performance at the low end of the flow. To determine the K_{sh} stem gauges were used.

3.3.2.3.1 Stem gauges measurements

The stem heat balance sap flow gauges used in this project (model SG10WS, Dynamax, Inc., Houston, USA) were tested for continuity. The stem gauges are precision instruments that sense milli-watt power transfer from a heater strip: to the ambient, to the stem, and into the sap flow. The gauge's two readings come from sensors signal temperature differences above and below the heater conducted during stem heat transfer. A third reading from the sensor measures radial heat flux and the heat lost to the ambient. A set of junctions are placed in series adjacent to the heater, and on the outside surface of a thin cork annulus

Figure 3.10: Installed stem gauge (a) without radiation shield, (b) with an aluminum bubble foil installed to shield the gauge from direct radiation.

The stem gauges were connected to the data logger (model CR23X, Campbell scientific Ltd., Shepshed, UK), in order to compare computed transpiration by irrigation control program and that computed by the standard instrument. The stem gauge and data logger were instrumental in determining the thermal conductance constant *Ksh.*

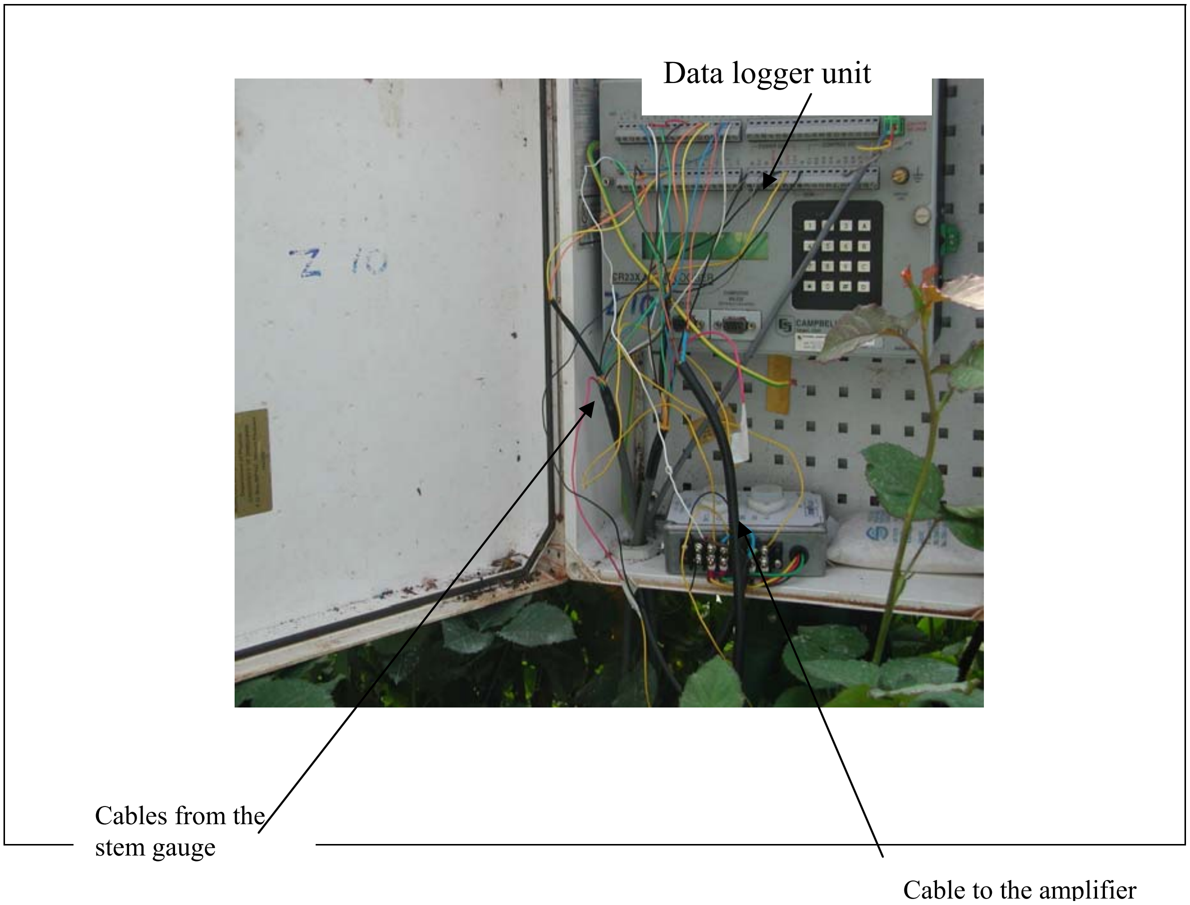

Figure 3.11: Data logger -sap flow gauge connection during field-testing

The data logger –stem gauge connection is as shown in fig 3.12.

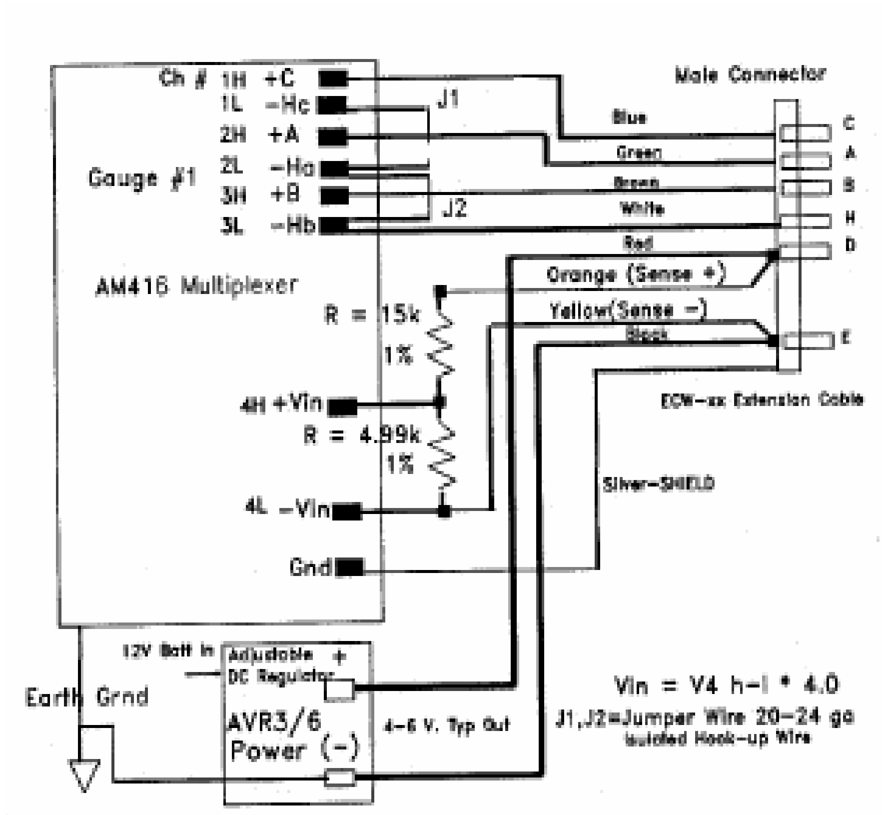

Figure 3.12: Schematic diagram of the data logger-stem gauge connection [22]

The (+) signals from the female connector side correspond to the (+) input channel on the logger. The signal reference H is the white wire and must be connected to the (-) of the differential inputs of CH, AH , BH , with two short jumper wires. The excitation power at Vin terminals labeled D and E are monitored with separate sensing wires, orange (+) and yellow (-) that comes all the way back from the sensor to the connector. The sense wires are separated so that the heater voltage is known precisely without regard to cable voltage drop.

The data logger records were downloaded to laptop, The downloaded files were copied or imported to the ascii data files. The flow rates in the determination of *Ksh* were calculated off-line in an excel program. At this point the full sap flow rate record for the period 20 July to 25 July 2009 was saved, and was used to establish the general sap flow trends. Gauge constants and K_{st} used in this project are as shown in table 3.1.

Table 3.1: Stem gauge constants

Serial No:	Resistances(R)/ Ω	dX/ m	K_{st} /(W/mK)
079325	155.9	4×10^{-3}	0.042

3.3.3 Treatments

Two treatments were set up in one flower bed near the centre of the greenhouse: treatment A (the current grower practice), and treatment B (the designed sap flow computer-based system), in which transpiration rates were determined at preset intervals using sap flow gauges and the time needed to replace the water lost by the plant was calculated using the emitter rate of the drip lines. Each emitter supplied water at a rate of 2 litres per hour and there were a total of 42240 emitters in the whole greenhouse. The designed sap flow based control system was evaluated by comparing it with the current grower practice treatment A (which uses weather conditions to initiate irrigation). The evaluation parameters included comparison of the water use per treatment, irrigation efficiency of each system.

3.3.3.1Treatment A

Drip irrigation system was used to water the flowerbeds. Each drip emitter supplied water at a rate of 2 litres per hour and the installed irrigation system applied water for a fixed period of 4 minutes each time it switches on. The irrigation was triggered whenever the accumulative solar radiation outside the greenhouse reached 1600 kJ m^{-2}.

3.3.2.2 Treatment B

In treatment B, the designed sap flow based system was set up such that the volume of water applied by the system was calculated by the developed irrigation control program. The developed irrigation control system computes the transpiration rates of the canopy from measurements sap flow in the stem and averaged it at preset intervals. All computations, control signals receiving and sending was done using the developed irrigation control program. The data logger was used in this treatment as the standard instrument for calculating the whole plant transpiration during the two day implementation period. Figs 3.13 and 3.14 show both the schematic and pictorial set-up of treatment this treatment.

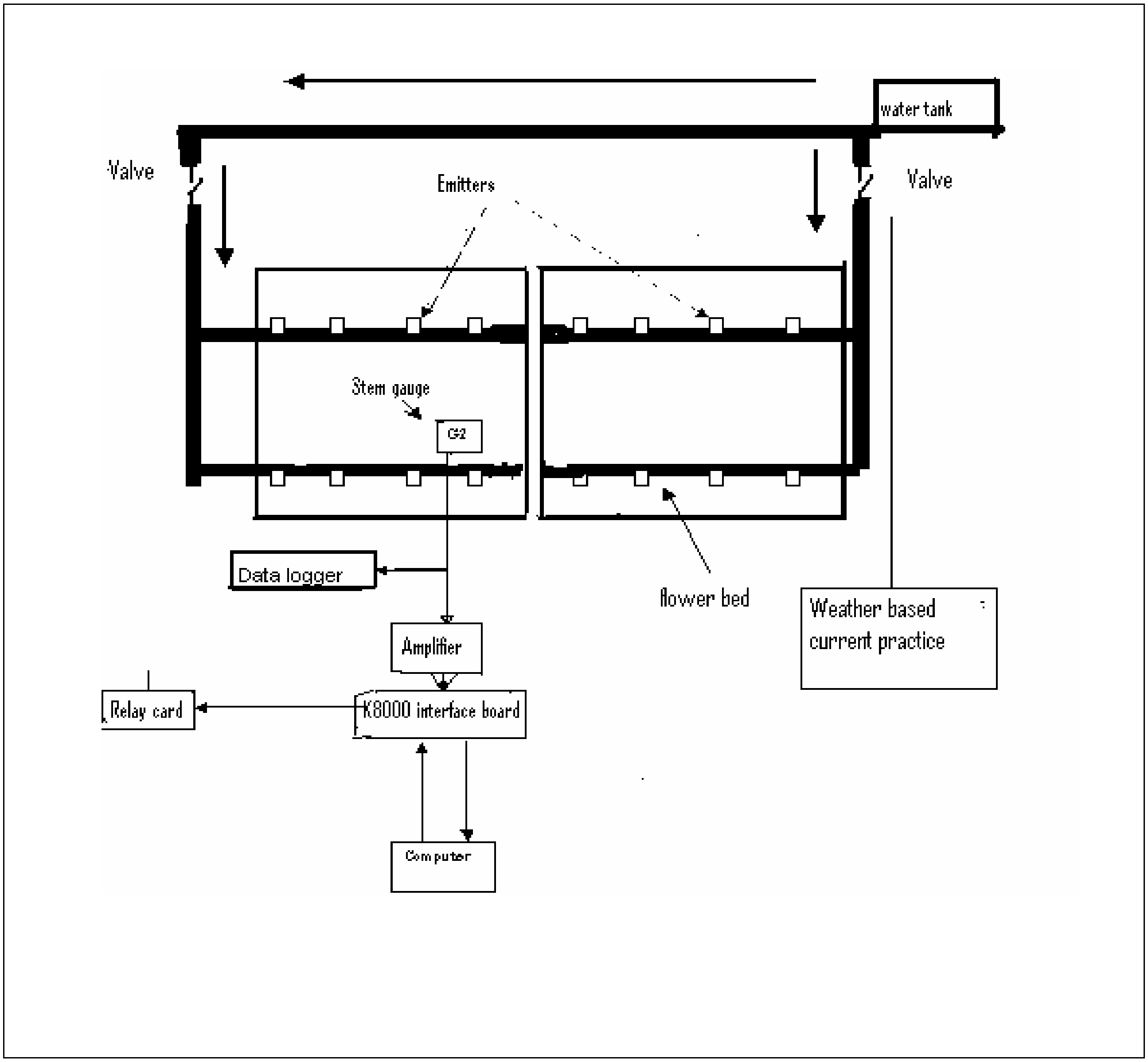

Figure 3.13: Schematic diagram of field-testing set-up

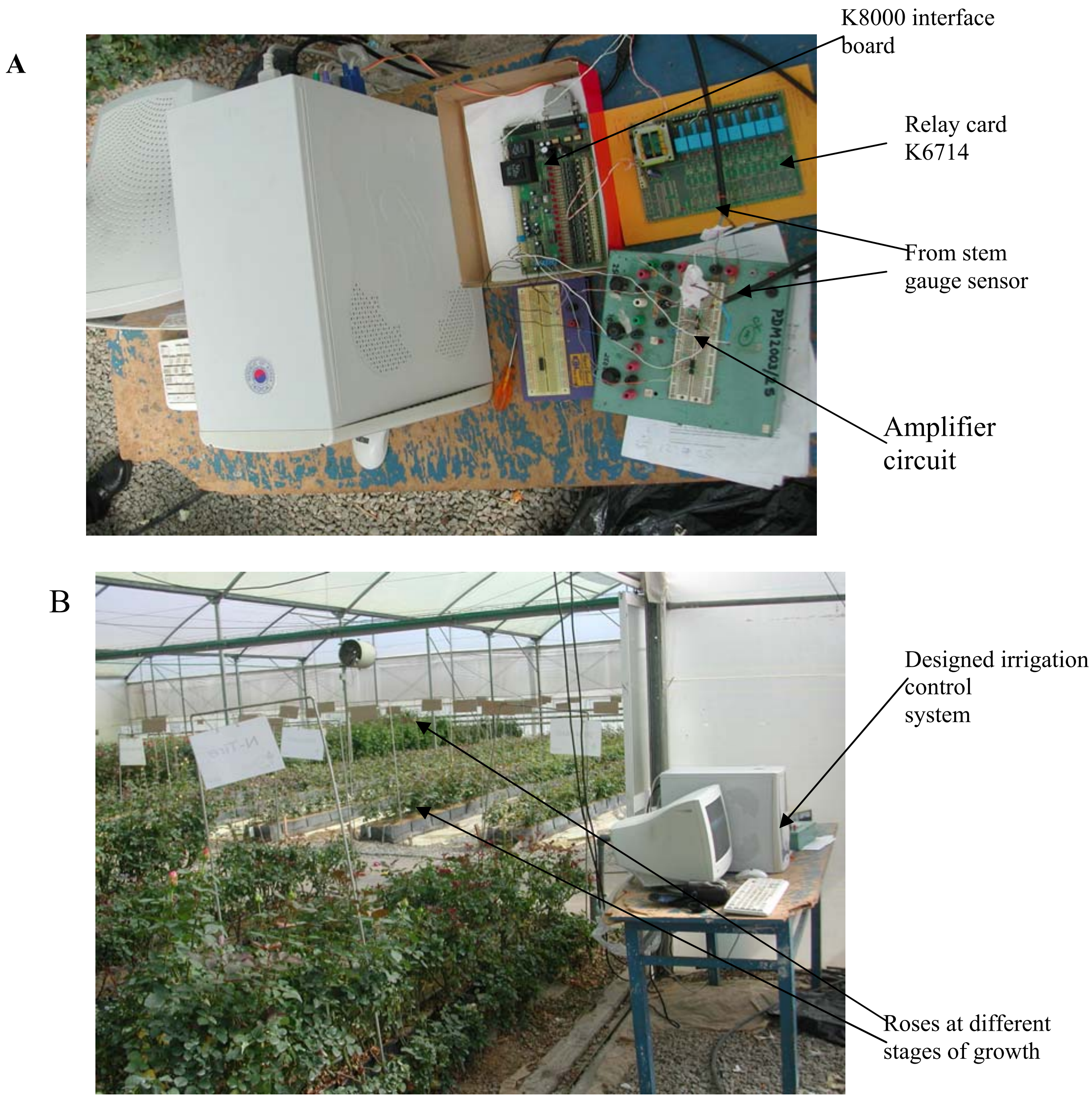

Figure 3.14: The set up of treatment B in the greenhouse, showing the pc interface and relay cards connected to the pc [ref: personal digital camera]

Due to the practical requirements of the interface board, the signal from the stem gauge to the interface board was amplifier. This voltage signal amplification was done cautiously in order to minimize computational errors.

3.3.2.2.1 Stem gauge (sensor) signal amplification

The sap flow data from previous installations were analyzed and showed that the sensor output voltage for channels AH, BH, CH varies in the range of mV, thus there was need for signal amplification. Two TL084CN quad- input operational amplifiers were used as shown in fig 3.5, to provide amplification of the three sensor signals AH, BH, and CH. The heater voltage, V was not amplified since it was in ranges of voltages compatible with the interface board. The pin connection of the TL084CN is as shown in Fig 3.15

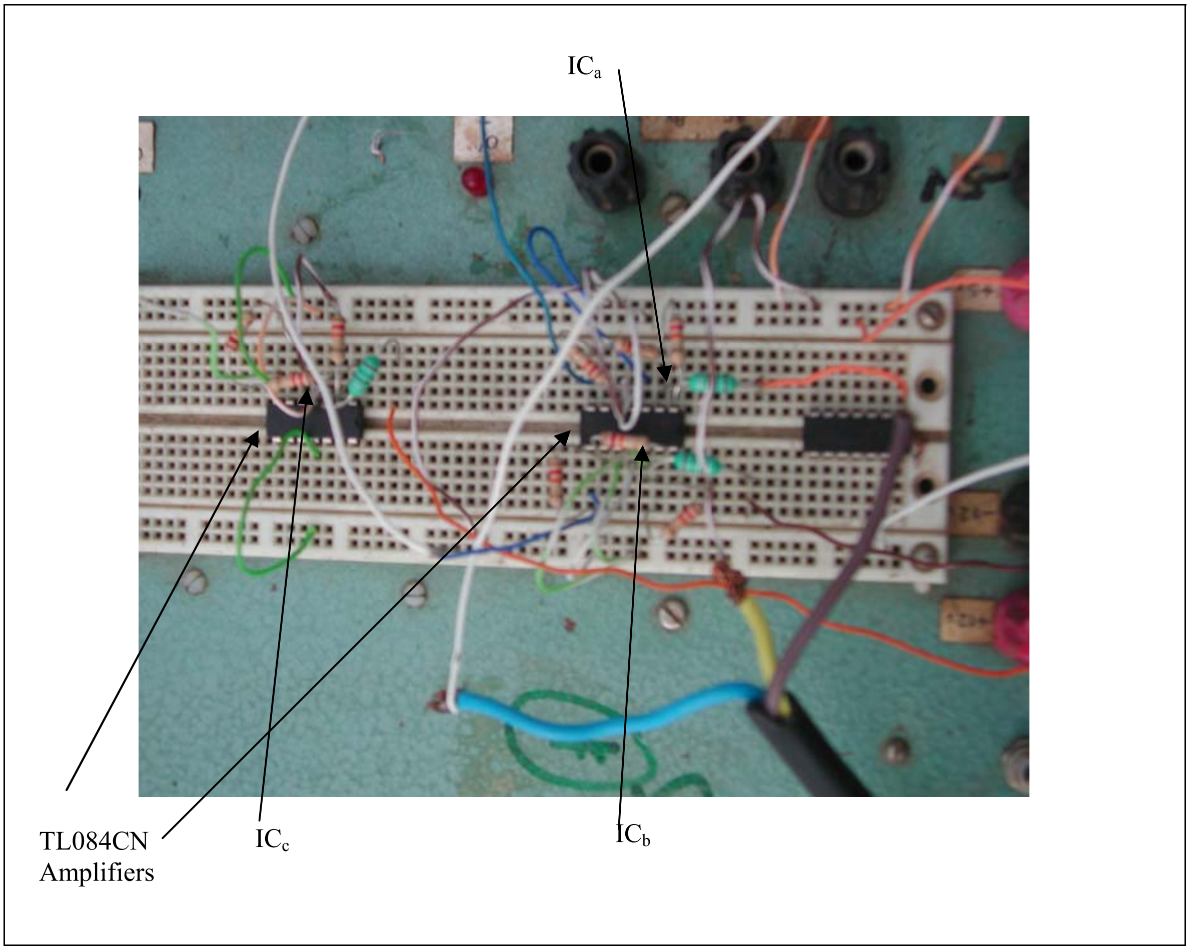

Figure 3.15: Amplifier circuit for amplification of stem gauge signals, IC_c , IC_b and IC_a e are amplifying units constructed from two single amplifier units in TL084CN (see fig 3.16 for pin connections), i.e. the first unit provides the required gain and the second provides a unit gain amplification

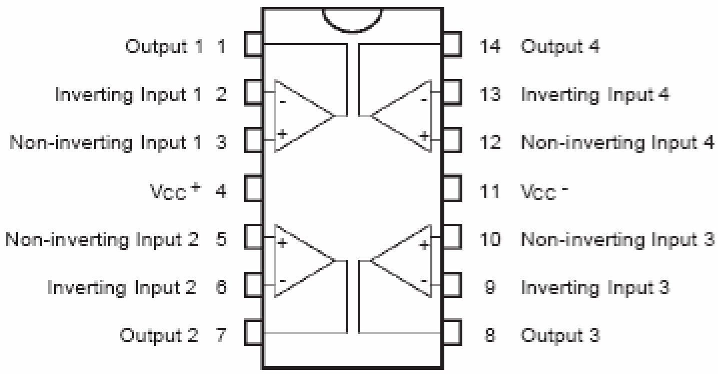

Figure 3.16: Pin connection for TL084CN

The TL084CN are high speed J–FET input quad operational amplifiers, incorporating a well-matched high voltage J–FET and bipolar transistors in a monolithic integrated circuit. It has a high slew rates, and low input bias.

The water use by the sampled plant was extrapolated to the entire stand or greenhouse using equation (2.23), outlined in §2.3.3.3. The recorded data was used to plot graph showing the diurnal variation of the whole plant transpiration as shown in fig 4.3

3.3.2.2.3 Determination of crop water use

The volumes of water lost computed by the irrigation control program (treatment B) was compared with the actual water applied by the current grower (treatment A). In treatment A, the irrigation system was controlled using outside weather parameter such as air temperature, humidity, and solar radiation, which was used to estimate time to trigger irrigation. irrigation was triggered whenever the accumulative solar radiation outside the greenhouse reached 1600 kJ m^{-2} Once the irrigation system has been triggered it would apply water for a fixed period of 4 minutes. . In treatment B (the designed irrigation control system), four voltage signal outputs from the sensor were connected to the interface board through an amplifier. The interface board performs analogue to digital conversion and send the binary result to the computer. The developed irrigation control program computed the crop transpiration rates and determines the time needed to irrigation in order to replace the volume of water lost, translating to volume of water irrigated during the implementation period.

CHAPTER 4

EXPERIMENTAL RESULTS AND ANALYSIS

4.0 Introduction

The chapter presents the basic research findings and discussions of the project. The project results include determination of control program parameters such as leaf area, leaf area index, thermal conductance constant *(Ksh)*. The implementation (field testing) results forms the most significant findings in this research project.

4.1 Integrity test results

The testing program was developed using visual basic applications (VB6). The program could read four analogue inputs voltages and display the results in an excel program. The input voltage was displayed as steps due preset protocol of sampling (conversion process) in the analogue to digital converter (ADC). The results of this integrity test are as shown in fig 4.1(a) and fig 4.1(b) for the modified program.

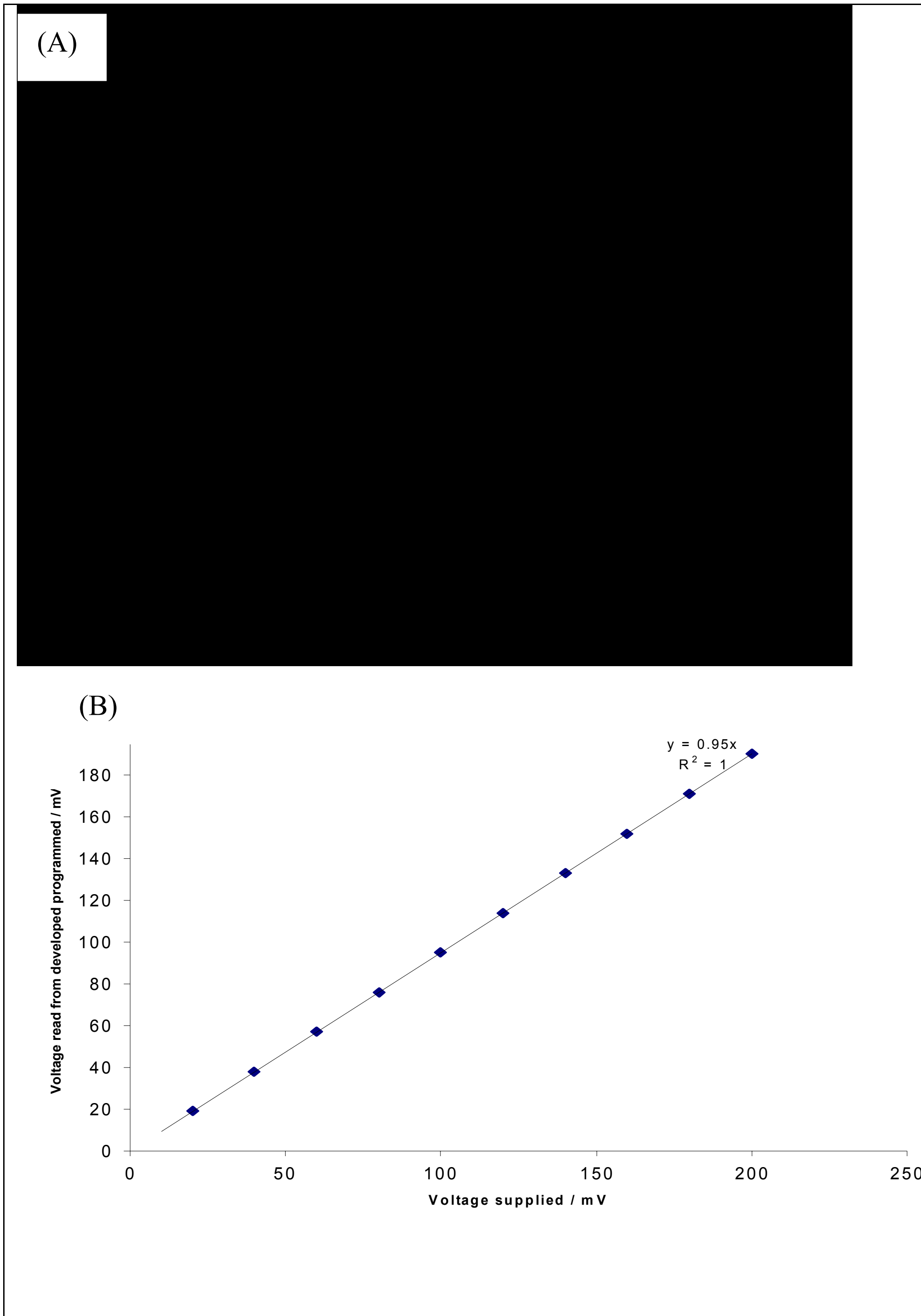
(A)
(B)
y = 0.95x
R^2 = 1
Voltage read from developed programmed / mV
0
20
40
60
80
100
120
140
160
180
0
50
100
150
200
250
Voltage supplied / mV

Figure 4.1(a) and (b): The calibration curve of the analogue input signals for AD channels 1

From Fig 4.1 the experimental resolution was found to be 19mV/step, this value is the same as that supplied by the manufacturer, which is 19mV/step. It can also be observed from fig 4.1, that the curve gradient was found be 1, this reflects that resolution had not shifted. This preliminary test confirms the proper functionality of the card. It is clear that the ADC on the K8000 interface board did not shift from its manufacturer's set resolution.

4.2 Implementation/field testing results

In field testing and evaluation two treatments were set up in one flowerbed near the centre of the greenhouse: treatment A (the current grower practice), in which irrigation control system was based on measurements of weather parameters in and out of the greenhouse, and treatment B (the sap flow computer-based system), the designed control system. Each drip emitter in the greenhouse supplied water at a rate of 2 litres per hour, and a total number of 42240 emitters were installed in the whole greenhouse.

4.2.1 Climatic and physiological parameters

Table 4.1 gives a summary of the prevailing outside weather conditions during the experimental period.

Table 4.1: Summary of outside weather conditions for the experimental implementation period. Prevailing winds were mostly north-to-north-easterly.

Date	Air temperature (°C)			Relative humidity (%)			Total solar radiation, (MJ m^{-2} d^{-1})	Mean wind speed (m/s)
	Min.	Max.	mean	Min.	Max.	mean		
20 July	4.81	18.62	10.22	25.57	78.28	54.37	18.20	0.50
21 July	4.02	18.73	9.95	34.36	93.39	68.05	10.05	0.39
22 July	4.50	17.96	9.77	30.21	96.51	62.87	15.83	0.73
23 July	4.25	19.91	10.63	26.88	89.80	64.20	16.33	1.25
24 July	4.01	19.15	10.25	36.25	95.44	66.03	17.12	1.10
25 July	4.08	18.14	11.16	41.47	96.10	68.83	9.14	1.14
26 July	4.04	19.61	11.37	38.40	96.92	65.20	18.20	0.50
27 July	4.10	21.40	10.98	23.45	87.60	57.66	10.05	0.39

4.2.2 Determination of control program parameters

Control program parameters determined includes plant stem diameter, leaf area, leaf area index and thermal conductance constant (Ksh). The quantities in table 4.2, $\bar{A}$ and ΔA denotes stem cross sectional area and the associated error respectively. The associated error was evaluated using the standard deviation formula as in (§4.2).

Table 4.2: Measurements of stem diameter in evaluating the cross sectional area of the stem. The stem diameter measurement was done at the midpoint of the gauge installation.

Stem diameters/m	**Stem cross sectional area** $/10^{-4}m^2$
0.01115	1.25
0.01106	1.24
0.01189	1.26
0.01137	1.24 ± 0.01

From table 4.2, the stem diameter to be entered as an input parameter to the data logger was found to be 11.37mm, thus an SGW10 stem gauge was used.

4.2.2.1 Leaf area determination

The leaf area was determined as shown in table 4.3. The quantities $\bar{LA}$ and ΔLA denote averaged leaf area and its associated error respectively. The error was evaluated using the standard deviation formula as in (§4.2)

Table 4.3: Leaf area for sampled leaves.

Leaf Area/ cm^2	**Leaf Area/** $\times 10^{-3} m^2$
291.81	29.18
292.14	29.21
293.56	29.36
$LA \pm \Delta LA$	29.25 ± 0.06

It can be seen from table 4.3 that the leaf area was determined with a relative degree of accuracy..

4.2.2.2 Leaf area index

Table 4.4 shows the results from the sun scan analysis system. The quantities $\bar{LAI}$ and ΔLAI denote leaf area index and the associated error respectively. The error was evaluated using the standard deviation formula as in (§4.2) **.**

Table 4.4: The leaf area index was determined at 8 different positions across flower bed beneath the canopy**.**

Distances along the flowerbed/m	**LAI**
1	1.7
5	2.5
7	2.4
9	3.3
11	3.2
13	2.1
15	2.7
17	2.7
$LAI \pm \Delta LAI$	2.58 ± 0.19

From table 4.4, it can be observed that the leaf area index varies from 1.7 to 3.3 this shows that the vegetative cover (canopy) of the bed was not uniform, nevertheless an average value of 2.58 is acceptable for practical applications.

4.2.2.3 *Ksh* Zero set calculation

In this project the K_{sh} value was evaluated from stem gauge signal parameters AH, BH, CH and V as shown in table 4.5. The quantities $\bar{K}_{sh}$ and ΔK_{sh} denotes average *Ksh* the associated error respectively. The error was evaluated using the standard deviation formula as in (§4.2) **.**

Table 4.5: Signal parameters AH, BH, CH and the heater voltage ,V in the determination of K_{sh} during the period of measurement.

Vin/V	**AH/mV**	**BH/mV**	**CH/mV**	**Calculated(Ksh)**
4.05	0.124	0.148	0.185	0.845
4.05	0.183	0.126	0.164	0.845
4.07	0.245	0.182	0.142	0.843
4.06	0.165	0.127	0.139	0.845
4.05	0.195	0.141	0.136	0.847
4.04	0.216	0.164	0.143	0.846
4.06	0.187	0.146	0.153	0.847
4.06	0.134	0.135	0.164	0.849
4.05	0.153	0.148	0.132	0.848
4.06	0.221	0.176	0.157	0.847
4.06	0.132	0.096	0.121	0.847
4.04	0.211	0.164	0.143	0.845
4.07	0.178	0.126	0.171	0.847
4.06	0.139	0.068	0.128	0.849

$K_{sh} \pm \Delta K_{sh}$				0.846 ± 0.002

4.2.3 Treatments

Two treatments were set up in one flower bed near the centre of the greenhouse: treatment A (the current grower practice), and treatment B (the designed sap flow computer-based system). Drip irrigation system was used to water the flowerbeds. Each drip emitter supplied water at a rate of 2 litres per hour and there were a total of 42240 emitters in the whole greenhouse.

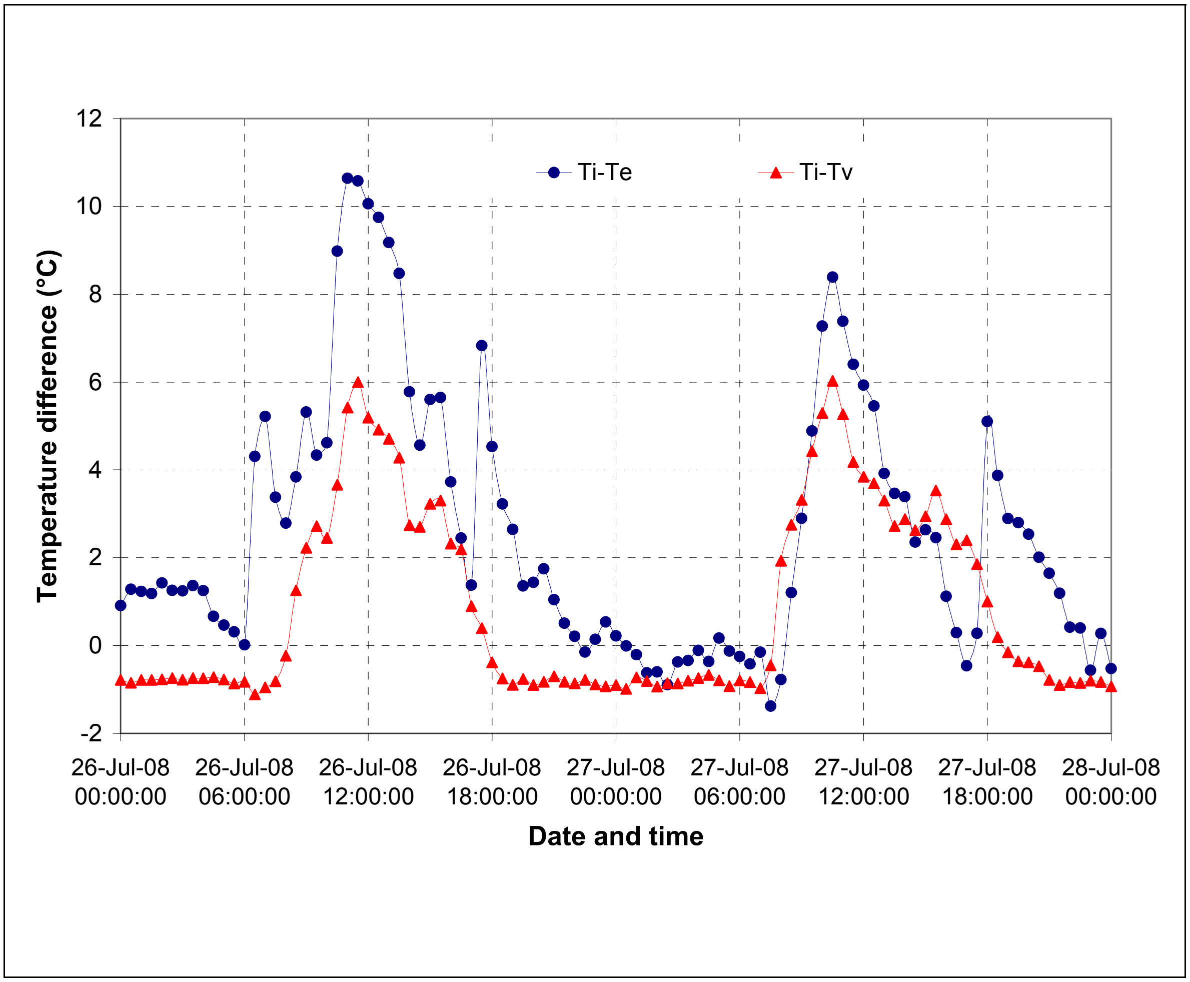

Figure 4.2: Diurnal variation of greenhouse to external air temperature difference and greenhouse to canopy temperature difference on 26 and 27 July 2008

Figure 4.2 shows the diurnal variations of the greenhouse to external air temperature differences (T_i-T_e) and the greenhouse air to canopy temperature differences (T_i-T_v) on 26 and 27 July 2008, respectively. The air temperatures within the greenhouse were up to 10ºC above the external air temperature in strong sunlight (around midday). The daytime air to canopy temperature differences followed the same trend as the temperature difference between the internal and external air. However, the nighttime canopy temperatures, T_{v} were significantly higher than the air temperature. This implies that there is reduced risk of disease incidence during this period as the conditions favorable for diseases are normally when the canopy temperature is lower than the air temperature (and dew forms on the leaf surfaces).

Fig 4.3 shows the diurnal variation of the whole plant transpiration on the two days on which the sap flow based irrigation control system was compared to the current grower practice (26 – 27 July 2008).

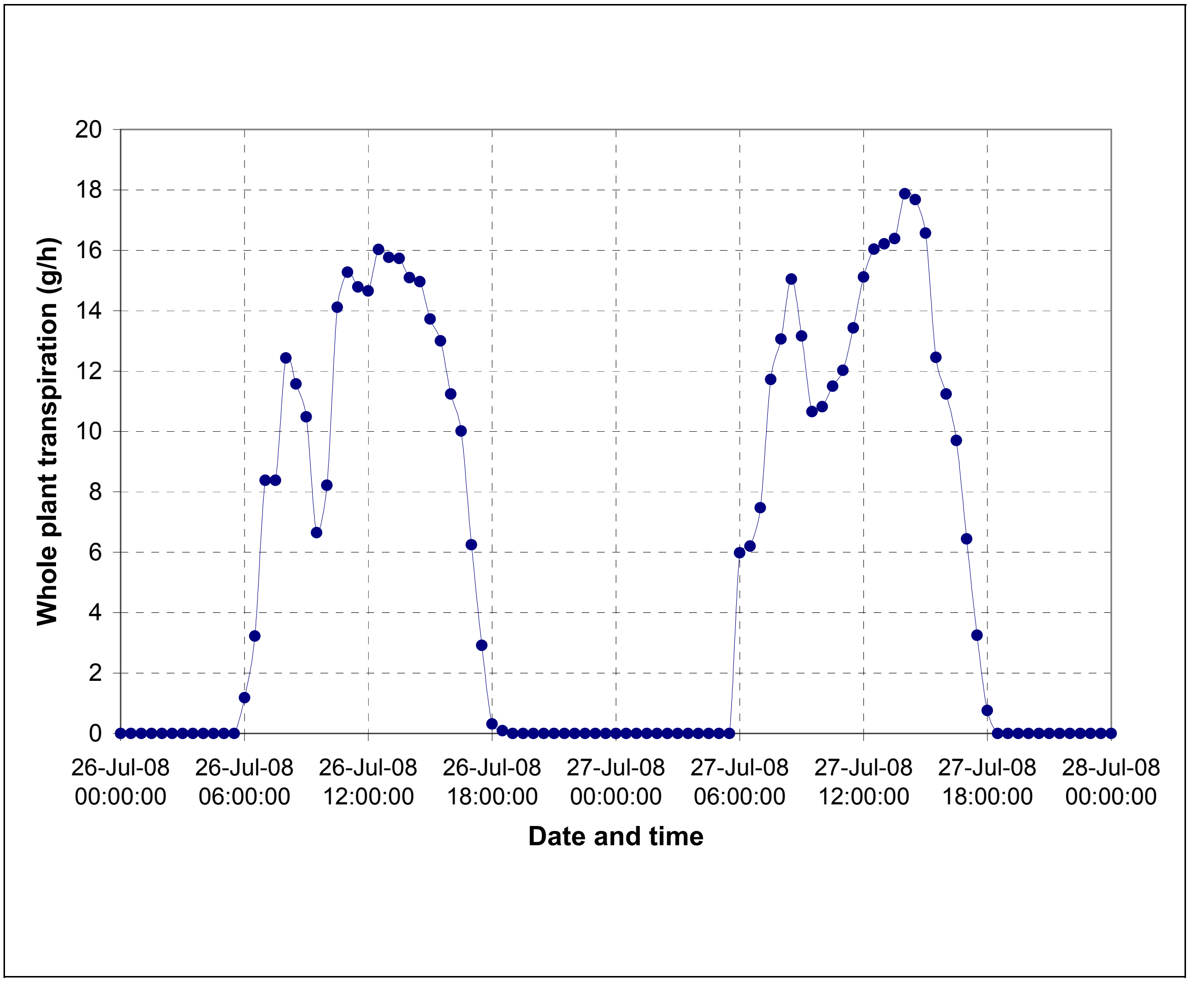

Figure 4.3: Diurnal variation of whole plant transpiration on 26 and 27 July 2008

Fig. 4.3 shows peak stem sap flow rates of about 16 - 18 g h^{-1} (corresponding to crop transpiration rates of about 0.03 kg s^{-1}), while the LAI averaged 2.6. The total crop water use was higher on 27 July than on 26 July 2008 (see table 4.5, figure 4.2). From table 4.6, figure 4.2 and 4.3, it can be observed that during the implementation period, the maximum air temperature differences were higher on 26 July 2008 than on 27 July 2008. The relative humidity was less on 27 July 2008 than on 26 July 2008 and the total solar radiation received was greater on 27 July 2008 than on 26 July 2008. These conditions encouraged high transpiration rates on 27 July 2008 than on 26 July 2008, suggesting more water was lost by the plants on 27 July 2008 than on 26 July 2008.

4.2.3.1 Treatment A: Current grower practice (Weather-based -system)

In this treatment (current grower practice), irrigation was performed whenever the accumulative solar radiation outside the greenhouse reached 1600 kJ $m^{-2.}$ .The installed irrigation system applied water for a fixed period of 4 minutes each time it switches on Tables 4.6 and 4.7 show the irrigation times and quantities of water applied on 26 July 2008 and 27 July 2008, by the current grower system respectively.

Table 4.6: The irrigation time and amount of water applied by the current grower on 26/07/08 (Control)

Starting time	**Ending time**	**Amount of water applied /L**
10:45	10:49	56.24
12:25	12:29	56.24
13:21	13:25	56.24
14:18	14:22	56.24
15:16	15:20	56.24
16:13	16:17	56.24

Total	**24mins**	**337.44**

Table 4.7: The irrigation time and amount of water applied by the current grower on 27/07/08 (Control)

Starting time	**Ending time**	**Amount of water applied /L**
10:42	10:46	56.24
12:08	12:12	56.24
13:14	13:18	56.24
14:25	14:29	56.24
15:09	15:13	56.24
16:06	16:10	56.24
Total	**24mins**	**337.44**

From table 4.6 and 4.7 it can be seen that the current grower system applied 337.44 litres of water for 24mins each day of the two field testing days, in other words the system irrigated the same number of times in the two days of field testing, although the solar radiation variation on 26/07/08 and 27/07/08 differs by a small margin. This result reflects that there is a great potential of saving water through the introduction of a better system that will take into account the slight variation in solar radiation.

4.2.3.2 Treatment B: Computer-based system (sap flow)

Treatment B (the designed sap flow computer-based system), in this treatment accumulated transpiration rates were determined at preset intervals using sap flow gauges. The time needed to replace the water lost by the plant was calculated by the developed control program using the emitter rate of the drip lines. Each emitter supplied water at a rate of 2 litres per hour. Tables 4.8 and 4.9 show the field-testing results.

Table 4.8: The irrigation time, duration of irrigation and amount of water that would have been applied on 26 July 2008 (designed irrigation controller)

Irrigation time	**Duration/mins**	**Amount of water applied /L**
11:00	1.9	26.752
11:30	2.2	30.976
12:00	3.4	47.872
12:30	3.2	45.056
13:00	2.1	29.568
13:30	2.8	39.424
14:00	2.3	32.384
14:30	2.0	28.16
15:00	1.8	25.344

15:30	1.2	16.896
16:00	0.8	11.264
Total	**23.0**	**323.8**

Table 4.9: The irrigation time, duration of irrigation and amount of water that would have been applied on 26 July 2008 (designed irrigation controller)

Irrigation time	**Duration/mins**	**Amount of water applied /L**
11:00	2.1	29.568
11:30	2.4	33.792
12:00	3.2	45.056
12:30	2.8	39.424
13:00	3.6	50.688
13:30	3.1	43.648
14:00	2.4	33.792
14:30	1.9	26.752
15:00	1.2	16.896
15:30	0.7	9.856
16:00	0.3	4.224
Total	**23.2**	**326.7**

From table 4.8 and 4.9, it can be seen that designed control system applied less water on 26 July 2008 than on 27 July 2008, suppling 323.8 and 326.7 litres respectively. According to theory, many automated systems would not have applied water during early hours of the day and later hours of the day. Fig 4.4 presents treatment comparison of both the designed and the currently used irrigation control systems, from the field- testing conduct on 26 and 27 July 2008.

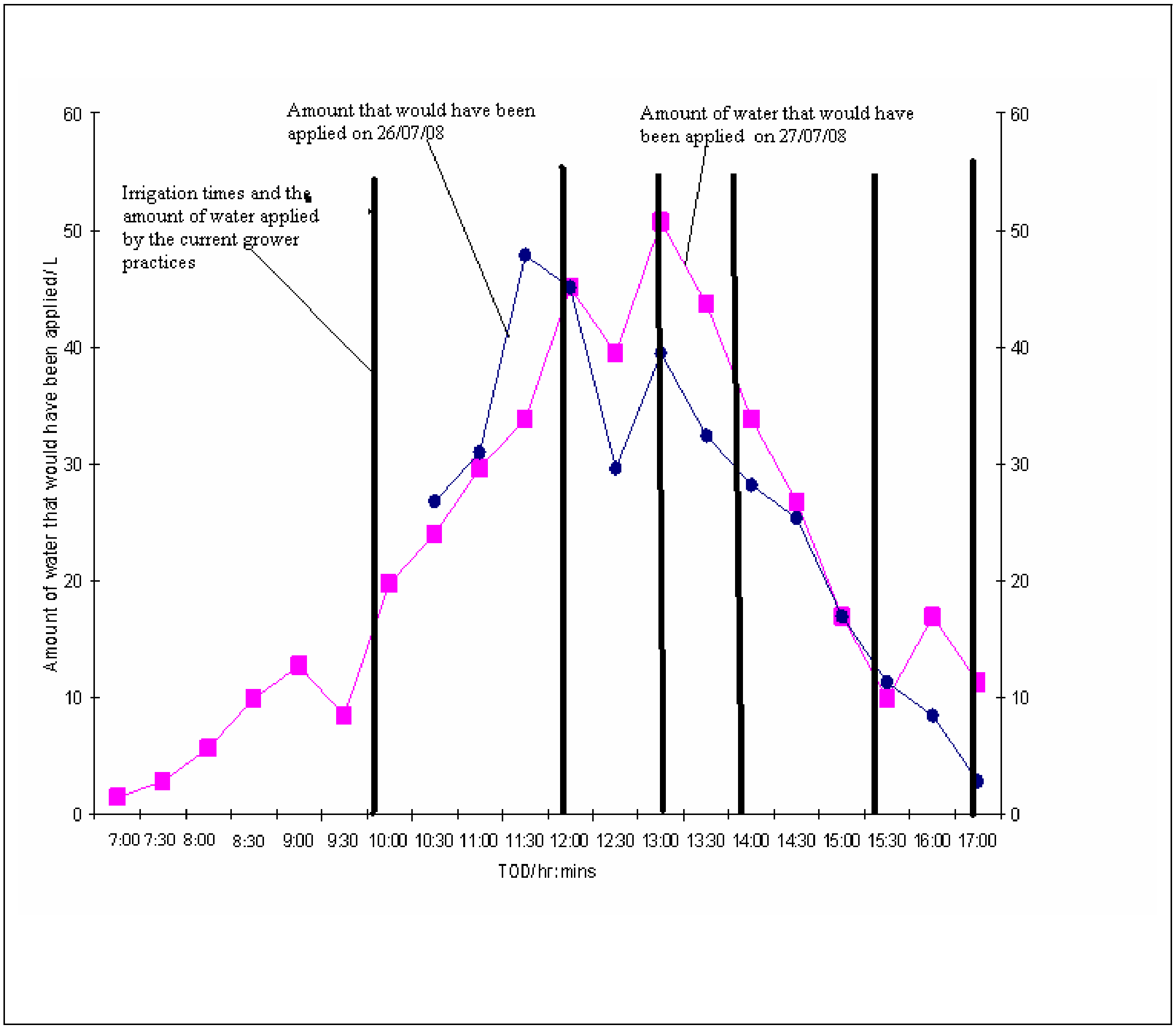

Figure 4.4: The variation of duration and irrigation time, volume of water that would have been applied by the designed irrigation (sap flow based) control system and the volume of water applied by the current (weather based) irrigation control system on 26/07/08 and 27/07/08.

The current grower applied water for fixed periods of 4 minutes and triggered irrigation whenever the accumulative solar radiation outside the greenhouse reached 1600 kJ m^{-2}. The research findings of the project form the base for further research in the commercialization of the designed irrigation control system.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Designed control system was found to be working satisfactorily, although some improvements on its performance are still possible. Since the research project was a feasibility study, it provided sufficient information for further research in this area, despite limited implementation time. The sap flow measurements were found to be a possible indicator for triggering irrigation. The irrigation control software program parameters were determined with relative errors as follows, average stem diameter of the rose plant (11.37 $\pm$ 0.04mm), the averaged total leaf area ($29.25 \pm 0.06 \times 10^{-3} m^2$), leaf area index ($2.58 \pm$ *0.19)*, thermal conductance constant (0.846 $\pm$ 0.002). During the implementation period the highest (peak) sap flow rate of 16g/h^{-1} was recorded at just about 12 noon on 26 July 2008 and the highest (peak) of 18 g/h^{-1} at around 1400hrs on 27 July 2008. The two treatments applied slightly different amount of water during field testing stage. The current grower practice applied water for fixed period of 4 minutes, supplying 337.4 litres of water on each day of the implementation period. From table 4.9 and 4.10, it can be seen that designed control system applied less water on 26 July 2008 than on 27 July 2008, supplying 323.8 and 326.7 litres respectively.

5.2 Recommendations

The designed irrigation automation system can be used on any other plant, provided that the basic control software is developed. Once the source code of an irrigation control program has been developed, the interconnection between the sensor devices and computer is straightforward, since most of the interfaces are standardized. Realisation of such an approach in a commercial greenhouse may be practical difficult due to problems associated with irrigation management, such as excessive vegetative growth on reference plants over time and the need for fertigation. From the finding of this research project I recommend that this designed irrigation control system be taken up for a testing and validation. For a proper testing and validation, a longer period of up to 6 month in the field is required to enable determination of effects of environmental factors and changing seasons on the operation of the designed system.

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APPENDICES

Appendix 1(microprocessor system)

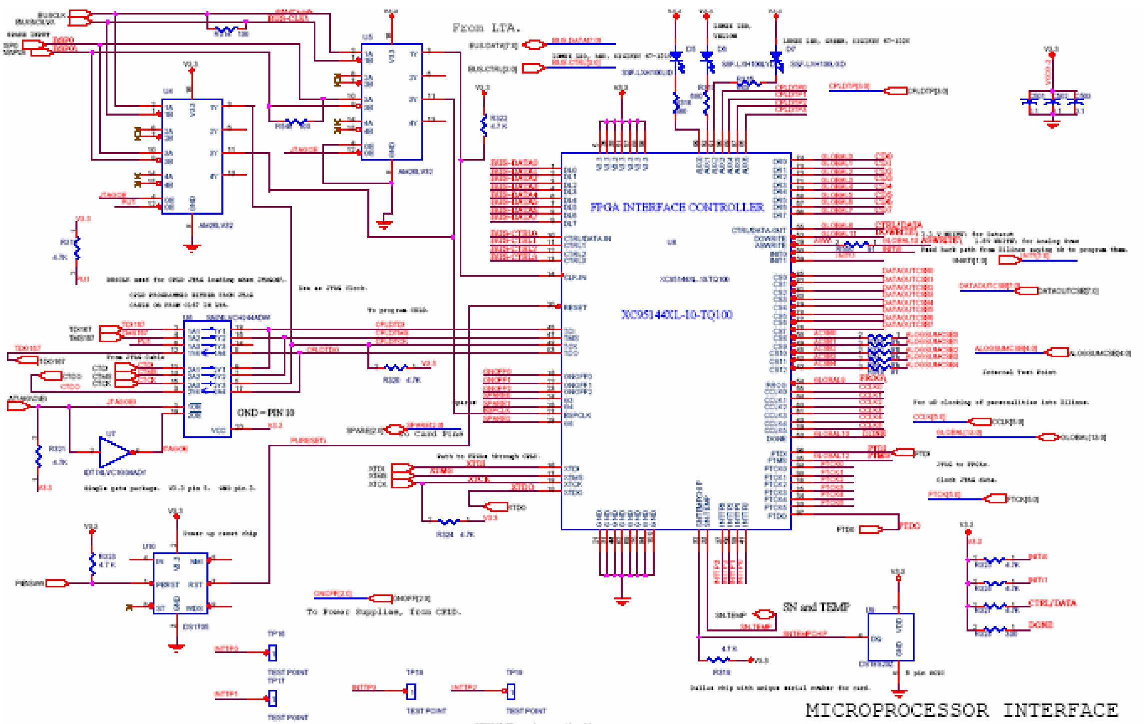

Figure A: Typical microprocessor based system

Appendix 2(K8000 circuit)

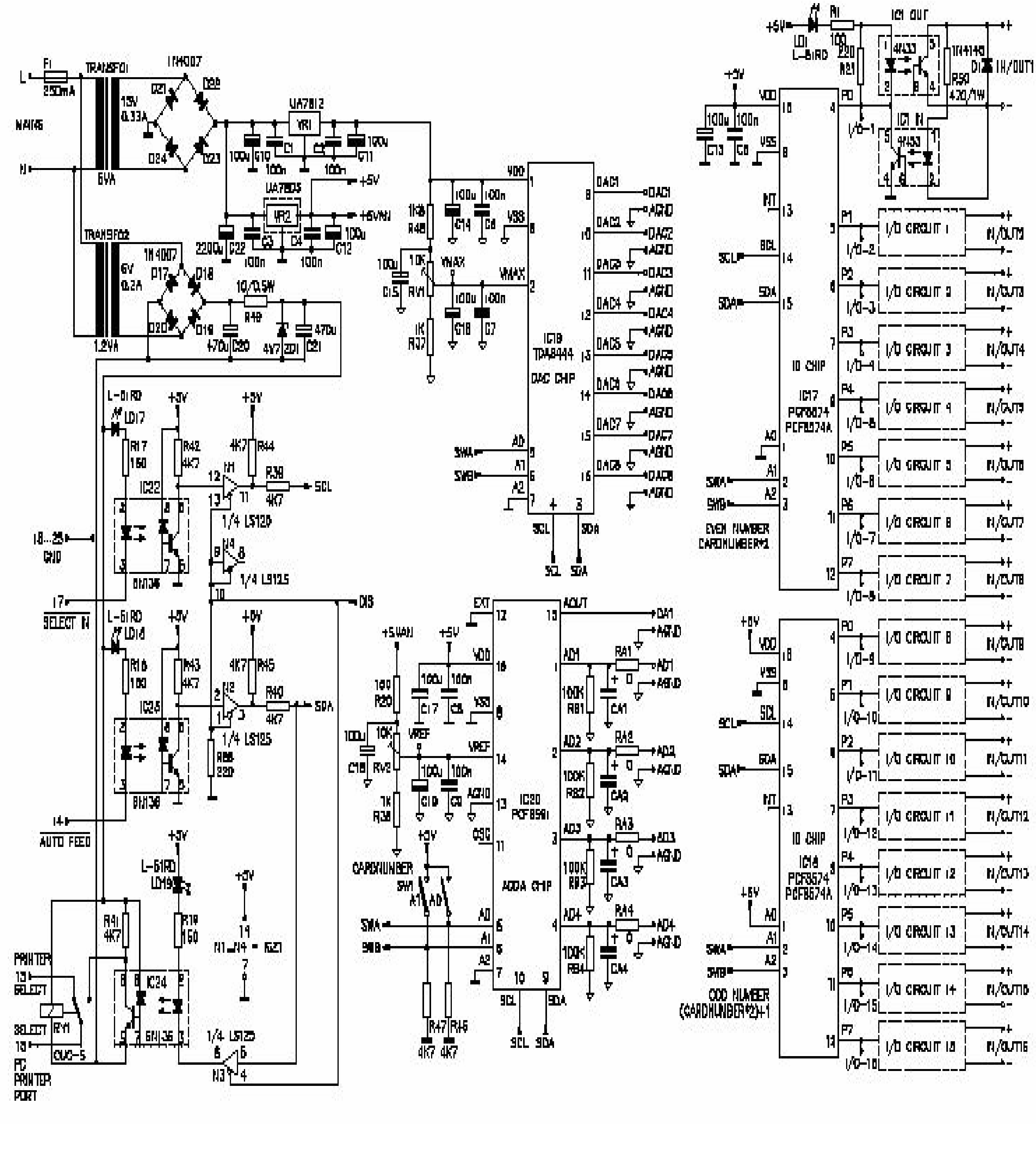

Figure B: K8000 interface board circuit

Appendix 3(data logger program)

3-1 Measurements

Parameter 1: Four sensor voltages are stored sequentially begning with the location (Loc) option stated and defined in parameter 1

Parameter 2: K_{sh} (W/mV)- a constant to be related to the thermopile output, which is proportional to the radial heat transfer.

Parameter3: Heater resistance, measured in ohms, and is supplied by the manufacturer of the gauge.

Parameter4: The cross-sectional area of the stem (cm^2)

Parameter 5: K_{st}

Parameter6: dX

3-2 Input locations

Loc1: CH- Thermopile (mV)

Loc2: AH-Upper TC (mV)

Loc3: BH-Lower TC (mV)

Loc4: Voltage input (V)

These voltages are measured using the instruction twice. The voltage for locations 1-3 are measured on 5mV slow range for the 2X or 25mV range for CR10, where the voltage for location 4 is measured on the 5000mV slow range for 2X and 2500mV, 50/60Hz rejection range for the CR10.

3-3 Instruction processing, a Pascal type software description

Pin = <<loc4>*<loc4>>/<par4>

Qv = <<<loc3>-<loc2>/<4.0*<par6>>>*<par4>*<par5>

Qr =<loc1>*<par2>

Qf = Pin – Qv – Qr

Kshapp = (Pin – Qv)/loc1

dT = <<loc2+loc3>/2.0>*25.0

Sap flow = Qf/<dT*4.186>

If multiplexer =1, units =g/s

If multiplexer =3.6, units = Kg/hr

If multiplexer = 3600,units = g/hr

If par7< the go to XXXXXXXX

If Qf<(0.2*Pin) and if dT<par&

If Qf<0.2*Pin and if Qf<0.0 then sap flow = 0.00001xx

If par 8<0.0 then go to yyy

Fmax = (par8)*(par4)

If sap flow> Fmax , then flow rate F = F max

APPENDIX -4 Developed control program

```
Dim winplc As Object

Dim AD1 As Long
Dim AD2 As Long
Dim AD3 As Long
Dim AD4 As Long


Dim trn As Double
Dim total As Double
Dim Vt As Double
Dim Vol As Double
Dim tx As Double
Dim Er As Double
Dim tp As Double
Dim Den As Double
Dim Dn As Double
Dim Enr As Double
Dim N As Long
Dim V As Double
Dim CH As Double
Dim BH As Double
Dim AH As Double

Dim Kst As Double
Dim Ksh As Double
Dim dX As Double
Dim R As Double

Dim X As Double
Dim w As Double
Dim Y As Double
Dim z As Double

Dim dT As Double
Dim s1 As Double
Dim s2 As Double

Dim C As Double
Dim Fs As Double
Dim tr As Double
Dim Agv As Double
Dim Al As Double
```

```
Dim LAI As Double
Dim Tr1 As Double
Dim Tr0 As Double
Dim trn1 As Double
Dim trn2 As Double
Dim trp As Double
Dim d As Double
Dim d1 As Double

Dim rnd As Long
Dim countx As Long
Dim start As Long
Dim start2 As Long
Dim tt As Long
Dim t2stop As Long
Dim m As Double
Dim tt1 As Double
Dim A As Double
Dim h As Double

'these are time counters

Dim globaltimecounter1 As Long ' for timer1
Dim cnt1 As Long
Dim globaltimecounter2 As Long ' for timer2
Dim cnt2 As Long
Dim globaltimecounter3 As Long ' for timer3
Dim cnt3 As Long
Dim subtr As Long  'to be used in timer3


Private Sub command1_Click()
If (Text1.Text = "" Or Text4.Text = "") Then
MsgBox ("Make Sure You have provided all the input value")
ElseIf (Text1.Text = 0 Or Text4.Text = 0) Then
MsgBox ("       Zero Values are not Accepted!    ")
Else:

start2 = 0
countx = 0
rnd = 0
start = 1
t2stop = 0
trn = 0

Er = 2
```

```
N = 42240
Den = 1.00035
tx = Text4.Text

A = 0.00010159623
R = 155.9
Ksh = 0.0865
Kst = 0.42
dX = 0.004

C = 4.186
Agv = 363
Al = 0.001459
LAI = 2.575

'latest change. we want to use global timecount1 for
' the interval


'Global time variableinitialization
globaltimecounter1 = Text1.Text
globaltimecounter2 = Text4.Text
'**Timer1.Interval = Text4.Text
'Timer1.Enabled = True
Call timer2code   'this will start timer1
End If
End Sub

Private Sub Command3_Click()
winplc.clearioch (1) 'off

'****************************
'code to exit application here
'****************************

End Sub

Private Sub Timer1_Timer()


cnt1 = cnt1 + 1
'If (rnd = 1 And t2stop = 0) Then
 'Call Computations1

'MsgBox ("tr0 " & Tr0)
'ttr0.Caption = Tr0
```

```
'rnd = 2
'countx = countx + 1
'Timer1.Enabled = True

 'now the globaltimecounter will be used

If (rnd = 2 And cnt1 >= globaltimecounter1) Then

Call Computations2
'MsgBox ("tr1 " & Tr1)
ttr1.Caption = Tr1
m = Tr1 - Tr0
'MsgBox ("m " & m)
mm.Caption = m
        If (m <= 0) Then
        trn = trn

        Else:
        trn = (m + trn)
        End If
ttrn.Caption = trn
rnd = 1
cnt1 = 0   'the counter is reset to enable count restart
countx = countx + 1
trate.Caption = tr
'trn = trn1 + trn2

'MsgBox "" & p & trn

'Timer2.Enabled = False
Call timer1code
Else:

End If
'Call timer1code


End Sub

Private Sub Timer2_Timer()
cnt2 = cnt2 + 1          ' counter for timer2. timer2 must
                    ' execute when this reaches globalcounter2

If (countx > 0 And cnt2 >= globaltimecounter2) Then
Timer1.Enabled = False
t2stop = 1      'inside loop must stop
```

```
countx = 0
rnd = 0       ' inside loop stops but is still counting
start = 0

h = 1 / (Er * N)

                Vt = trn * (1 / Den)

                Vol = Round((tx * Vt), 3)

                tp = Vol * h

tt = tp
ttt.Caption = tt
vvv.Caption = Vol
'att.Text = m
'MsgBox ("Value of tp is: " & tt & "")
'tt = tt1 / 3

'the new interval is put in globaltimecounter3


If (tt > 0) Then

globaltimecounter3 = tt * 0.0166667 'interval b4 timer3 switch 0ff
subtr = globaltimecounter3   'used to show remaining time

trn = 0 ' reset values
Tr0 = 0
Tr1 = 0
m = 0
tt = 0
tp = 0
start2 = 1  'condition for timer3 to start
winplc.setioch (1) 'on

cnt3 = 0

Timer3.Enabled = True   '**** edit counter
t2stop = 1 'stop timer1
start = 0  ' stop timer2

ttr1.Caption = "" 'clear all lables
ttr0.Caption = ""
ttrn.Caption = ""
mm.Caption = ""
```

```
'ttt.Caption = ""

Timer2.Enabled = False
Else:
start2 = 0 'timer3's switch off condition
start = 1   'timer3 can start
countx = 0
trn = 0
Tr0 = 0
Tr1 = 0
m = 0
tt = 0
tp = 0

ttr1.Caption = "" 'clear all lables
ttr0.Caption = ""
ttrn.Caption = ""
mm.Caption = ""
ttt.Caption = "0"
rtime.Caption = "0"
subtr = 0

cnt2 = 0   'restart counter
Timer2.Enabled = True
Call timer2code

End If
End If

End Sub


Private Sub Timer3_Timer()
        If (subtr <= 0) Then
        ttt.Caption = "0"
        subtr = 0
        Else:
        subtr = subtr - 1
        End If

rtime.Caption = subtr
cnt3 = cnt3 + 1
If (start2 = 1 And cnt3 >= globaltimecounter3) Then
winplc.clearioch (1) 'off
start2 = 0
start = 1          'timer2 start conditions
```

```
countx = 0
trn = 0
Tr0 = 0
Tr1 = 0
m = 0
Timer2.Enabled = True
Call timer2code

Else:

End If

End Sub


Private Sub timer2code()
'MsgBox "started"
If (countx = 0 And start = 1) Then  'conditions for execution

rnd = 1       ' conditions for timer1 start
start2 = 0      ' timer3 switch off
t2stop = 0      ' condition for timer1 start
cnt1 = 0        ' counter for timer1 is reset
cnt2 = 0        ' counter for timer2 is reset
Timer2.Enabled = True   ' starts timer2 as well for the first time.
Call timer1code         ' this will initialize the inside loops
End If
 End Sub

 Private Sub timer1code()

 't2stop = 0 is the condition for timer1 to execute

 If (rnd = 1 And t2stop = 0) Then


 'Call Computations1

 'MsgBox ("tr0 " & Tr0)
 ttr0.Caption = Tr0
rnd = 2
countx = countx + 1 'enables timer2 to know whether to
Timer1.Enabled = False   ' restart timer1

cnt1 = 0
Timer1.Enabled = True
```

```
ElseIf (rnd = 2) Then

'Call Computations2

'MsgBox ("tr1 " & Tr1)
'ttr1.Caption = Tr1

'm = Tr1 - Tr0
'MsgBox ("m " & m)
'mm.Caption = m
'If (m <= 0) Then
'trn = trn
'Else:
'trn = m + trn
'End If
'trate.Caption = tr
'MsgBox ("trn " & trn)
'ttrn.Caption = trn
'rnd = 1
'countx = countx + 1
'Timer1.Enabled = False
'Call timer1code
'MsgBox
Else:

End If

End Sub

 Private Sub Computations1()
 Set winplc = CreateObject("PWinPLC.PowerWinPLC")

AD1 = winplc.getADState(1)
AD2 = winplc.getADState(2)
AD3 = winplc.getADState(3)
AD4 = winplc.getADState(4)

V = AD1 * 0.526
CH = AD3 * 0.0526 * 0.0001302
BH = AD2 * 0.0526 * 0.0001736
AH = AD4 * 0.0526 * 0.000125

'MsgBox ("tr1 " & V & CH)
```

```
w = V * V / R
X = Ksh * CH
Y = (BH - AH) * A * Kst
z = 1 / (dX * 0.04)

Qf = w - X - Y * z

               s1 = (AH + BH) / 2
                s2 = 1 / 0.04

                dT = s1 * s2



                d1 = 1 / C * dT

                Fs = Qf * d1

                d = Fs / Al

                tr = (d * LAI * Agv * 0.001 * 0.00015)
                tr = Round(tr, 3)

               Tr0 = Round(tr, 3)

        'MsgBox "started"
 End Sub

 Private Sub Computations2()
 Set winplc = CreateObject("PWinPLC.PowerWinPLC")

AD1 = winplc.getADState(1)
AD2 = winplc.getADState(2)
AD3 = winplc.getADState(3)
AD4 = winplc.getADState(4)


V = AD1 * 0.526
CH = AD3 * 0.0526 * 0.0001302
BH = AD2 * 0.0526 * 0.0001736
AH = AD4 * 0.0526 * 0.000125

w = V * V / R
X = Ksh * CH
Y = (BH * -AH) * A * Kst
z = 1 / (dX * 0.04)
```

```
Qf = w - X - Y * z


        s1 = (AH + BH) / 2
        s2 = 1 / 0.04

        dT = s1 * s2

        d1 = 1 / C * dT
        Fs = Qf * d1
        d = Fs / Al
        tr = Round((d * LAI * Agv * 0.001 * 0.0015), 3)
        Tr1 = Round(tr, 3)
        'MsgBox "tri" & Tr1
 End Sub

Private Sub Command2_Click()
winplc.clearioch (1) 'off
trn = 0 ' reset values
Tr0 = 0
Tr1 = 0
m = 0
tt = 0
tp = 0

Timer1.Enabled = False
Timer2.Enabled = False
Timer3.Enabled = False

t2stop = 1   ' timer1 stops
start = 0    ' timer2 stops
start2 = 0   ' timer3 stops


Timer1.Enabled = False

ttr1.Caption = "" 'clear all lables
ttr0.Caption = ""
ttrn.Caption = ""
mm.Caption = ""
ttt.Caption = ""
vvv.Caption = ""
rtime.Caption = ""

End Sub
```