A PORTABLE CHAMBER TO MEASURE PLANT WATER USE: DESIGN CONSIDERATIONS AND ANALYSIS

By

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DEDICATION

To Rhea: my extraordinary example

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A = Sensible heat transfer (W/m^2)

E = Latent heat transfer (W/m^2)

ET = Chamber estimated ET (cm/hr)

R_n = Net radiation (W/m^2)

S = Soil heat transfer (W/m^2)

R_s = Incoming solar radiaition (W/m^2)

R_L = Solar radiation absorbed by leaf (W/m^2)

IR = Infrared radiation (W/m^2)

IR_L = Emitted infrared radiation from leaf (W/m^2)

IR_a = Emitted infrared radiation from atmosphere (W/m^2)

IR_s = Emitted infrared radiation from surroundings (W/m^2)

IR_c = Emitted infrared radiation from chamber cover (W/m^2)

T = Temperature (C)

T_d = Air dry bulb temperature (C)

T_w = Air wet bulb temperature (C)

T_C = Average crop temperature (C)

T_L = Leaf temperature (C or K)

T_e = Effective sky temperature (K)

T_s = Temperature of surroundings (K)

T_c = Temperature of chamber cover (K)

t = Time (s)

Δt = Time increment (s)

z = Height above zero point displacement (m)

∇_H = $\partial/\partial x + \partial/\partial y$ (m^{-1})

h = Height of crop canopy (m)

h_L = Average leaf thickness (m)

L = Length of leaf in direction of air movement (m)

l' = Length of stomatal cavity (cm)

l'_{eff} = Effective length of stomatal cavity (cm)

d = Diameter of stomatal cavity (cm)

δ = Thickness of unstirred boundary layer (m)

A' = Cross sectional area of stomatal cavity (cm^2)

u = Horizontal wind velocity in crop canopy (m/s)

v = Wind velocity over leaf surface (m/s)

ρ_L = Density of leaf (Kg/m^3)

ρ_a = Density of air (Kg/m^3)

C_L = Specific heat of leaf (KJ/Kg-C)

C_a = Specific heat of air (KJ/Kg-C)

K_A = Sensible heat transfer coefficient (m^2/s)

K_E = Latent heat transfer coefficient (m^2/s)

k = thermal conductivity (W/m-C)

D = Diffusivity of water vapor in air (m^2/s)

r_D = Diffusion resistance (s/m)

r'_s = Resistance of single stomate to water transport (g/cm^3)

r_s = Stomatal resistance (s/m)

r_{bl} = Boundary layer resistance (s/m)

r_A = Sensible heat transfer resistance ($C-m^2/W$)

e = Vapor pressure of the air (Pa)

e^0_w = Saturated vapor pressure at the wet bulb temperature (Pa)

e_L = Saturated vapor pressure within leaf stomatal cavity (Pa)

P = Atmospheric pressure (Pa)

M_W = Molecular weight of water (Kg/mole)

M_a = Molecular weight of air (Kg/mole)

ε = Ratio of mole weights of water to air

L = Latent heat of vaporization (KJ/Kg)

R = Gas constant (KJ/K-mole)

σ = Stephan-Boltzmann constant (5.67×10^{-8} W/m^2-K)

ρ'_L = Leaf albedo

ρ'_c = Chamber cover albedo

α'_L = Leaf absorptivity

τ'_c = Chamber cover solar transmissivity

τ''_c = Chamber cover infrared transmissivity

ρ''_L = Leaf infrared reflectivity

ρ''_c = Chamber cover infrared reflectivity

ε''_L = Leaf infrared emissivity

ε''_c = Chamber cover emissivity

ε''_a = Emissivity of atmosphere

ε''_a = Emissivity of surroundings

WP1 = Weighed pots group 1

WP2 = Weighed pots group 2

CH2OT = Chamber open top group 2

CH2CT = Chamber closed top group 2

INTRODUCTION

In the last 25 years researchers have begun using a chamber technique to measure evapotranspiration (ET) and canopy apparent photosynthesis (CAP) in the field. Most of these chambers required the control of the chamber environment in an attempt to simulate field conditions. Since the chamber was left in place over plants in the field for periods exceeding one hour and in some cases for several weeks, the crop's energy exchange was a steady state process over short periods of time. The weakness of the technique is the requirement to simulate actual field conditions which researchers have found difficult to do.

A distinctly different type of chamber technique places the chamber over the crop for periods usually less than one minute in duration and it is this type of chamber which is the focus of this study. The technique attempts to obtain an instantaneous rate of ET or CAP during the short measurement interval in the field. This type of chamber uses no environmental control methods except those that might be considered passive controls such as a high infrared transmission chamber cover material. It has been assumed by users of such a type of chamber that the shortness of the chamber measurement would assure negligible modification of the crop environment and therefore the ET and CAP rates. However, only little experimental and no theoretical work has been done to support this assumption.

The goal of this study was to investigate by analytical and experimental means the sources, magnitudes and directions of potential error in ET estimation under specific environmental conditions using a portable field chamber, with special emphasis on disturbances of the plant environment. Specific objectives were:

1. Review of previous work done using the chamber technique for estimating gas exchange rates.

2. Identify crop canopy parameters affected by the presence of the chamber.

3. Develop recommendations for the design and development of a portable measurement chamber.

The approaches taken to acheive these objectives were:

1. The development of a single leaf energy balance simulation model with which to observe the trends of nonconstant parameters for a leaf enclosed in a portable measurement chamber for a short period time.

2. Design, construct and test a portable measurement chamber from which to evaluate the chamber technique.

3. Perform laboratory experiments to obtain statistically valid information regarding chamber design and plant microclimate effects.

This analysis will attempt to serve as a base for much needed further research and as an aid to those who wish to apply the technique in their research.

CHAPTER 1

LITERATURE REVIEW

Most work done with chambers for measuring plant water use (ET) and/or canopy apparent photosynthesis (CAP) has been with chambers that are placed in the field over several hours, days or weeks (Musgrave and Moss, 1961; Decker et al,1962; Baker, 1965; Sakamoto and Shaw, 1967; Jeffers and Shibles, 1969; Puckridge,1969; Connor and Cartledge, 1970; Egli, Pendleton and Peters, 1970; Leafe, 1972; Puckridge 1978). It can be assumed that in this type of chamber the energy balance due to incoming and outgoing radiation, and sensible and latent heat transfer is steady state for short periods of time. The energy exchange in this type of chamber is similar to that of a greenhouse and has been described by Businger (1963). Lee(1966) reviewed literature on tent enclosures and discussed effects of such a chamber on the microclimate and crop ET.

Another type of chamber used for determining ET and/or CAP in the field is the so called instantaneous measurement chamber which is the subject of this thesis. It is called "instantaneous" because the measurement is made usually in a period of time less than one minute. The data obtained from a measurement of this length is presumably a reasonable estimate of the parameter flux for a given point in time.

Reicosky and Peters(1977) and Reicosky(1981) did not distinguish between the two types of chambers in their literature reviews. It should, however, be noted that the non-instantaneous and instantaneous type chambers are fundamentally different in the theory of their measurement approach.

In the case of the non-instantaneous chamber the crop environment is affected by the presence of the chamber and is altered from the surrounding environment. Some researchers employing this type of chamber have attempted to artificially simulate the natural outside conditions by contolling the temperature, humidity and CO_2 concentration of the chamber air but without exception have been forced to accept conditions different from those in the field. Musgrave and Moss(1961), for example, replenished their chamber with CO_2 at a rate equal to the assimilation rate of the enclosed plants. An attempt to control air temperature was made but the thermostat used resulted in fluctuating air temperatures. The measured reduction in solar radiation was 20% and the humidity was not controlled. Sakamoto and Shaw(1967) reported similar problems but in addition found the maintainence of a constant CO_2 level was difficult to acheive resulting in CO_2 concentration fluctuations. Jeffers and Shibles(1969) who measured CAP rates for soybeans stated that the chamber produced "somewhat artificial conditions".

The point here is that when a chamber of this type is used, although an attempt be made to control the chamber environment, complete simulation of the outside conditions cannot be expected. The result is a group of plants which may have very different rates of ET and CAP than the surrounding plants in the field. Despite the inherent weakness in the technique to measure absolute rates of ET in the field (Lee, 1966), this approach has been found reliable in comparing treatment effects on ET (Puckridge,1978).

The goal of the instantaneous measurement chamber is to obtain an accurate, absolute point measurement of ET and/or CAP in the field. To acheivement this goal, the chamber is lowered over or is placed around a group of plants and a rapid measurement is taken, typically by means of an aspirated thermistor psychrometer. It is hoped that the shortness of the measurement duration will minimize a plant response to the presence of the chamber. If the plant response is negligible, then the measured ET and/or CAP will be essentially the same as that of the plants prior to chamber placement. It would seem that this approach would give values much closer to the actual field values than the non-instantaneous chamber and this may be true. However, the speed with which mechanisms controlling ET and CAP can be changed by the plant must be considered, both analytically and experimentally, before a judgement can be made.

This study will address some the physical aspects of the instantaneous type measurement chamber used for ET estimation which may affect its operation and performance. In the pages that follow it can be assumed that any reference made to the "chamber" refers to the instantaneous type chamber unless otherwise specified or that the distinction is not important.

Peters, et al.(1974) developed a chamber for the measurement of both plant water use and photosynthesis in the field. The chamber moved on tracks from one plot to the next where the number of plots was limited by the length of track, electrical cable and the infared gas analyzer tubing. The track used for chamber movement required the elimination of two plant rows adjacent to the plot. The measurement procedure consisted of moving the chamber with front and back open over the desired plot. When the chamber was properly positioned the front and back "doors" closed and the chamber became sealed preventing any gas exchange with the outside. Wet and dry bulb temperatures as well as gas samples were obtained over the measurement interval. Upon completion of the measurement, the front and back of the chamber opened and the chamber was moved to the next experimental plot.

The chamber was covered with 0.1 mm Mylar film. On the front and back sides of the chamber the film was wound around horizontal cylinders the width of the chamber. The cylinders were kept near the top of the chamber until the chamber was positioned over the crop, at which time they were rolled down, covering the front and back sides of the chamber with the film. Rubber seals were used between the rolls and the ground for sealing the chamber from the outside. The rolls took approximately 18 seconds to lower.

The researchers stated "The time of measurement depends on the rate of gaseous flux and the precision of the measurement instruments". Some measurements were as short as 20 seconds. Determination of the rates of photosynthesis and evapotranspiration were determined from the slope changes of CO_2 concentration and the wet and dry bulb temperatures, respectively. Data presented showed the wet and dry bulb temperature changes to be quite linear over the measurement period. Although a careful calibration was carried out for the CO_2 concentration a calibration on the psychrometer was not done.

In the introduction of the article Peters, et al. states that in measuring ET and CAP in the field it is essential that "the measurement technique disturb as little as possible the spatial and aerodynamic characteristics of the plot", and they go on to say that the described chamber "meets the above mentioned criteria". Whether or not this is true can not be determined from the information given in the article. The chamber CO_2 calibration was done by injecting a known amount of CO_2 into the chamber. That the chamber measured the control flux may be of only secondary importance if the chamber altered the plants microclimate and rate of CO_2 assimilation. Schulze(1978) suggested that the two open rows along side the plot for the chamber tracks allowed light to penetrate into the lower canopy, a fact which may have increased photosynthetic rates. From the article one must conclude that the extent of the psychrometer calibration was the calibration of the thermistors (although this information was not given). Again, even if the psychrometer worked well, if the transpiraton rate of the plants was changed by the presence of the chamber then the measured ET rate must be considered in error.

Reicosky and Peters(1977) developed a chamber for measuring plant water use in the field. The chamber was made of aluminum conduit covered with 0.127 mm Mylar film and was entirely closed except for its bottom side. The chamber was appropriately sized for use with soybeans and the height could be altered for use with corn.

The measurement procedure consisted of lowering the chamber over a crop by means of a fork lift vehicle. A psychrometer was used for measuring the rate of vapor density in the chamber over the measurement interval. While the chamber was suspended above the crop, the instrument readings were observed until wet and dry bulb temperatures in the chamber stabilized, at which time the temperatures were recorded. The chamber was then lowered to the ground for a period of one minute and the final temperatures were read and recorded. After the measurement was completed the chamber was lifted above the crop, the internal air purged and the chamber was ready for the next measurement. The initial and final values of wet and dry bulb temperatures were used to obtain the change in vapor pressure. Using the change of vapor pressure in the ideal gas equation along with the chamber dimensions and measurement time yielded the ET rate in an equivalent depth per unit time.

The chamber could be lowered to the ground in 5 seconds and raised in 8 seconds. Fans were used to continuously mix the air and recycled the air 9 times per minute. The wet and dry bulb thermistors were held inside a psychrometer shielded from direct radiation.

The chamber was tested by placing it over soybean plants grown in a hydroponic solution where the solution uptake could be measured. The plants in solution were placed in the field and exposed to natural sun light. An entire test run lasted 5 hours.

The data obtained from the test for August 28, 1975 showed very good agreement. Data obtained on cloudy days, however, showed significant disagreement between the solution uptake and the measured transpiration rate where the transpiration rate measured by the chamber was higher than the solution uptake rate. This disagreement was attributed to water stored earlier by the plants which was subsequently released during the test, being measured by the chamber but not by the control. Reicosky(1981) later suggested that the disagreement may be partly due to an insufficient number of data points collected over the time of interest since the chamber measures instantaneous values of ET which may vary considerably with minute to minute changes in radiation.

A sensitivity analysis described by Doeblin(1966) was used to calculate the total error of the system. With wet and dry bulb air temperatures assumed to be read to +/- 0.1 C the overall error was found to be 19% while the probable error was not larger than 11%. Reicosky(1981) compared measurements made by the chamber with a weighing lysimeter covered with alfalfa at the Minnesota Agricultural Experiment Station. For a clear day on July 2, 1980 the lysimeter measured 8.0 mm/day and the chamber measured 7.8 mm/day. Reicosky, Deaton and Parsons(1980) subsequently used the chamber for measuring ET, attempting to relate canopy temperatures to plant water status in irrigated and nonirrigated soybeans. Mason et al.(1980) used this same chamber to determine ET from irrigated and nonirrigated soybeans on selected days in Iowa. The data obtained was quite scattered due to the variations in radiation resulting from intermittent cloudiness, but clearly showed that the irrigated beans consumed more water than did the nonirrigated beans. The reseachers, however, attributed this not to water stress in the nonirrigated treatment since the soil water status was found not to be different for the two treatments, but to leaf area index which was greater for the irrigated treatment.

Reicosky(1981) modified his approach by reducing the 1 minute measurement to 30 seconds as a result of observing the wet bulb air temperature in the chamber become asymptotic as saturation was approached. In addition he covered the chamber with 3.18 mm plexiglass instead of Mylar.

In 1974 Schulze(1978) developed a chamber for measuring CAP from soybeans. The chamber design consisted of a 1 m body with a removable lid which increased the height of the chamber by 0.3 m and was covered with 0.1 mm thick mylar film. To prevent gas exchange with the outside, one side of an aluminum angle was attached to the bottom of the chamber frame so that the other side of the angle could be projected into the soil. The chamber was small enough so that it could be manually placed over the plants without the use of lift equipment. The lower edges of the lid frame were lined with 1.3 x 2.5 cm foam rubber weather stripping to provide a seal. Two fans of capacity 9062 l/min were used to mix the air in the chamber. The fans cycled the air in the chamber about 7 times per minute. Chamber air temperatures were measurued during the CAP measurements with shaded thermocouples.

In 1975 the height of the lid was increased to 0.6 m to accommodate taller plants. With the greater height the air exchange rate within the chamber became 5.5 chamber volumes per minute. Schulze stated that this rate of air mixing was adequate to produce a representative air sample at the inlet to the CO_2 gas analyzer hose which was placed at the upper fan outlet. The new design also included setting the chamber in a wooden frame which was placed on the ground before the measurement to further insure a minimum of gas exchange with the outside.

The measurement consisted of placing the chamber over the plants prior to the CAP measurement. The measurement commenced when the lid was placed on the chamber and clamped shut. Most runs lasted less than 1.5 minutes. At the end of the run the chamber lid was opened and the chamber equipment was moved to a second chamber for the next measurement. The use of two chambers allowed CAP measurements to be taken once every 5 minutes.

CO_2 concentrations inside the chamber were observed to decrease linearly with time. The mean rise in chamber air temperatures over the first minute observed during the 1974, 1975 and 1976 tests were 1.4, 1.13 and 1.09 C, respectively. The mean temperature rise for the second minute for the 1974, 1975 and 1976 tests were 1.21, 1.09 and 0.84 C, respectively. He also observed how the temperature rise was affected by different levels of solar radiation. The data demonstrated a tendency for chamber air temperatures to increase with increasing solar radiation yet the data were quite scattered.

Schulze commented that notwithstanding the techniques obvious ability to obtain rapid measurements of CAP in the field it necessatated a high labor requirement of 3 to 4 people.

Harrison, Boerma and Ashley(1980) used a chamber similar to the design used by Schulze(1978) for measuring CAP rates in a genetic study on soybeans. Measurement rises during the chamber measurement were reported as being under 2 C. Wells, et al.(1982) used the same design for measuring cultivar differences in CAP and their relation to seed yield in soybeans. Reported temperature rises within the chamber averaged 1 C.

CHAPTER 2

CHAMBER DESIGN CONSIDERATIONS

The presence of the portable chamber over a group of plants causes an immediate change in the stored internal energy of the crop canopy. It is desirable, as in any measurement, to minimize the effect of the measurement system. One way to minimize the effect of the chamber's presence is to make the measurement before the crop canopy is significantly effected by the measurement chamber.

Equally important is the design of the chamber itself including the size of the chamber, the placement of instruments within it, and the choice of materials with which the chamber is constructed. Ideally the chamber should cause no change in the radiant, sensible and latent energy exchange ongoing in the crop canopy. By choosing chamber materials carefully, the influence of the chamber on the energy exchange can be minimized.

The instantaneous measurement chamber technique is a relatively new approach for measuring canopy gas exchange. The energy processes which take place within the chamber and which determine the rates of gaseous exchange have not yet been fully addressed in the literature and therefore will be discussed in the sections that follow.

Physical Considerations

From basic thermodynamics it is known that if a system is in equilibrium with respect to the transfer of energy across its boundaries and the boundary conditions are changed so as to change the net energy flux across the boundaries, a state of nonequilibrium will prevail until such time as the first derivative of the stored internal energy of the system with respect to time is again zero (Van Wylen and Sonntag, 1973). Since latent heat which is produced at the plant and soil surfaces (and is proportional to ET) is closely linked to the other forms of energy transfer it will no doubt change when the chamber is introduced. Whether or not the changing internal energy within the measurement chamber will cause significant error in ET estimation depends partially on the length of the chamber measurement and on the degree to which the chamber's original environment has been changed. The complete energy balance for a crop canopy was given by Tanner (1960) as:

$$\begin{aligned} R_n + A + E + S + \int_0^z C_a \nabla_H(\rho_a u T_a)\delta z + \int_0^z (L\varepsilon/R)\nabla_H(ue/T_a)\delta z \\ = \int_0^z C_C \rho_C (\partial T_C/\partial t)\delta z + \int_0^z C_a \rho_a (\partial T_a/\partial t)\delta z \\ + \int_0^z (L\varepsilon/RT)(\partial e/\partial t)\delta z \end{aligned} \tag{2.1}$$

where

R_n = net radiation (W/m^2)

A = sensible heat transfer (W/m^2)

S = soil heat transfer (W/m^2)

E = latent heat transfer (W/m^2)

T_C = average crop temperature (C)

T_a = air dry bulb temperature (C)

L = latent heat of vaporization (J/Kg)

C_a = heat capacity of air (J/Kg-C)

C_C = heat capacity of crop (J/Kg-C)

R = gas constant (Pa-m /Kg-C)

$\nabla_H = \partial/\partial x + \partial/\partial y$ (m^{-1})

ε = ratio of mole weights of water to air

ρ_a = density of air (Kg/m^3)

ρ_C = mean density of crop (Kg/m^3)

ρ_W = density of water (Kg/m^3)

e = vapor pressure (Pa)

t = time (s)

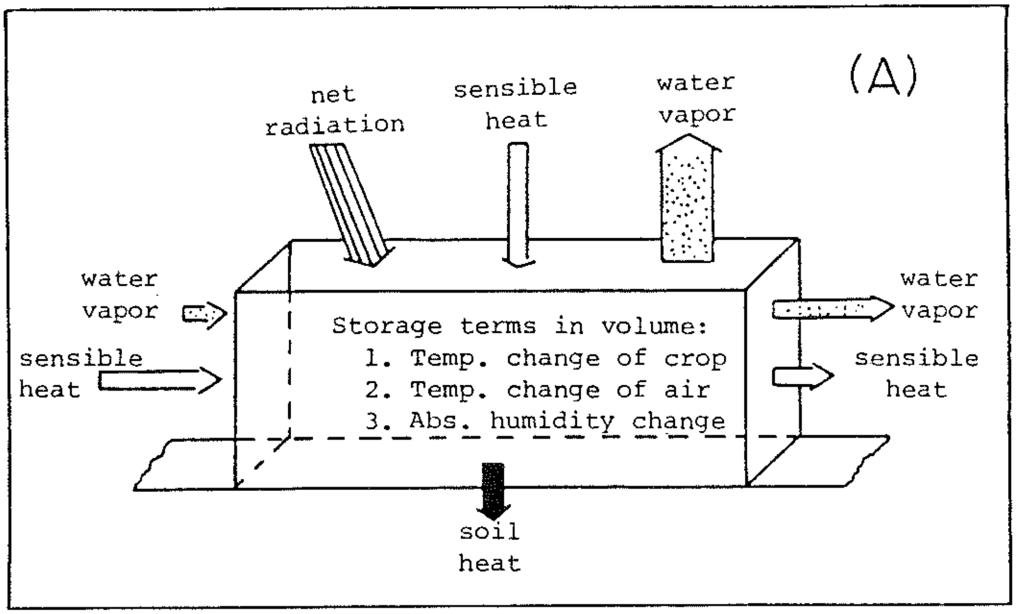
u = horizontal wind velocity (m/s)

z = height above zero point displacement (m)

The energy balance of the crop canopy is illustrated in Figure 2.1.

The left side of equation 2.1 accounts for the net radiation, horizontal divergence of sensible and latent heat and the vertical fluxes of sensible , latent and soil heat. The right side of equation 2.1 accounts for the change in internal energy with time within the crop and crop-air volume. The left side of the expression is positive for energy moving into the canopy and the right side is positive for an increase in the canopy's stored internal energy. Equation 2.1 neglects energy used by photosysthesis.

For short periods of time in the field the storage terms are approximately zero. The divergence terms may be significant for an irrigated crop surrounded by nonvegatated land in arid regions. In humid regions, however, these terms are usually small, especially well



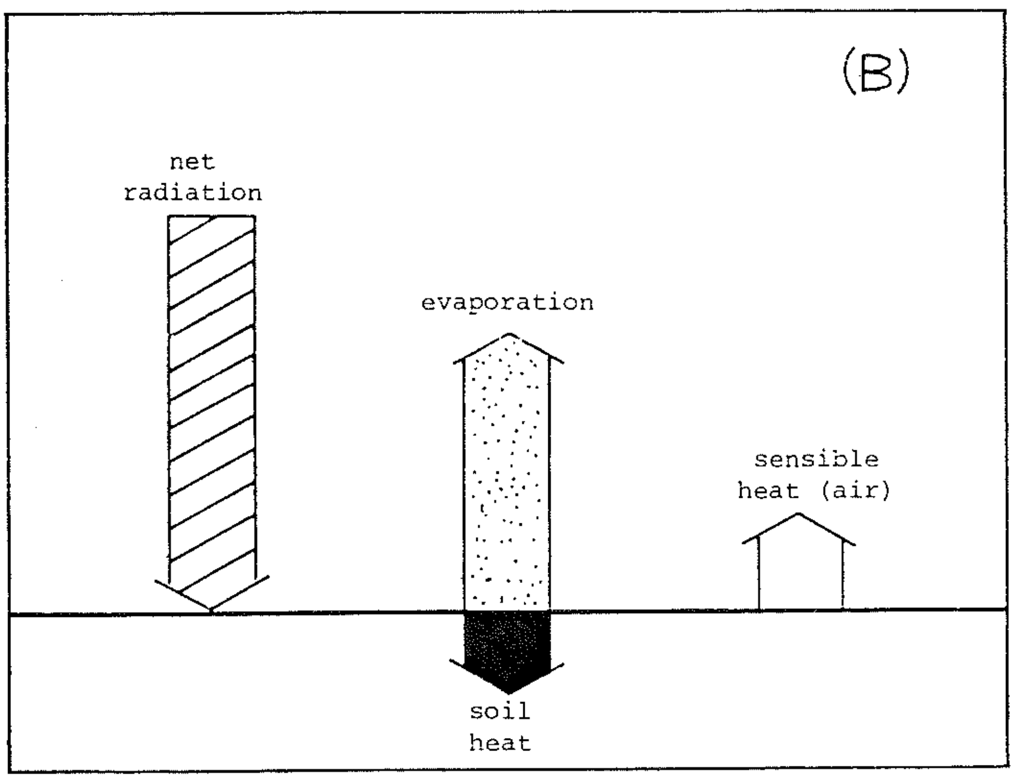


Figure 2.1 Horizontal and verticle energy balance of a crop canopy (A). Vertical energy balance of a crop canopy (B). (After Tanner, 1960)

inside the borders of a cropped field (Tanner, 1960). Assuming both the storage and divergence terms to be zero and letting δz go to zero causing the control volume to become a control plane (Figure 2.2B) simplifies equation 2.1 considerably giving

$$R_n + A + E + S = 0 \tag{2.2}$$

Equation 2.2 is a viable expression for describing the energy tranfer of a crop over short periods in the field. Wright and Brown (1967) gave expressions for the sensible and latent heat transfer as

$$A = -\rho_a C_a K_A (dT/dz) \tag{2.3}$$

and

$$E = -(\rho_a \varepsilon L/P) K_E (de/dz) \tag{2.4}$$

where

K_A = sensible heat transfer coefficient (m^2/s)

K_E = latent heat transfer coefficient (m^2/s)

T = temperature (C)

e = vapor pressure (Pa)

z = heat transfer path (m)

ρ_a = density of air (Kg/m^3)

C_a = heat capacity of air (J/Kg-C)

ε = ratio of molecular weights of water to air

L = latent heat of vaporization (J/Kg)

P = atmospheric pressure (Pa)

Equations 2.3 and 2.4 are given here to show how each of these modes of energy transfer are dependent on the temperature difference between two points in space. The vapor pressure which is a function of the wet and dry bulb temperatures was given by List(1958) as

$$e = e_w^0 - 66000P(T_w - T_d)(1 + 0.00115T_w) \tag{2.5}$$

where

e = vapor pressure (Pa)

e_w^0 = saturated vapor pressure (Pa)

T_d = dry bulb temperature (C)

T_w = wet bulb temperature (C)

The saturated vapor pressure must be calculated at the wet bulb temperature (Nantou, 1979) and is given here in a simplified form of the Clausius-Clapeyron equation (Merva, 1975).

$$e_w^0 = 133 \ln(21.07-(5336/(T_w + 273.15))) \tag{2.6}$$

The transfer coefficients depend on wind velocity and therefore depend on height above a datum since the wind velocity varies approximately logarithmically with height in the field. Figure 2.2 shows the relationship of several of the variables in equations 2.2, 2.3 and 2.4 with height above the ground in a typical crop canopy. Figure 2.2, though idealized, conveys a general picture of the sensitive, interrelated energy complex within a crop canopy. One can imagine that with a slight modification in one of these parameters the entire system might be significantly altered from its original state. Such a modification might be affected by the placement of an enclosure or chamber over the crop canopy. If the chamber is left over the crop for a long period of time, for example one or two hours, then equation 2.2 would apply since a psuedo-equilibrium condition would exist. If, however, the chamber were over the crop for a period less than one minute (as in the case of an instantaneous measurement chamber), equation 2.2 would not apply during this time since the energy components would be changing in time and thus, equation 2.1 must be used. The divergence terms can still be neglected but now the storage terms may be considerable. Integrating over the height h of the chamber equation 2.1 becomes

$$R_n + A + E + S = C_a h \rho_a \partial T_d / \partial t + C_c h \rho_c \partial T_c / \partial t + hL\varepsilon / RT_d \partial e / \partial t \qquad (2.7)$$

The instant the chamber is put in place a dynamic process begins since the chamber's presence causes changes in transfer coefficients as well as gradients. A discussion of the terms on the left side of equation 2.7 is in order.

Radiation

The net radiation, the sum of the various components of radiant energy transfer in the crop canopy, plays a major role in the energy process and in some cases may be virtually the sole energy input in the field, (i.e. R_n is positive while other terms in equation 2.6 are negative). The net radiation is one of the components of the energy budget which the designer has some control over. By using a cover material on the chamber which transmits infrared and visible radiation well (and by using minimal structural members) it is possible to minimize a change in the net radiation flux.

As the chamber is lowered into place the crop canopy which it encloses receives an altered quantity of radiation. The radiation received at the chamber cover surface is mostly transmitted, but some is reflected and some is absorbed. The ideal case would exist if the reflected and absorbed components of the flux were zero. If this were the case and all the radiation was transmitted through the cover, this situation would be equivalent to the condition when the chamber was not present so far as the radiant exchange is concerned. The transmission of radiation through a transparent medium is a function of the wavelength of the radiation (Duffie and Beckman, 1974; Duffie and Beckman, 1980). Many transparent materials (film or rigid sheet) transmit about 90% of the normally incident visible radiation (wavelengths between 0.3-0.7 microns) but may transmit radiation poorly that is composed of wavelengths greater than 0.7 microns (Trickett and Goulden, 1958). For instance, plexiglass though capable of transmitting about 90% of the normally visible radiation only transmits about 10% of radiation composed of longer wavelengths. Radiation of wavelengths greater than 0.7 microns is referred to as infrared radiation (Rosenburg, 1974). Figure 2.3 shows the infrared radiation transmission spectra for plexiglass and polycarbonate (Lexan), two commonly used plastic materials. Curves similar to those shown in Figure 2.3 are given by Walker and Slack (1970) and Trickett and Goulden (1958) for other commonly used films. Measurement equipment for the determination of transmissivities of materials' for radiation between the wavelengths of 0.7 and 2.5 microns is not commonly available and therefore rarely reported. However, this does not imply that this incoming or outgoing radiation is negligible or unimportant and therefore transmission information for this range should be obtained if possible.

Since all bodies above absolute zero emit radiant energy, the flux of solar radiation is balanced partly by radiation emitted by the crop canopy (Davies and Idso, 1979). The radiation emitted from the crop is infrared and, based on the data for the two cover materials' given above, a large amount of the radiation will either be reflected back into the chamber or be absorbed by the chamber cover. This radiation, which is essentially trapped inside the chamber, will be absorbed by the air and at the chamber surfaces. The molecules, whether in the air or at a surface will either absorb or reflect a particular wavelength photon depending upon the type of molecule involved. Water vapor, for

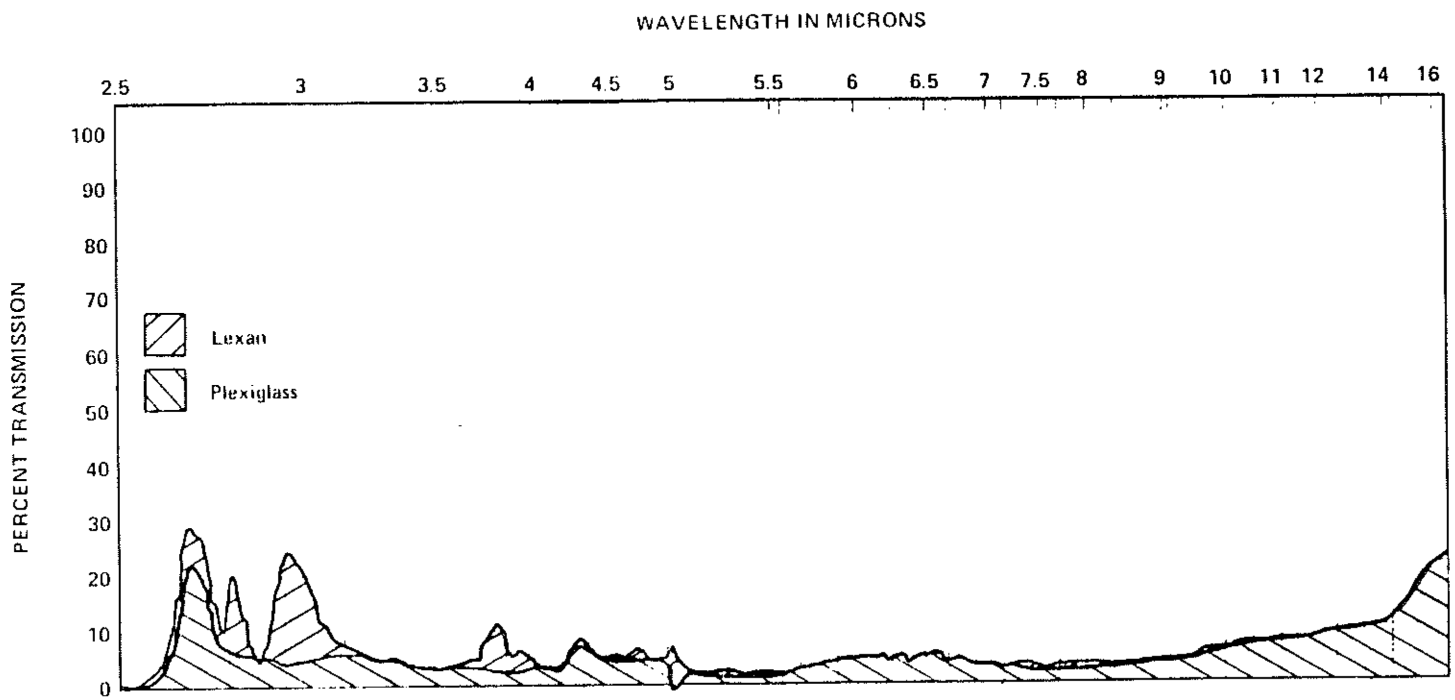


Figure 2.3 Infrared radiation transmission with wavelength for two possible chamber cover materials. The data was collected in December, 1981 at Michigan State Univeristy by the author.

instance, absorbs long wave radiation quite well (an unfortunate coincidence since the goal of the chamber is to trap water vapor and not radiant energy). The absorption of energy by a molecule will raise the energy level of the molecule. The increase in energy is manifested as an excitation which is conveyed to other molecules via molecular collisions. This process which is less than 100% efficient results in some sensible heating. Simultaneously, the molecule is emitting radiant energy to other molecules. If radiation originally received was from a source of higher temperature than the molecule then the reradiation will be a lower grade, i.e. of a longer wavelength. This process will continue until the temperature of the molecules in both the air and surfaces are elevated sufficiently to counteract the inflow of radiant energy. This phenomenon has been called the "greenhouse" effect and has been described by Businger (1963). This effect should be minimized if possible and can be at least partially overcome by choosing a chamber cover material which transmits a maximum in the infrared.

In view of the goal to minimize alteration of the radiant flux (i.e. maximize transmission) Sestak et al.(1971) recommended a polyvinylidene chloride (PVDC) coated polypropolene film (Propafilm) or polyethylene film. The latter should not be used in photosynthesis work as the film is rather permeable to CO_2.

A film which has been used by many of the chamber reseachers with apparent success is Mylar. Mylar is a thin film material with a high transmission for infrared radiation but it lacks the ability to give structural strength to the chamber as would plexiglass or lexan. Polyethylene, along with being relatively permeable to CO_2, also becomes cloudy when left in the sun for only a few days (Decker et al., 1962). Propafilm C, a thin PVDC coated polypropolene film, has been found to stand up well in sunlight and is strong and easy to work with based on this author's experience.

The shape of the chamber can also affect the transmission of radiation by either reducing or exaggerating the radiation reflected (Duffie and Beckman, 1980 ; Monteith, 1973). As the angle of the incident radiation increases with respect to a line normal to a transparent medium the reflected radiation also increases. Figure 2.4 shows the relationship between beam angle and radiant transmission for some commonly used transparent materials. Most of the chambers used have been rectangular in shape. One exception to this was a cylindrical noninstantaneous measurement chamber used by Decker et al. (1962) for measuring ET from Tamarisk shrub.

The framework of the chamber and the instruments inside can cause a reduction in the visible radiation while increasing the the infrared radiation load on the crop due to emittance from the chamber materials. A change in the quality of the radiation will cause a repartitioning of the energy within the chamber since the boundaries of the system (e.g. plant surfaces) absorb, transmit and reflect different kinds of energy in different ways (Nobel, 1970). For this reason the framework and instruments should block as little of the sun light as possible and should be painted white or silver to minimize visible radiation absorption.

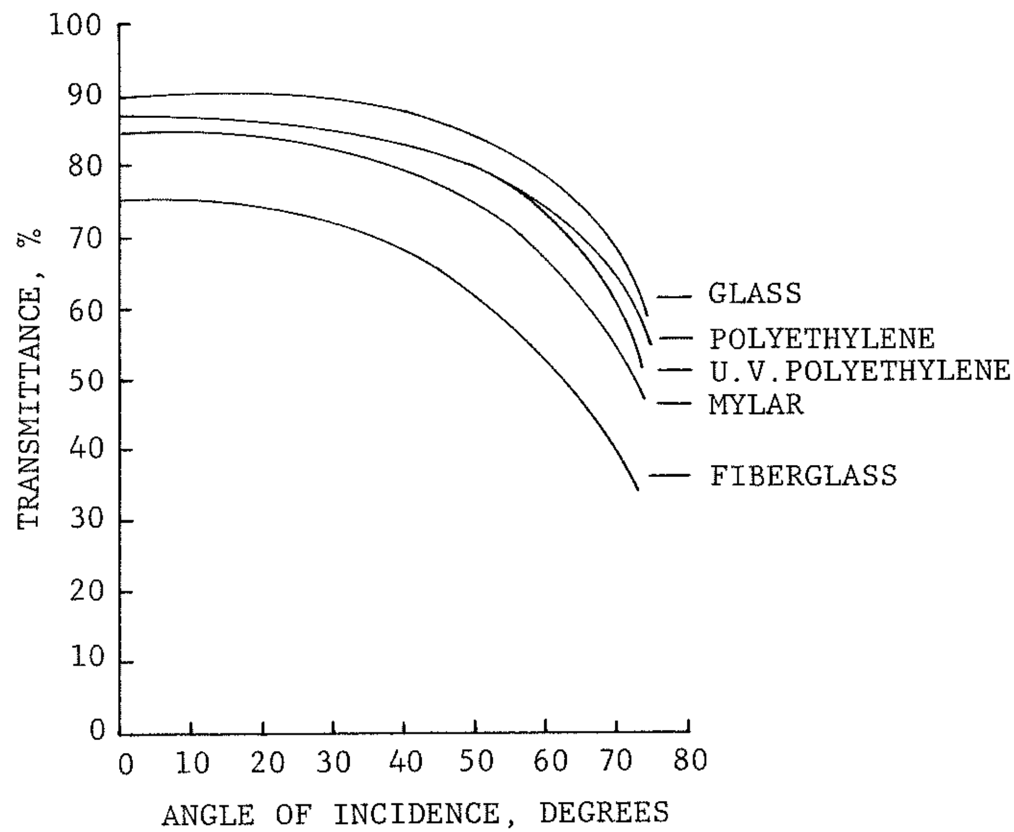


Figure 2.4 Solar radiation transmission with angle of incidence for five possible chamber cover materials. (Trickett and Goulden, 1958)

Sensible, Latent and Soil Heat Transfer

In addition to the radiant effects, another contributing factor to changes in the chamber air temperature is the sensible heat transfer from the plant, soil and chamber surfaces. Chamber surfaces here includes "active" modes of sensible heating such as fan motors. Of these modes a very important point of heat transfer is the plant leaf since it is the point of the most latent heat production. From equation 2.3 it is seen that the sensible heat transfer is directly proportional to the temperature difference between two points. In this case the temperatures include that of the leaf and of the air around it. If the air temperature is initially above that of the leaf and the air temperature increased due to the presence of the chamber then the rate of heat transfer to the leaf would increase. If, however, the leaf temperature was above the air temperature an increase in air temperature would reduce the rate of heat transfer from the leaf. The latter case would be desirable if for example the radiant heat load on the leaf decreased.

The latent heat exchange is also related to leaf temperature since the transpiration from the leaf is proportional to a vapor pressure difference. Assuming the evaporating surface on the leaf to be in a saturated state (Slavick,1974) then the relationship of leaf temperature to saturated vapor pressure can be seen by using the leaf temperature in equation 2.6. This shows that any change caused in leaf temperature will affect the rate of transpiration. One way in which the temperature of the leaf might be changed is by a reduction in the visible radiation intensity by either direct shading from chamber equipment and framework or a reduction in the quantity of solar radiation received by the leaves as a result of the chamber cover. Numerous workers have shown the dramatic and immediate effect on leaf temperature by shading (Arsari and Loomis, 1959; Meidner and Mansfield, 1968; Platt and Wolf, 1950; Avery, 1967). The expected change in incident solar radiation for a canopy covered by a measurement chamber is around 10%. Peters et al.(1974) measured a 7% decrease in solar radiation after the placement of their chamber covered with mylar, while Decker et al. (1962) found an 11% reduction for a polyethylene covered chamber. This same chamber reduced incident solar radiaition by 30% after becoming dirty. Reicosky(1981) measured an 8% reduction in solar radiation in a chamber covered with 3.18 mm thick plexiglass.

Equally important if not more important than the gradients in equations 2.3 and 2.4 are the transfer coefficients for sensible and latent heat, K_A and K_E. With specific changes in the environment these coefficients may change by many times their original values. These coefficients are highly dependent on wind speed (Wright and Brown, 1967) and are considered equivalent under slightly neutral conditions (Rosenberg, 1974). "Slightly neutral conditions" refers to atmosheric stability which is determined by the vertical direction of sensible heat movement in the environment. A neutral condition exists when the vertical temperature gradient is zero. Since the chamber air is mixed during the measurement, and therefore of approximately equal temperature throughout, the atmospheric conditions would be approximately neutral making K_A approximately equal to K_E.

Therefore, the mixing rate of the fans inside the chamber is an important design consideration. The transfer coefficients change instantaneously with changes in wind speed by either reducing or increasing the thickness of the unstirred boundary layer over the plant surfaces (Raschke, 1960). By adjusting the mixing rate of the fans appropriately an attempt can be made to maintain the original transfer coefficients when the chamber is lowered into place and the mixing fans are on. An inherent flaw in this strategy occurs when the ambient wind speed is low. By adjusting the fan speed to a low level, the mixing rate may be below the lower limit allowable for accurate sensing by the psychrometer.

In a situation where a canopy is covered by a chamber, K_E may change differently than K_A if the leaf stomatal conductance is made to change. The diffusion resistance (effective diffusion path length divided by the diffusivity of water vapor in air) is related to the bulk transfer coefficient and therefore should be considered in this analysis. The diffusion resistance from a plant leaf (neglecting cuticle resistance) can be described as

$$r_D = r_s + r_{bl} \tag{2.8}$$

where

r_D = diffusion resistance to water vapor (s/m)

r_s = stomatal resistance (s/m)

r_{bl} = boundary layer resistance (s/m)

From equation 2.8 the diffusion resistance is directly proportional to the sum of the stomatal and boundary layer resistances. The expression shows that if either r_s or r_{bl} are large relative to the other then the larger of the two resistances will control r_D. Raschke (1960) gave the typical range of r_s as 30 s/m to 18000 s/m and the typical range of r_{bl} as 6 s/m to 180 s/m. Using his example to illustrate the usual control of r_D by r_s suppose r_s is 3000 s/m, then the total possible range of r_D is 3006 s/m to 3180 s/m. The example shows that unless r_s is quite small r_{bl} should have a relatively small effect on r_D.

The boundary layer resistance was given by Nobel (1970) as δ/D where δ is the thickness of the unstirred boundary layer and D is either the thermal diffusivity or the diffusivity of water vapor in air. Nobel gave the boundary layer thickness to be proportional to the square root of the ratio of the length of the leaf in the direction of air movement L in meters to the wind velocity over the leaf v in meters per second.

$$\delta = 0.4(L/v)^{1/2}/100 \tag{2.9}$$

Other expressions for δ and r_s can be found in the literature (Raschke, 1960; Drake, et al. 1970; Gates, 1968; Slavik, 1974).

The stomatal resistance is a function of stomatal aperture and its theoretical form for a single stomate was given by Meidner and Mansfield (1968) as

$$r_s' = (l' + \pi d/4)DA' = l'_{eff}/DA' \tag{2.10}$$

where

r_s' = stomatal resistance for single stomate (s/cm^3)

A' = area of stomatal opening (cm^2)

l' = length of stomatal passage (cm)

l'_{eff} = effective length of stomatal passage (cm)

d = diameter of stomatal opening (cm)

D' = diffusivity of water vapor in air (cm^2/s)

The stomatal resistance is seen to increase with decreasing diameter. If d is small compared to l' then r_s' varies approximately inversely with the square of diameter. If d is not small compared with l' then r_s' will not increase so greatly with a decrease in d.

Experimental values for r_s as well as functional relationships have been determined for a wide variety of plant leaves. Gates(1968) has summerized experimental values obtained by many researchers. Some of these data were given as high and low values and thus give a range for the particular plant type. Other researchers have shown the dependence of r_s on light intensity, ambient CO_2 concentration and leaf temperature. Experimental data showing these relationships can be found in Whiteman and Koller(1964), Whiteman and Koller(1967), Meidner and Mansfield(1968) and Pallas(1965). To summerize these effects: a decrease in light intensity caused an increase in r_s; an increase in the ambient CO_2 concentration increased r_s; the relationship between leaf temperature and r_s has not been fully resolved but seems to be plant and environment specific. Drake et al.(1970) related stomatal resistance to leaf temperature for Xanthium strumarium L. The control of stomatal resistance by leaf temperature (or vice versa) was hypothesized as a result of findings which showed that for air temperatures above 35 C leaf temperatures were below air temperatures while for air temperatures below 35 C leaf temperatures were higher than air temperatures. Using a purely physical energy analysis (which neglected the relationship of r_s to leaf temperature) these trends could not be simulated. Drake developed regression equations for Xanthium relating r_s to leaf temperature for high and low humidity levels. The 35 C crossover point is not significant as this value would change under a different energy environment. For a comprehensive review of leaf temperature studies the reader is referred to Jackson (1982). Whiteman and Koller(1967) found the water vapor conductance for Pinus Halennis to increase with increasing leaf temperature up to 25 C. Baker(1965) observed a decrease in stomatal diffusion resistance with increasing cotton leaf temperatures.

The design implications are relatively straight forward. The chamber should not cause a decrease in light intensity as might be caused by a dirty chamber cover or the casting of shadows by the chamber instruments and framework. Additional CO_2 which is produced by a running tractor in the vicinity of the chamber measurent should be deverted away from the area , perhaps by means of an exhaust stack with its outlet at a remote position. Pallas(1965) reported decreased transpiration rates in soybeans from 34 to 53% when CO_2 levels were increased from 250 to 500 ppm. His microscopic inspection of stomates indicated that closure had occured. Baker(1965) found cotton stomatal apertures became affected at CO_2 concentrations exceeding 600 ppm. Egli et al.(1970) observed a 20% decrease in transpiration rates for one of their soybean varieties when CO_2 concentrations were increased from 300 to 450 ppm while transpiration rates at 600 ppm were only slightly less.

The possibility of increased concentrations of CO_2 in the crop environment must be viewed in light of the fact that a decrease in CO_2 concentration within the chamber occurs during the chamber measurement since the crop is using CO_2 for photosynthesis. Schulze (1978) observed a decreasing CO_2 concentration within a measurement chamber of 18 ppm/min. The effect of decreasing CO_2 concentration in the plant environment causes a decrease in stomatal resistance and may tend to increase transpiration rates slightly.

Leaf temperature changes though harder to control are probably not as critical since the temperature changes are on the order of 0.5 to 1.5 C and a change of this magnitude will not alter r_s seriously (based on regression equation given by Drake for Xanthium, 1970).

Heat transfer to or from the soil may also contribute to a modification of the environment inside the measurement chamber. During the daytime the sensible energy transfer is usually into the soil (Tanner, 1960). This means that the air temperature is higher than the soil temperature at the surface or that the radiant load on the soil surface is large. If the former is true and the chamber causes an elevated air temperature then the soil will tend to moderate the effects of the chamber by taking heat from the air. This moderating capacity of the soil is probably small, however, since the heat capacity of the soil is relatively large.

Under all conditions the soil is emitting infrared radiation. This source of energy will be especially significant during periods of little ground cover by the crop when soil surface temperatures are high. Therefore, any moderating effect due to the sensible soil heat transfer would probably be small compared to the radiation heat transfer from the soil.

Before moving on to some of the mechanical considerations of the chamber design a last look at equation 2.7 is in order. If both sides of the equation are divided by the height of the chamber h the energy balance can be expressed in units of energy per unit time per unit volume. From the new form of the equation it is clear that a smaller chamber height will cause a greater change in internal energy with time. This means that for a similar time rate of change of the chamber internal energy, a small chamber must make a measurement over a shorter period of time. For example, if a 1 m chamber was use over potatoes and a 3 m chamber over irrigated corn, the time rate of change of the chamber internal energy for the 1 m chamber would be approximately 3 times as great as for the 3 m chamber and for this reason it may be prudent to use an over sized chamber if practical. Schulze(1978) found this to be true when he observed greater mean temperature rises in his smaller chamber than in one which was 23% taller.

Chamber Soil Contact

A critical area where water vapor (or CO_2) may escape from the chamber is the interface between the soil surface and the chamber frame. Several methods can be employed to minimize leaks from this interface. A 10 to 15cm deep piece of foam can be glued to the bottom of the frame. It is not necessary that the material be highly resistant to water vapor transport since the foam will deform from the weight of the chamber, thereby greatly decreasing its conductivity to water vapor. Leveling the ground where the chamber makes contact was suggested by

Reicosky(1981).

Schulze(1978) used a wooden frame which was carefully placed on the ground prior to the chamber placement. As the chamber was lowered to the ground it was set into the frame for proper sealment.

Crop Damage

Some crop damage will occur as the chamber is lowered over the plants even though the chamber size is chosen to fit between rows. Potatoes, for instance, cover the ground almost completely and some damage from the chamber is unavoidable. Moving the chamber over a new group of plants for each successive measurement may minimize influences of crop damage. In the case of a freely suspended chamber researchers must walk into the crop canopy to control the position of the chamber while lowering. Damage caused by trampling can be reduced by using long gaff poles to control the position of the chamber from a distance.

Measurement Location

To reduce the influence of border effects, the measurements should be taken as far into the crop canopy as possible where the environment more closely represents field conditions. The collection of data successively for several measurement periods from the same plants may result in inaccuracies in ET estimation introduced by the possible onset of stomatal closure and/or crop damage. The influence of the chamber on the crop physiology is not yet fully understood and will be addressed more closely in Chapter 5.

Chamber Mobility

The portable measurement chamber along with the associated chamber equipment for chamber movement need to be designed with mobility and ease of operator use in mind. The designer must consider the following with respect to chamber design:

1. size
2. weight
3. ease of chamber assembly and disassembly
4. manual and automated control
5. within and between field movement
6. ease of equipment repair in the field
7. total system height
8. intended system operators
9. electric and mechanical power requirements
10. ruggedness of equipment

Specific examples of designs can be found in Peters et al.,1974, Reicosky and Peters, 1977 and Schulze, 1978 as well as in chapter 4 of this thesis.

CHAPTER 3

ENERGY BALANCE OF A LEAF IN MEASUREMENT CHAMBER

To better understand the complicated interrelations of the transport of energy to and from a leaf (and therefore transpiration which is usually the major fraction of ET) in a crop canopy covered by a measurement chamber a computer model was developed. The modeling of an entire crop canopy is difficult since there are a great number of factors involved. Modeling the complete crop canopy was discussed by Norman (1979). His analysis included simple statistical models as well as ones more physically based.

It is our objective here to investigate the various energy trends which occur within the chamber with special attention paid to evapotranspiration. Since the major fraction of evapotranspiration is leaf transpiration we have chosen to limit our analysis to the nonsteady state analysis of a single leaf enclosed by a measurement chamber. Valuable information can be gleaned from a single leaf model. For instance, given that the wind velocity over a leaf in the chamber increases and/or the radiation load decreases and/or the wet and dry bulb air temperatures increase over the period of the measurement, what is the effect on leaf temperature and transpiration rate? Perhaps more importantly,to what degree is transpiration changed and how does this change or error (relative to the initial or field condition) vary with time.

The energy balance on a horizontally oriented leaf can be described by the following equation:

$$R_n + A + E = \rho_L C_L h_L (\partial T_L / \partial t) \tag{3.1}$$

where

R_n =net radiation on the leaf (W/m^2)

A =sensible heat transfer to or from leaf (W/m^2)

E =latent heat transfer to or from leaf (W/m^2)

C_L =leaf specific heat capacity (KJ/Kg-C)

ρ_L =leaf density (Kg/m^3)

h_L =average leaf thickness (m)

T_L =leaf temperature (C)

t =time (s)

Equation 3.1 when expressed in a more fundamental form and adapted to a condition which simulates the presence of the chamber is a function of time, dry bulb and wet bulb air temperatures, leaf temperature, effective sky temperature, wind velocity, leaf length in the direction of air movement, solar radiation, emissivities of the leaf, chamber cover and sky, solar absorptivity and reflectivity of the leaf, the infrared transmissivity of the chamber cover, and the leaf density, thickness and heat capacity.

The placement of an instantaneous measurement chamber over a crop generally occurs in the following manner. The chamber is prepared by positioning it over the canopy but spacially above it so that the crop is in a state of relative equilibrium and in a state similar to the rest of the plants in the area. Next, the chamber is lowered to the ground and the measurement taken for the next 30-60 seconds. At the end of the measurement the chamber is raised from the canopy and it gradually returns to it's initial state.

Before and/or during the chamber measurement a given leaf in the chamber is exposed to solar radiation as well as infrared radiation from the sky, surroundings and the chamber itself. The leaf cools itself by emitting infrared radiation and by latent (and possibly sensible) heat transfer. When the chamber is lowered over the canopy the leaf is exposed to both a different radiant and ambient environment. A portion of the visible and infrared radiation is reflected or absorbed by the chamber cover and frame and therefore does not reach the leaf. However, with the chamber in place infrared radiation emitted from the chamber cover and framework becomes incident on the leaf. The radiation emitted by the leaf which normally is released from the canopy may be partially trapped in the chamber because the chamber cover does not transmit infrared radiation perfectly. This trapping may result in elevated surface and air temperatures over the period of the chamber measurement. If heat was originally leaving the leaf the increased air temperature will cause a reduction in the leaf/air temperature deficit and a rise in leaf temperature. With time, the production of vapor in the chamber will cause the leaf/air vapor pressure deficit to decrease and also the leaf temperature to rise. Decreasing these gradients tends to decrease the rate at which sensible and latent energy leave the leaf. A compensating effect, however, is at work via the resulting rise in leaf temperature which produces larger deficits. The wind velocity over the leaf works to either increase or decrease the unstirred boundary layer thickness at the leaf surface. If the chamber causes reduced air movement over the leaf then the boundary layer will increase in thickness reducing the sensible and latent heat transfer to or from the leaf. An increased chamber air speed would result in an opposite effect.

In order to better understand the effect of the chamber on a leaf inside it is necessary to analyze equation 3.1 and observe the action of each of the components of equation 3.1 over the period of the chamber measurement.

The solution of equation 3.1 requires its simplification so that only one dependent variable exists for one or more independent variables. Parameters which change over time and upon which the terms in equation 3.1 depend are leaf temperature and the chamber air wet and dry bulb temperatures. To support this statement the terms in equation 3.1 will now be replaced with expressions involving the temperatures mentioned above. The expressions given below will transform equation 3.1 into a functional form that can be solved on a digital computer. A simplifying assumption which will be made is that the leaf is oriented horizontally so that all energy transfer is in the vertical direction.

The net radiation term in equation 3.1 is the sum of the solar radiation, both direct and diffuse, and the infrared radiation from the sky, surroundings, and leaf. The net radiation can be expressed as

$$R_n = R_L + IR_a + IR_s - IR_L \qquad (3.2)$$

where

R_L = solar radiation absorbed by leaf (W/m^2)

IR_a = infrared radiation from atmosphere absorbed by leaf (W/m^2)

IR_s = infrared radiation from surroundings absorbed by leaf (W/m^2)

IR_L = infrared radiation from leaf emitted to the surroundings (W/m^2)

The components of energy transfer to or from the leaf are depicted under field conditions in figure 3.1 and under chamber conditions in figure 3.2.

Solar radiation absorbed by a leaf was given by Nobel (1970) as

$$R_L = R_s (1 + \rho_L') \alpha_L' \qquad (3.3)$$

where

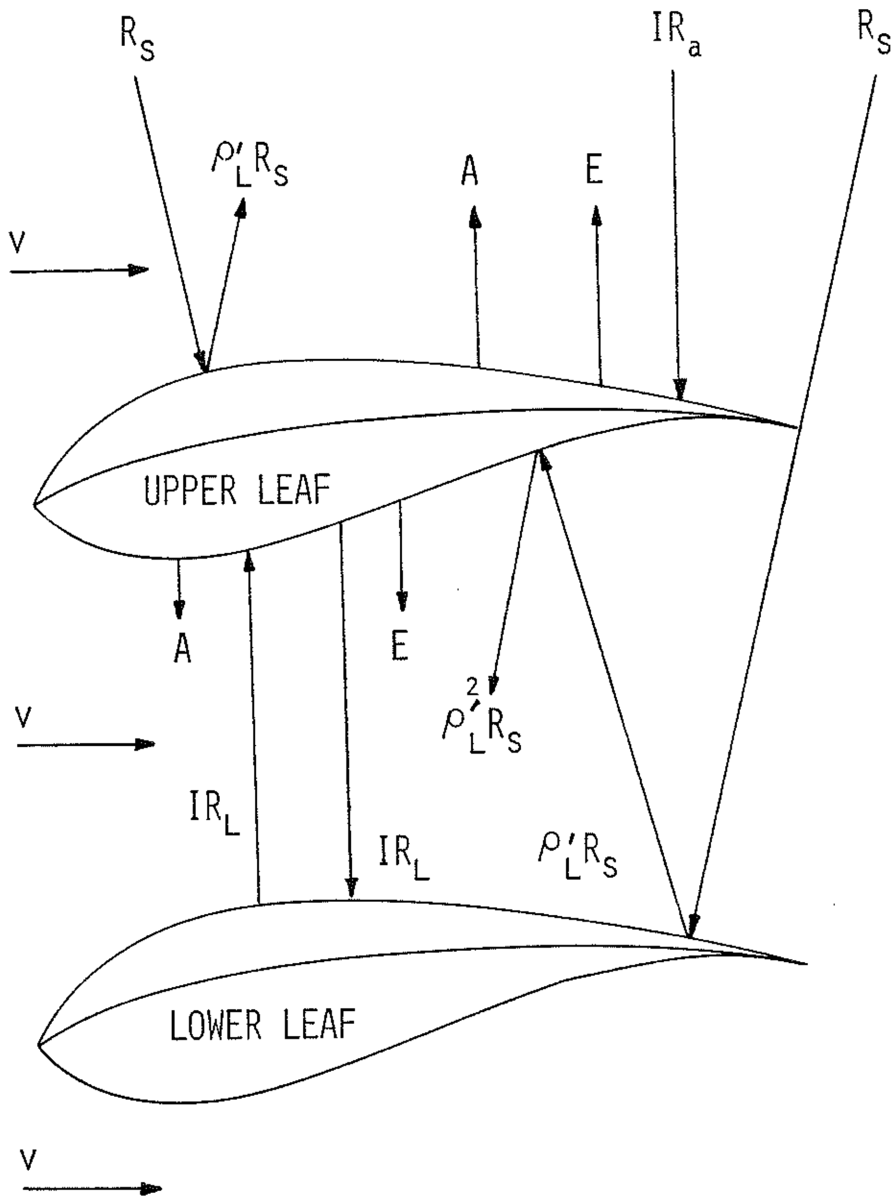
R_s = incoming solar radiation (W/m^2)

ρ_L' = leaf albedo

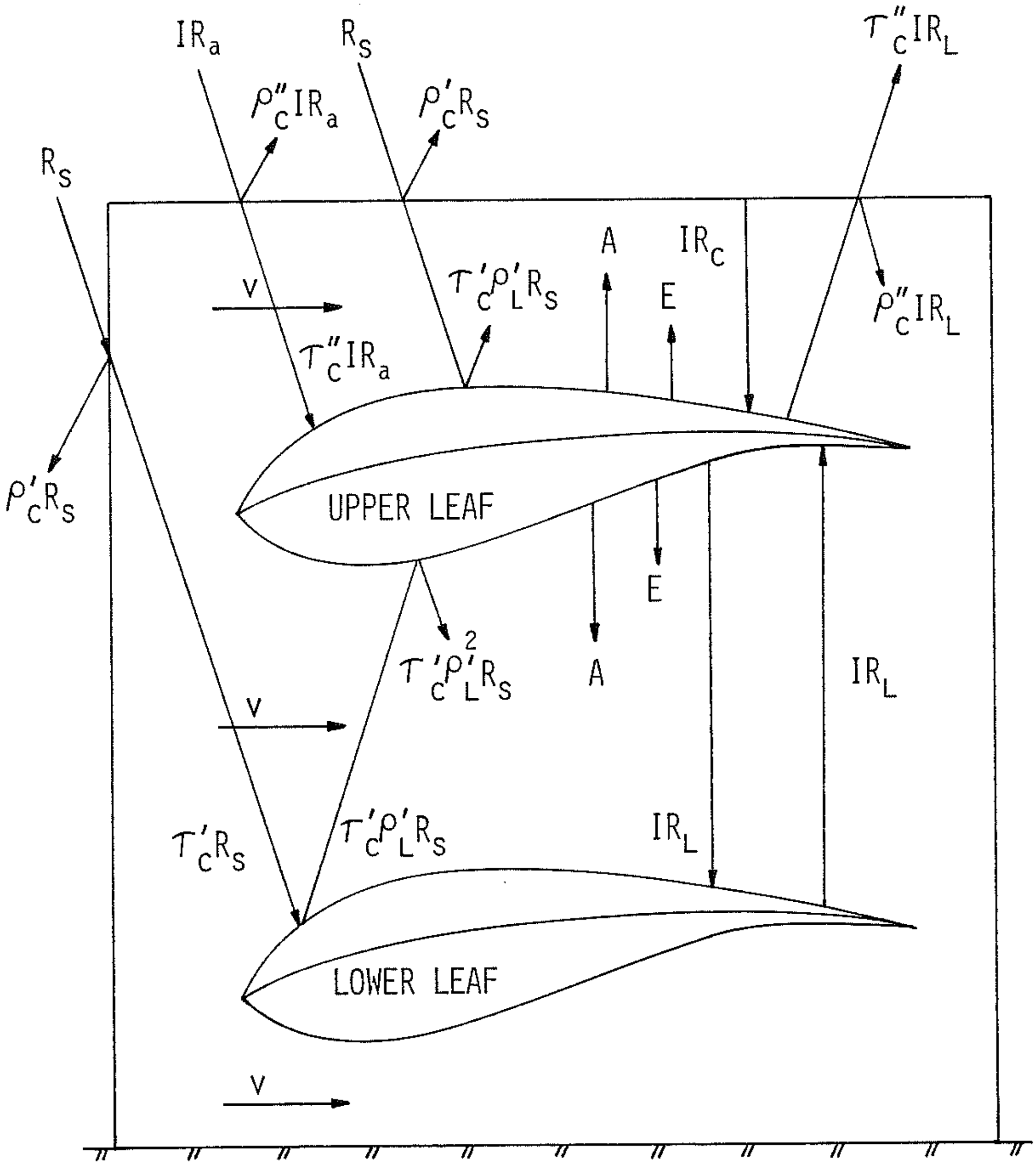
α_L' = leaf absorptivity

The product $\alpha_L' \rho_L' R_s$ accounts for the solar radiation reflected to the leaf from the leaves below it. Radiation heat transfer can more fundamentally be described by the Stephan-Boltzman equation

$$R = \varepsilon'' \sigma T^4 \qquad (3.4)$$



3.1 Leaf energy exchange in field.



3.2 Energy exchange of leaf enclosed in measurement chamber.

where

R = infrared radiation heat transfer (W/m^2)

ε'' = emissivity

σ = Stephan-Boltzman constant (5.67×10^{-8} W/m^2-K)

T = absolute temperature of emitting body (K)

The terms in equation 3.2 which involve the transfer of long wave radiant energy are given by

$$IR_e = \varepsilon''_e \sigma T_e^4 \qquad (3.5)$$

$$IR_s = \varepsilon''_s \sigma T_s^4 \qquad (3.6)$$

$$IR_L = \varepsilon''_L \sigma T_L^4 \qquad (3.7)$$

where

ε''_e = effective sky emissivity

ε''_s = emissivity of surroundings

ε''_L = emissivity of leaf

T_e = effective sky temperature (K)

T_s = average temperature of the surroundings (K)

T_L = average leaf temperature (K)

It can be assumed that any infrared radiation emitted from the leaves below to the leaf in question is approximately equal to that emitted by the leaf to the lower leaves and that their sum is nearly zero since their temperatures are approximately equal. It follows then that the quantity of long wave energy from the surroundings is entirely due to the chamber cover and frame. Since, however, we have restricted our analysis to the vertical direction we will further assume that a typical leaf is not aligned with the chamber frame or instruments so that the infrared radiation from the chamber is recieved only from the chamber cover. With this qualification equation 3.6 becomes

$$IR_c = \varepsilon_c'' \sigma T_c^4 \tag{3.8}$$

where

IR_c = infrared radiation emitted from the chamber cover (W/m^2)

ε_c'' = chamber cover emissivity

T_c = chamber cover temperature (K)

Equation 3.8 would of course not be applicable for periods when the chamber is not enclosing the leaf.

Sensible heat transfer to or from the leaf can be expressed as

$$A = -k\,(dT/dz) \tag{3.9}$$

where

k = thermal conductivity of the air (W/m -C)

T = temperature (C)

z = heat transfer path direction (m)

The functional form of equation 3.9 is

$$A = -(T_L - T_d)/r_A \tag{3.10}$$

where

T_L = leaf temperature (C)

T_d = air temperature (C)

r_A = sensible heat transfer resistance (m^2-K/W)

The sensible heat transfer resistance is a function of the unstirred boundary layer resistance or

$$r_A = \delta/k \tag{3.11}$$

where

δ = unstirred boundary layer thickness (m)

The functional form of the latent heat transfer is given by

$$E = -LM_w(e_w^0 - e)/RT_d r_D \tag{3.12}$$

where

L = latent heat of vaporization (2.47×10^3 KJ/Kg)

R = gas constant (KJ/K-mole)

T_d = air temperature (K)

e_w^0 = saturated vapor pressure in leaf stomatal cavity (Pa)

e = vapor pressure of the air (Pa)

r_D = diffusion resistance (s/m) (see chapter 2)

M_w = molecular weight of water (0.018 Kg/mole)

The derivative in equation 3.1 can be approximated by using a finite difference form involving the leaf temperature at the real time and one time step earlier. This form has been called the backwards difference approach (Von Rosenberg, 1969) and is given as

$$\partial T_L/\partial t = (T_{L,i} - T_{L,i-1})/\Delta t \qquad (3.13)$$

where

$T_{L,i}$ = temperature of leaf at time i

$T_{L,i-1}$ = temperature of leaf at time i-1

Δt = time step (s)

By replacing the terms in equation 3.1 with equations 3.3, 3.5, 3.6, 3.8, 3.10, 3.12 and 3.13 the functional form of the nonsteady state energy balance for a leaf enclosed within a measurement chamber is obtained.

$$\tau_c' R_s (1 + \rho_L')\alpha_L' + \tau_c'' \varepsilon_e'' \sigma T_e^4 + \varepsilon_c'' \sigma T_c^4 - \varepsilon_L'' \sigma T_L^4 - (T_L - T_d)/r_A - LM_w(e_w - e)/(RT_d r_D) = \rho_L C_L h_L (T_{L,i} - T_{L,i-1})/\Delta t \qquad (3.14)$$

The transmissivities (τ) shown in the first two terms on the left side of equation 3.14 account for the reduction in radiation received by the leaf due to the chamber cover.

Parameters which vary in equation 3.14 are the wet and dry bulb air temperatures, the leaf temperature and time. Time is the independent variable which leaves three unknowns but only one equation. Therefore, we must either hold two of the temperatures constant or supply data at known points in time during a simulation run so that only one temperature is unknown. The way in which we will handle this requirement is to assume initial and final wet and dry bulb air temperatures for any given run. We will further assume that these air temperatures vary linearly with time. The assumption of linear changes in air temperatures appears justified based on data in the field. Example data collected in the field over turfgrass on August 31, 1982 at East Lansing, Michigan are shown in figure 3.3. With air temperatures known the only unknown variable is leaf temperature and the boundary condition required to solve equation 3.14 is the initial leaf temperature.

The energy balance model (equation 3.14) was put into the form of a computer program coded in the Fortran V computing language (see Appendix A for program listing). The computer program first computes the steady state leaf temperature in the field ($\partial T_L / \partial t = 0$). With the initial leaf temperature determined the leaf temperature at discrete points in time can be determined. With leaf temperatures known the terms in equation 3.1 can also be determined.

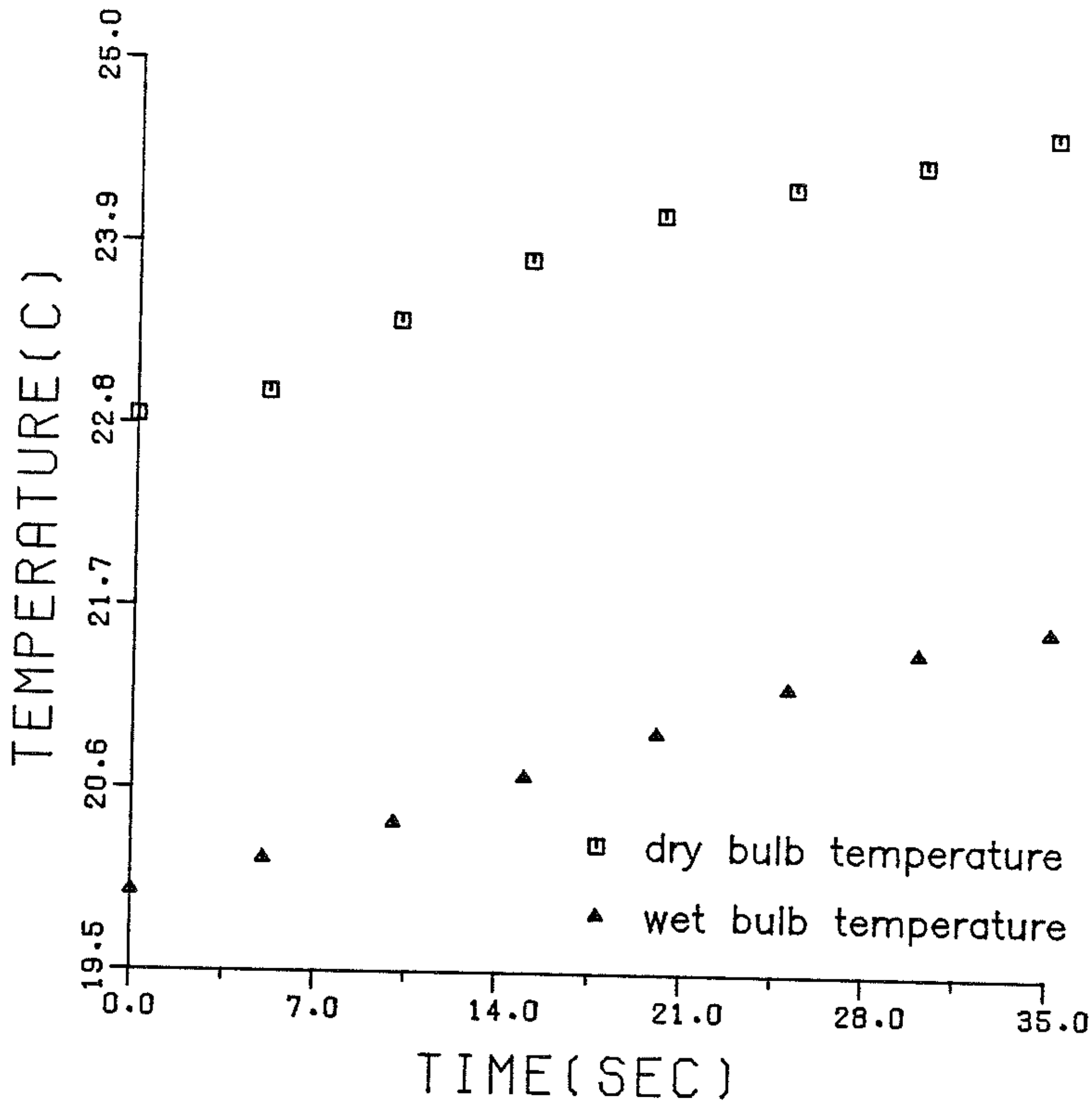


Figure 3.3 Example of air temperatures during chamber measurement taken on August 31, 1982 over turf grass at East Lansing, Michigan.

Energy Balance Simulation Model Inputs

Equation 3.14 is a general expression describing the transport of energy to and from as well as heat stored in a leaf. With the appropriate coefficients a simulation can be run for any type of leaf enclosed in a chamber covered by any type of material. In the simulation data that follows, an attempt has been made to use parameters which might be similar to those possessed by a field bean leaf. The parameters pertaining to the chamber are those found for a film such as mylar or Propafilm C. A list of the parameters used and their sources are list below.

1. Solar radiation, R_s=872 W/m^2 (Shaw and Decker, 1979).
2. Effective sky temperature, T_a= 2 C (observed).
3. Wind velocity in the field, v =1.0 m/s (Monteith, 1973).
4. Wind velocity in the chamber V =0.5, 1.0, 1.5 m/s.
5. Length of leaf in direction of wind velocity, l=0.08 m (observed).
6. Average leaf thickness, h_L=1.7x10^{-3} m (observed).
7. Specific heat capacity of the leaf, C_L=4 KJ/Kg-C (for asparagus, Heldman, 1981).
8. Density of the leaf, ρ_L=1.03 kg/m (for asparagus, Heldman, 1981).
9. Leaf stomatal resistance, r =220 s/m (for beans, Kruiper, 1961)
10. Solar absorptivity of the leaf, α_L'=0.78 (Rosenberg, 1974).

11. Solar reflectivity of the leaf, ρ_L'=0.22 (Rosenberg, 1974).

12. Infrared emissivity of the leaf, ε_L'' =.97 (Davies and Idso, 1979)

13. Solar transmissivity of the chamber cover, τ_c'=0.89 (observed, Propafilm C110).

14. Infared transmissivity of the chamber cover, τ_c''=0.75 (observed, Propafilm C110).

15. Infrared emissivity of chamber cover, =0.25 (observed, Propafilm C110).

16. Initial chamber air dry bulb temperatures, T_d=25 C and 35 C (low and high values).

16. Final chamber air dry bulb temperatures, T_d=26 C and 36 C (1 C rise observed in field).

17. Initial relative humidities, rh=20% and 80%. (low and high values).

18. Time increment, Δt=0.25 s

19. Total duration of run, t=36 s (measurement time used in field, see chapter 4)

20. Chamber cover temperature, T_c=T_d=25 and 35 C (assumed equal to initial air temperatures)

Energy Balance Simulation Run

Running the model using the parameters listed in the previous section yielded the results graphed in Figures 3.4-3.13. Figure 3.4 shows the simulated total energy balance of a leaf enclosed in the measurement chamber for 36 seconds. The initial air temperature and relative humidity were 25 C and 20%, respectively. For convenience each of the initial values of the components of equation 3.1 were subtracted from values obtained during the run, hence showing the change in energy transfers. The wind velocity over the leaf prior to the chamber placement was 1 m/s as with all the runs and the chamber wind speed was 1.5 m/s.

Net radiation (see Figure 3.4) is seen to decrease by 58 W/m^2 remaining approximateley constant throughout the rest of the run. Sensible heat transfer from the leaf decreased by 45 W/m^2 then increased above its initial rate at t > 9 seconds. The latent heat transfer from the leaf also decreased being reduced by 11 W/m^2 but then increased throughout the measurement until at t = 16 seconds it became constant until the end of the run. The storage term shows a marked drop at the beginning attaining a maximum negative value of -110 W/m^2 (recall that prior to the placement of the chamber the storage term is zero since steady state conditions exist). The storage term is composed of the time rate of change of the leaf temperature, the specific heat, density and thickness of the leaf. Since the last three cited components of the storage term are constants the storage term can be viewed as a relative measure of the rate and direction of leaf temperature changes. The immediate drop in the storage term at the beginning of the run means that at that point in time the leaf was dropping in temperature at the greatest rate. Between 0.25 s and 20 s the leaf temperature was dropping but at a lower rate until at 20 s the leaf began to experience a temperature rise. The leaf temperature change can be seen in figure 3.6 along with leaf temperature changes for three wind speeds and a high and low humidity level.

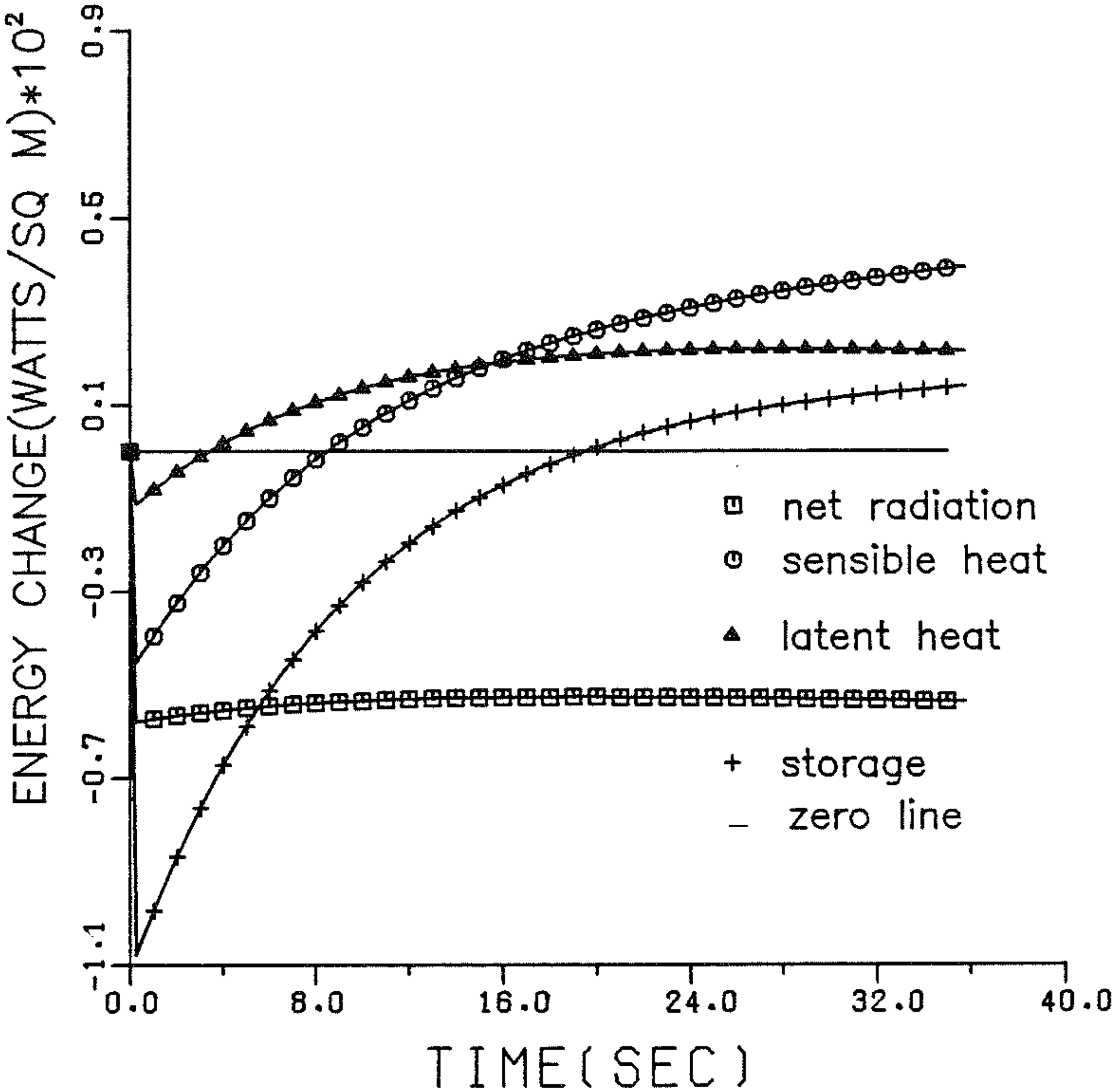


Figure 3.4 Change in components of equation 3.1 over a simulated chamber measurement where the initial air temperature, relative humidity and chamber wind speed were 25 C, 20% and 1.5m/s, respectively.

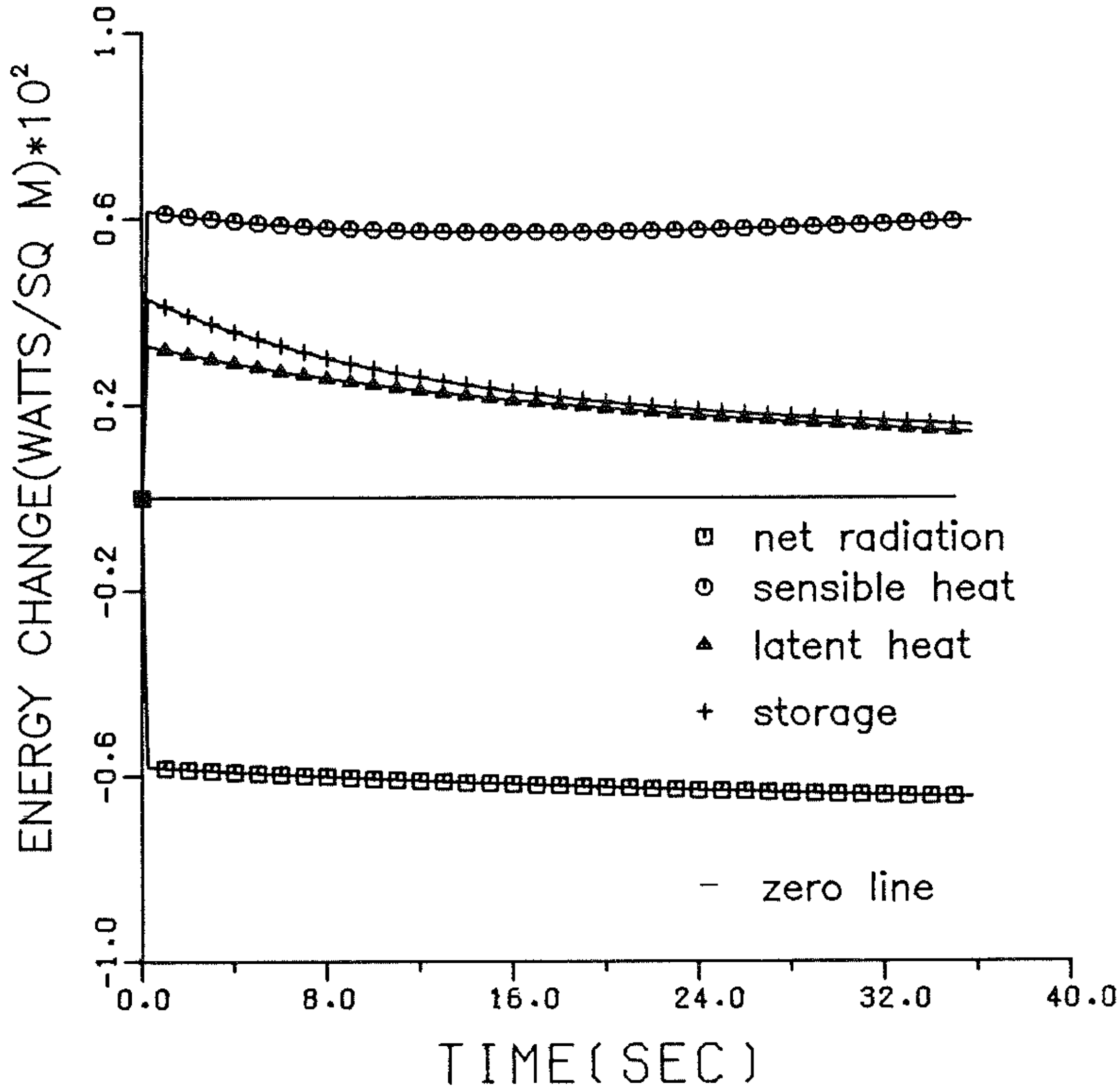


Figure 3.5 . Change in components of equation 3.1 over a simulated chamber measurement where the initial air temperature, relative humidity and chamber wind speed were 25 C, 20% and 0.5m/s, respectively.

Figure 3.5 shows the simulated change in energy with the placement of the measurement chamber for a chamber wind velocity, initial air temperature and relative humidity equal to 0.5m/s, 25 C and 20%, respectively. From this plot it can be seen that near the end of the run the latent heat transfer became approximately equal to the storage term. This means that the net radiation and sensible heat transfer were equal but opposite in sign.

At the highest chamber wind speed the leaf temperatures are seen to decrease throughout the first half of the run and increase during the second half (see Figures 3.6 and 3.7). The initial decrease was due to the sudden increase in sensible and latent heat transfer from the leaf. The increase in heat transfer tended to decrease the leaf/air vapor pressure and temperature deficits thereby causing the leaf temperature to increase during the last half of the run. At the lowest wind speed the latent and sensible heat transfer suddenly decreased so the leaf experienced a rise in temperature throughout the run. The rate of increase was, however, most extreme at the beginning and became approximately constant during the last half of the run due to the increasing rates of heat transfer. When the chamber wind speed was equal to the field wind speed the leaf temperature is seen to remain closest to the original leaf temperature. The slight drop in leaf temperature at the beginning of the run was due to the reduced radiation load on the leaf.

Figures 3.6 and 3.7 also clearly show the effects of relative humidity and initial air temperature on leaf temperature. The high relative humidity produces a low vapor pressure deficit and resulted in an elevated initial leaf temperature relative to the low humidity condition. The air temperature also plays a part in determining the initial leaf temperature and from the figures it can be seen that the higher initial air temperature causes higher initial leaf temperatures. At the higher initial air temperature at 20% relative humidity the initial leaf temperature is very close to the air temperature. From this it is reasonable to assume that the cross over for the leaf and air temperatures (i.e. when they are equal) is probably near 36 C at 20% relative humidity and a wind velocity of 1 m/s (Drake et al.,1970).

As mentioned above the leaf/air vapor pressure and temperature deficits change as a result of the changing leaf and chamber air temperatures and are shown in figures 3.8 and 3.9 for the 25 C initial air temperature runs. Wind can be seen as a controlling factor for the 0.5 m/s run where, notwithstanding the fact that the leaf/air vapor pressure deficit increased, a leaf temperature rise still occured over the run. This can be explained by the large initial reduction in latent heat transfer due to the decreased wind speed, which could not be offset by the increasing rate of transpiration over the run (see Figure 3.10). The chamber wind speed alters the thickness of the unstirred boundary layer at the leaf surface which controls the rate of heat transfer.

From a practical stand point the latent heat transfer is highly important since the latent heat transfer divided by the latent heat of vaporization yields the leaf transpiration rate. Figures 3.10 and 3.11 show the latent heat transfer during a run for 20 and 80% relative humidity for the three wind velocities and an initial air temperature of 25 C while Figures 3.12 and 3.13 show the same but for an initial air

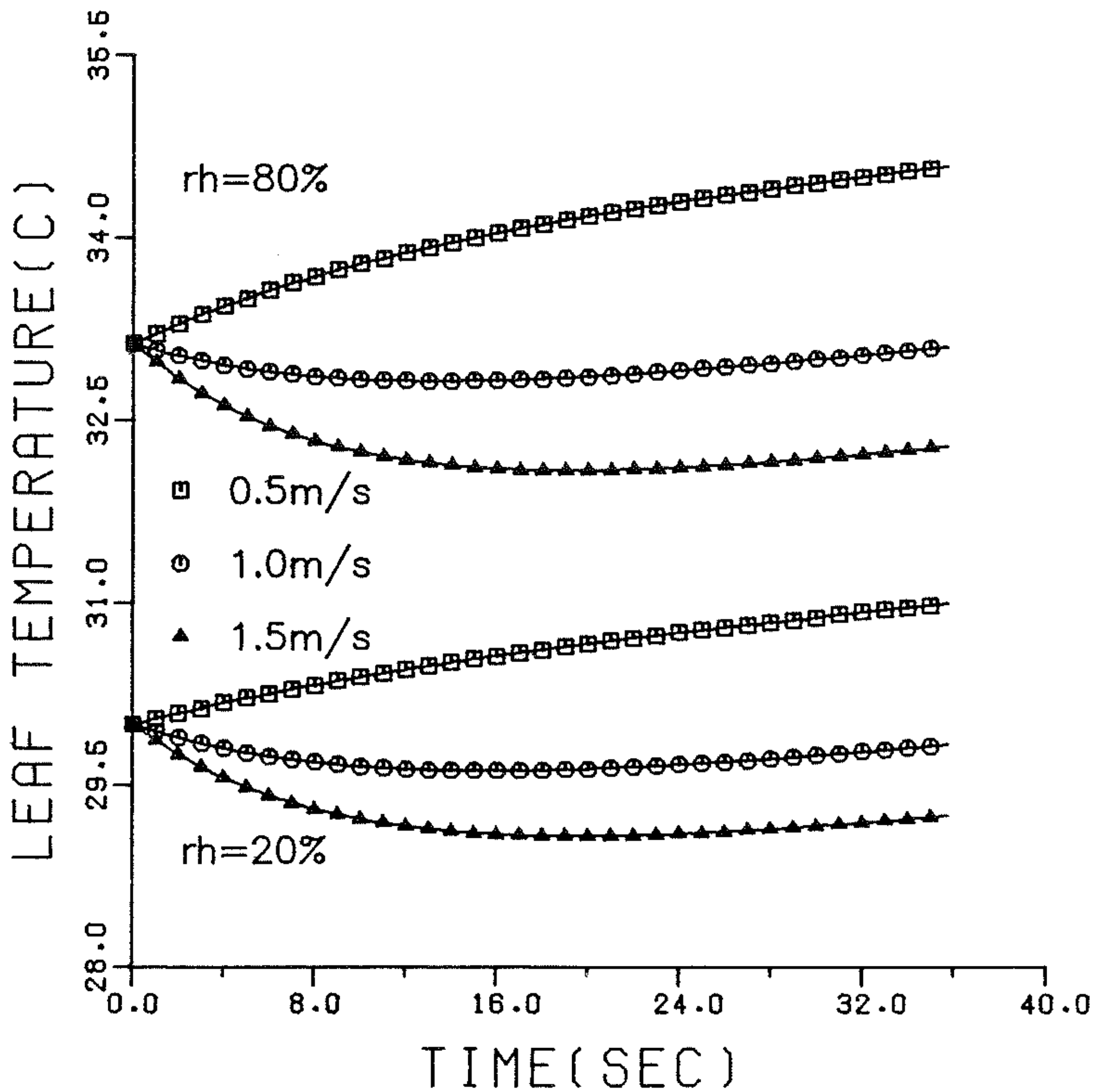


Figure 3.6 Leaf temperature changes over simulated chamber measurements for two levels of humidity and three chamber wind speeds where initial air temperature was 25 C.

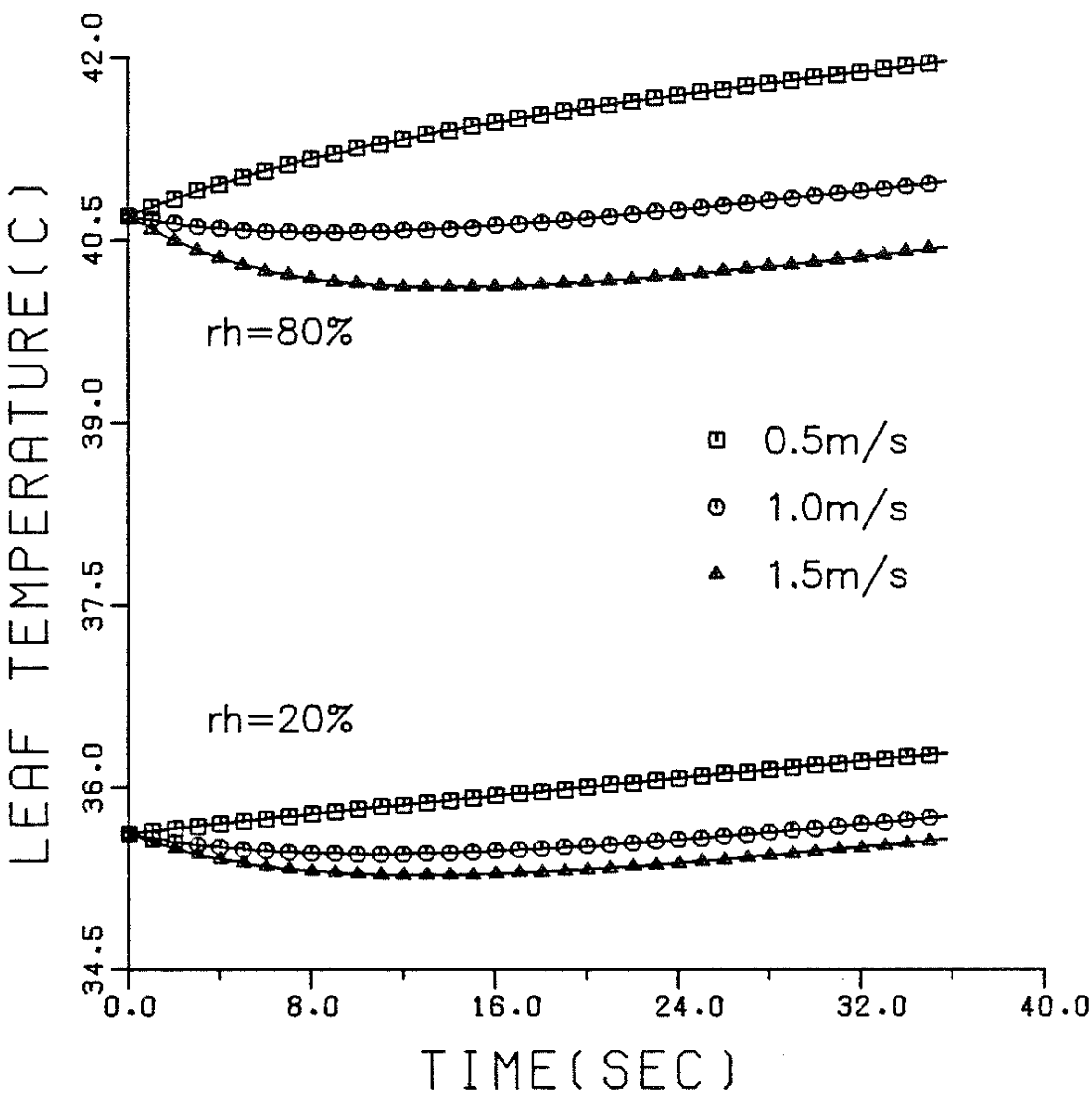


Figure 3.7 Leaf temperature changes over simulated chamber measurements for two initial humidity levels, three chamber wind speeds and initial air temperature of 35 C.

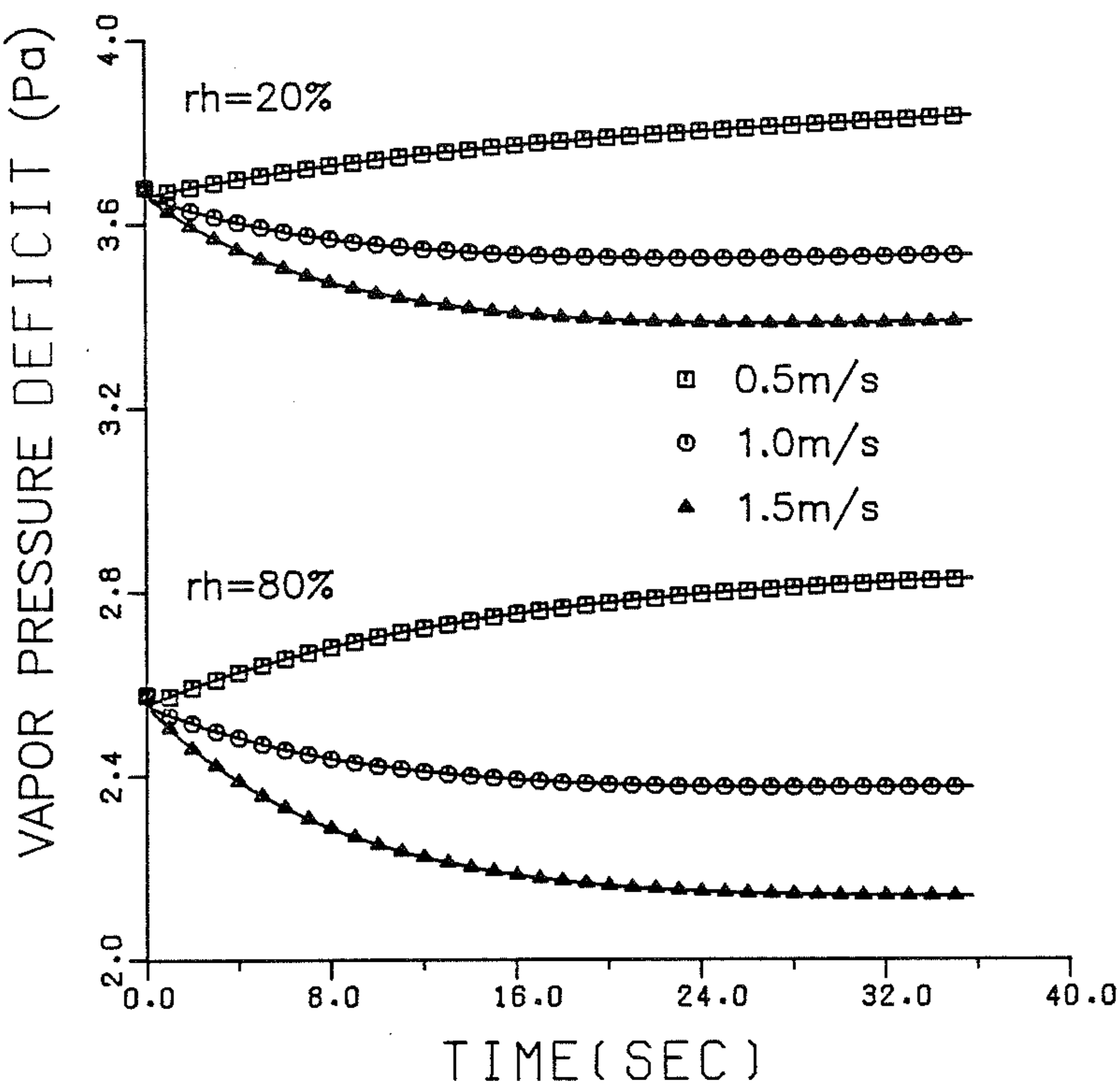


Figure 3.8 Vapor pressure deficit changes over simulated chamber measurements for two initial humidity levels, three chamber wind speeds and initial air temperature of 25 C.

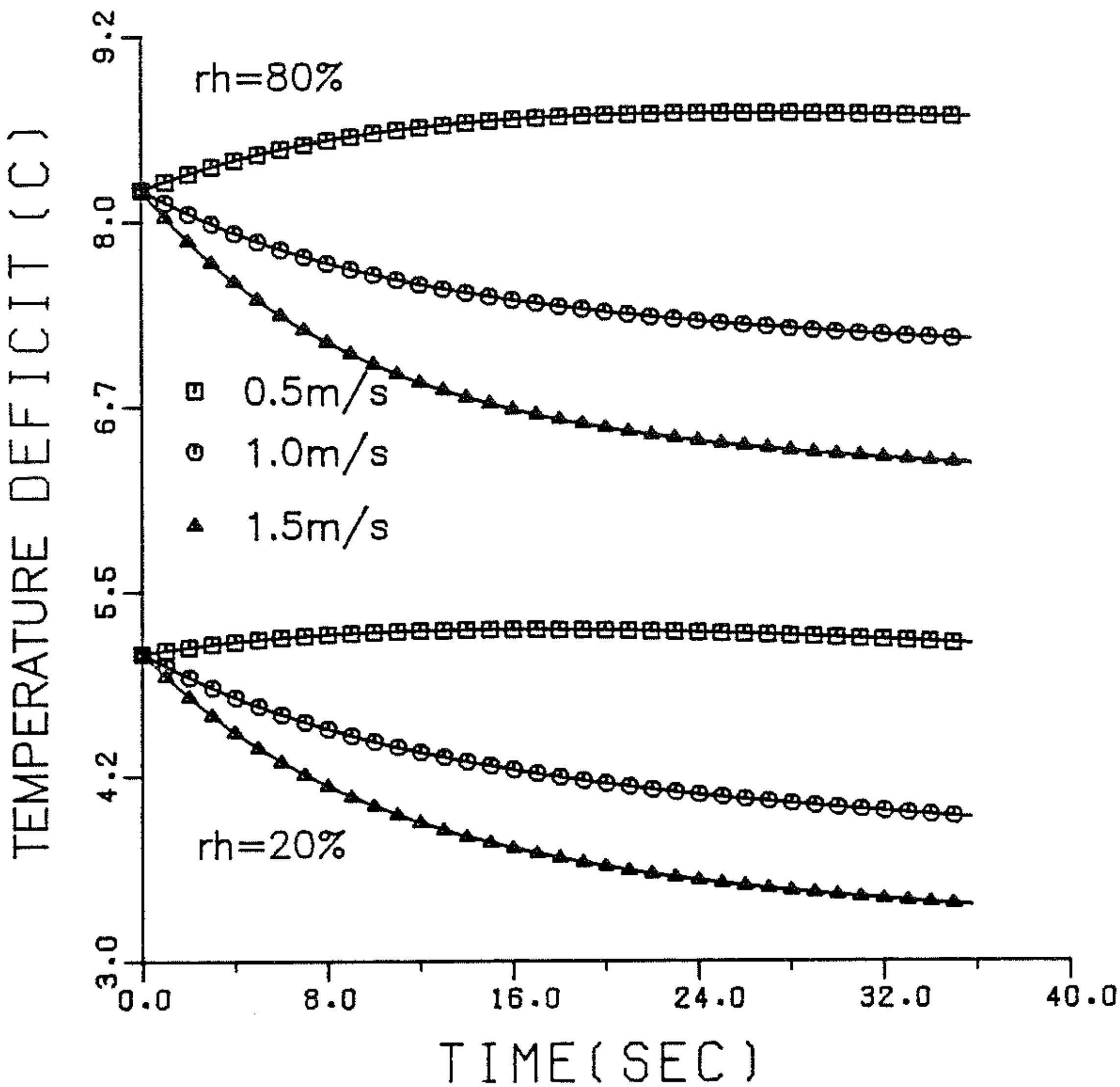


Figure 3.9 Temperature deficit changes over simulated chamber measurements for two initial humidity levels, three chamber wind speeds and intial air temperature of 25 C.

temperature of 35 C. The negative latent heat transfer values shown in figures 3.10-3.13 imply energy leaving the leaf. For the rh=20%, T =25 C run the change in wind speed due to the chamber had a large effect on altering the rate of latent heat transfer but almost as soon as the change occurred other parameters began to control until at around 20 seconds the rates for each wind speed became similar. This might lead one to assume that the rates of transpiration were approaching some similar value with time but from figure 3.11 we see this is not true, but that there is a strong dependence on the humidity level of the air.

In an actual measurement chamber the typical way of obtaining the rate of evapotranspiration is by observing the change in humidity over the period of the chamber measurement within the chamber. If the rate of leaf transpiation decreases as shown (fig. 3.10, 0.5 m/s wind speed) then the actual rate of humidity increase in the chamber will also be decreased and the measurement will be an underestimate of actual field ET. In fact the calculations indicate that the 1.5 m/s chamber wind velocity in figure 3.10 would yield an integrated quantity of energy (or water) closest to that of the actual rate or field rate over the same time interval.

At the higher humidity (see Figure 3.11), the latent heat transfer under the 1.5 m/s chamber wind speed, although increasing slightly at first, decreases throughout the measurement. Since the diffusion resistance becomes constant after its initial change all further change in the latent heat transfer can only be due to the vapor pressure gradient between the leaf and the air. The leaf temperature, which is

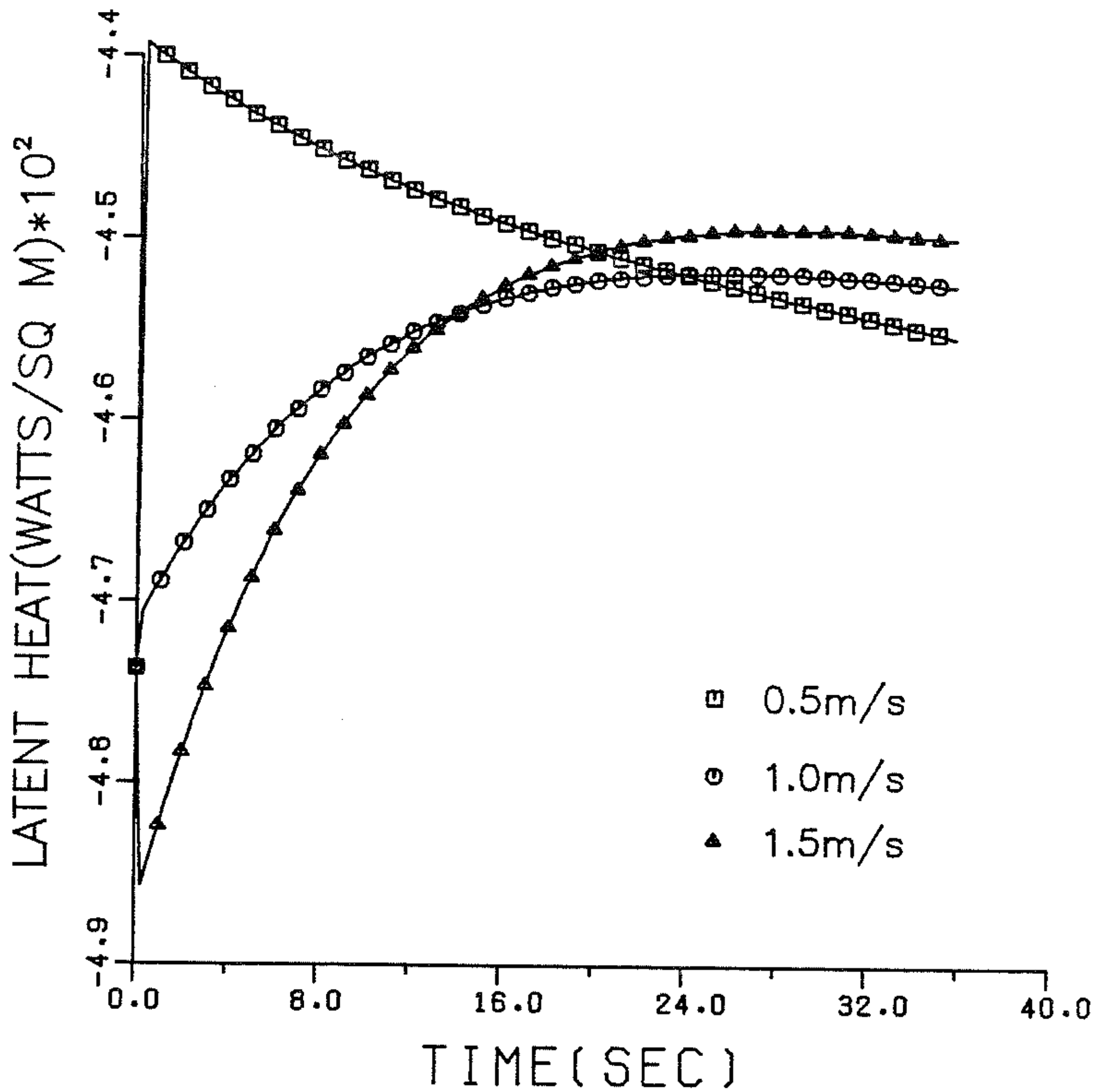


Figure 3.10 Latent heat transfer changes over simulated chamber measurement for three chamber wind speeds, inial initial relative humidity of 20% and initial air temperature of 25 C.

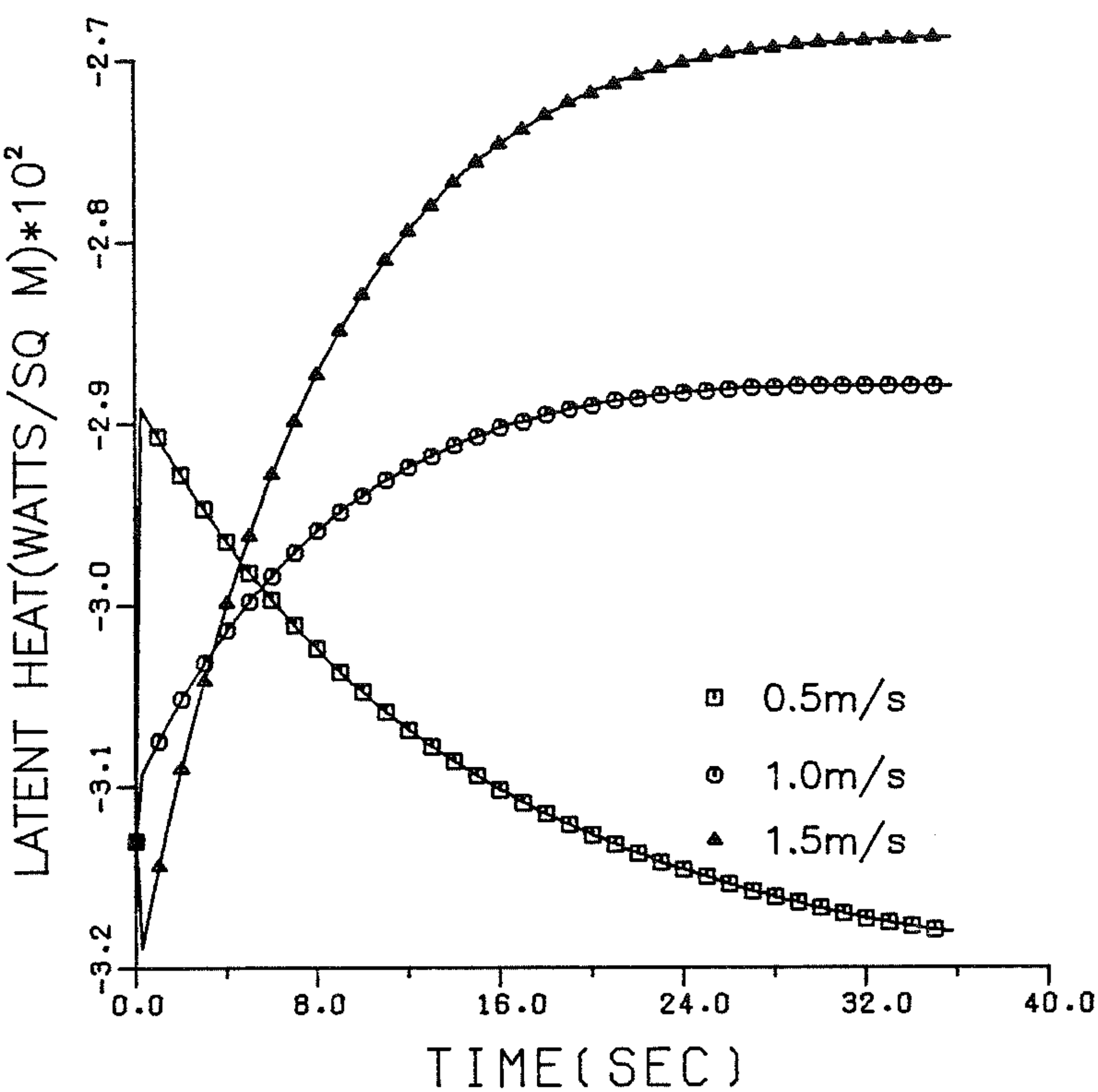


Figure 3.11 Latent heat transfer changes over simulated chamber measurement for three wind speeds, initial relative humidity of 80% and initial air temperature of 25 C.

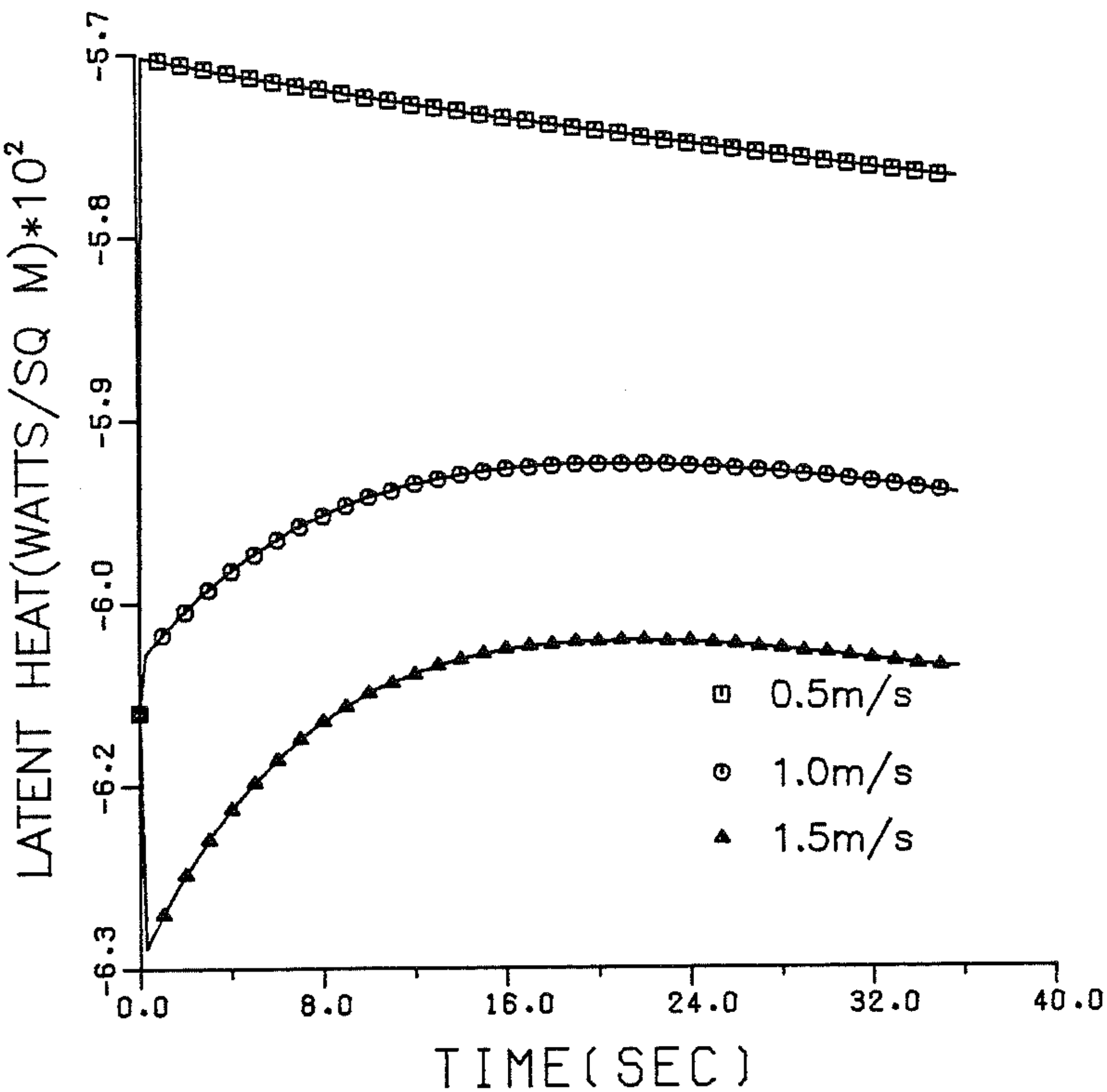


Figure 3.12 Latent heat transfer changes over simulated chamber measurements for three wind speeds, initial relative humidity of 20% and initial air temperature of 35 C.

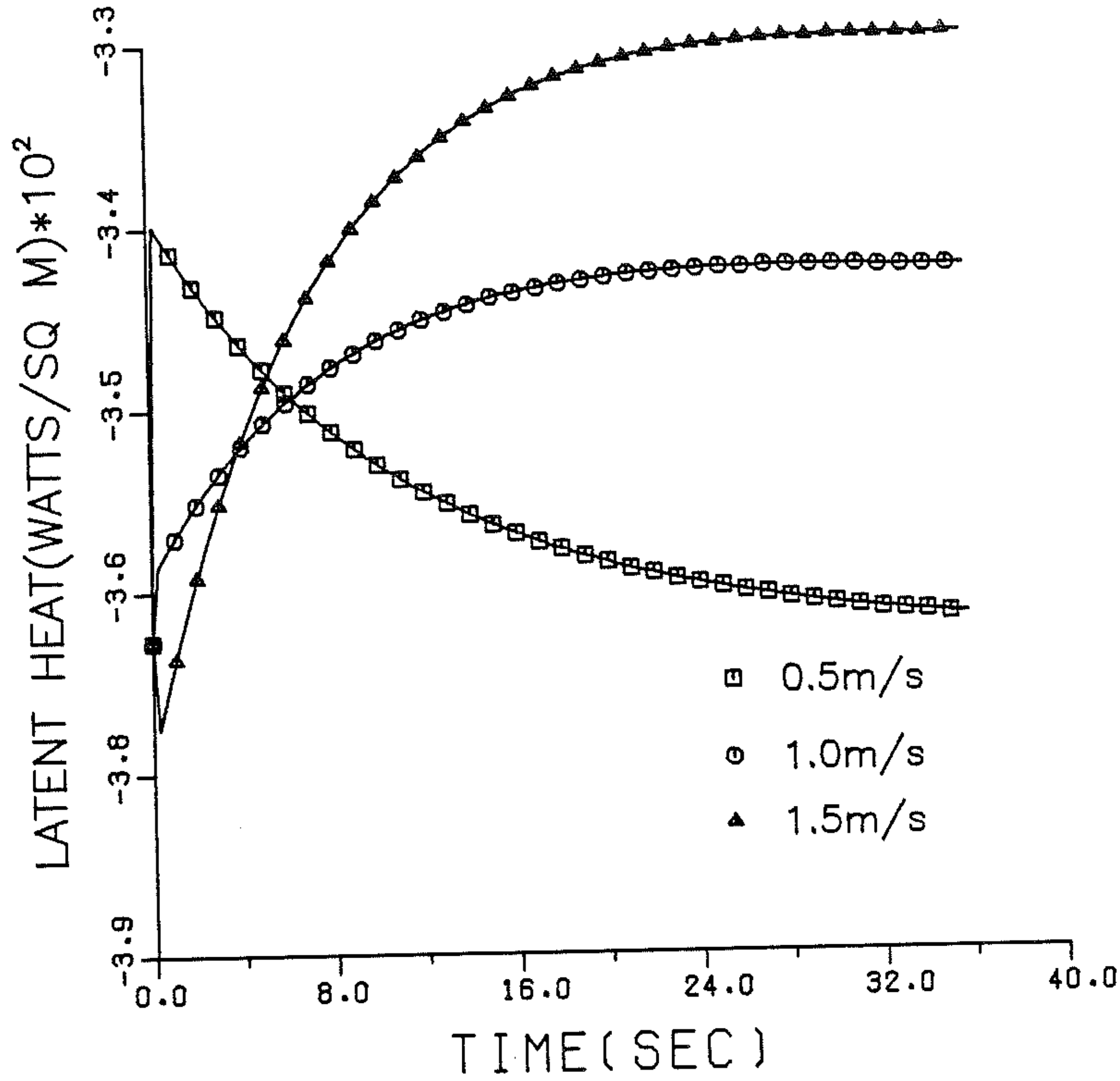


Figure 3.13 Latent heat transfer changes over simulated chamber measurements for three wind speeds, initial relative humidity of 80% and initial air temperature of 35 C.

higher than the air temperature, drops rapidly at t=0.25 seconds (see Figure 3.6, rh=80%, v=1.5m/s) and so the saturated vapor pressure (calculated at the leaf temperature) at the leaf's surface decreases. The air temperature increases linearly throughout the run yet so does the wet bulb air temperature and increases by the same amount so the vapor pressure of the air changes as the saturated vapor pressure of the air calculated at the wet bulb temperature. This is because the wet and dry bulb air temperature deficit ramains constant (see equation 2.5). Therefore if the leaf saturated vapor pressure decreases as a result of a decreased leaf temperature and the air vapor pressure increases with the saturated vapor pressure of the air at the wet bulb temperature then the vapor pressure deficit also decreases. At the low chamber wind speed the opposite is true . The leaf saturated vapor pressure increases and the response of the vapor pressure of the air remains as before, thus giving a leaf/air vapor pressure deficit which is increasing at a slower absolute rate. The result is that the absolute value of the rate of change of the leaf/air vapor pressure deficit is greater for the higher chamber wind velocity than for the low chamber wind velocity.

In Figures 3.10-3.13 the alteration of the latent heat transfer at the beginning of the run is less for the 1.5 m/s than for the 0.5 m/s chamber wind speed. This is due to the relationship of wind velocity to the thickness of the unstirred boundary layer. In Chapter 2 the thickness of the boundary layer was shown to be inversely proportional to the square root of the wind velocity over the surface of the leaf. The result is that, for increasing chamber wind speeds, the boundary layer resistance approaches zero while the diffusion resistance approaches the stomatal resistance. With increases in wind speed a reduced overall effect in latent heat production will be observed.

Figures 3.12 and 3.13 show the simulated latent heat production rate over the measurement interval at the 2 humidities and 3 chamber wind speeds for a 35 C initial air temperature. These figures clearly show how the wind has a greater effect at the lower humidity level and this is simply a result of the larger vapor pressure deficits at 20% relative humidity. Since the change in the chamber wind speed results in the same boundary layer resistance and therefore the same diffusion resistance for both humidity levels and since for the 20% relative humidity a larger vapor pressure deficit exists, then a larger initial change in latent heat transfer must result. At the higher humidity level the subsequent changes in the latent heat transfer are seen to be more severe. This is due to the larger changes in the vapor pressure deficits (see Figure 3.8).

In using an actual measurement chamber the fans used for mixing the air may either be running when the chamber is put into place (similar to Reicosky, 1977) or they may be left off until the chamber is in place and the measurement started (similar to Peters, et al. 1974 and Schulze, 1978). In the first case the leaf experiences the change in wind speed before the measurement begins while in the latter case the leaf experiences an increase or decrease in wind speed from t=0. Since the fans take a few seconds to reach their operating speed or mixing rate the effect is more gradual. In addition, and pertinent to both cases, the speed at which the air moves over the leaf may vary with time. In order to obtain a working model we have assumed that the fans produce a constant wind speed over the leaf, that they are started at t=0 and require one time increment to reach their operating speed.

The components of equation 3.1 for a leaf in an actual measurement chamber probably begin to change before t=0. If the chamber is suspended over the crop, the incident radiation may be reduced. As the chamber is being placed the wind velocity profile in the canopy changes which may alter the the ongoing processes at the plant leaf surface. In the development of the model this had to be ignored by assuming the placement of the chamber to be instantaneous. And finally, the leaf stomatal resistance, though known to change with leaf temperature, was held constant. Holding stomatal resistance constant was done based on resistance changes determined by a regression given by Drake, et al.(1970) when leaf temperature was increased by 1 C. The resulting changes in stomatal resistance were about 5%. Since stomatal resistance is primarily determined by stomatal aperture, and it is not known how quickly or if the stomatal aperture changes with the placement of a measurement chamber, the decision to hold stomatal resistance constant appears justified.

A question might be raised as to the nonlinear rates of latent heat transfer during the simulation runs shown in Figures 3.10-3.13, in light of the fact that researchers have observed linear increases in vapor density within the chamber during the chamber measurement. Peters et al.(1974) and Reicosky and Peters(1977) inferred that the linear increase in vapor density within the chamber meant that the chamber environment was not adversely changing the ET rate. The latent heat transfer rates shown in Figures 3.10-3.13 are shown at descrete points in time, whereas the production of vapor within the chamber is measured on a cumulative basis.

Figure 3.14 shows the instantaneous latent heat transfer values which were given in Figure 3.11 on a cumulative basis. Shown in this way, the latent heat production appears approximately linear. Comparing the curves calulated for the three chamber conditions to the curve for a leaf outside the chamber, each is seen to have a different slope. Therefore, a linear vapor density slope (which is used to determine the ET rate) does not imply that the ET rate measured is the same rate of ET which existed prior to chamber placement.

Despite the numerous assumptions required for the model's development, the model seems to illustrate logical trends which would occur for a leaf enclosed within a measurement chamber with regard to its energy budget.

To summerize and comment on the information discussed in this section:

1. A leaf enclosed in a measurement chamber was shown to experience a lower net radiant energy input because the portion of visible and infrared radiation from the sky, that was not transmitted through the chamber cover, was greater than the infared radiation emitted from the chamber cover towards the leaf, thus a drop in net radiation. The change in the leaf temperatures, which were typically < 1 C, caused the net radiation (an energy input) to decrease slightly over the simulated chamber measurement period with increasing leaf temperatures, and caused an increase with decreasing leaf temperatures.

2. Leaf temperatures decreased for a wind speed greater than that existing over the leaf before the chamber placement, whereas a lower chamber wind speed caused an increase in leaf temperatures. In addition

to the leaf temperature changes due to the initial radiation changes, the initial change in wind speed caused either an increase or decrease in the unstirred boundary layer at the leaf surface which changed the rate of sensible and latent heat transfer.

3. Leaf temperature changes as well as the leaf/air vapor pressure and temperature deficits changed nonlinearly during the first half of the simulation runs but became linear during the second half. This was due in part to the relatively small leaf thickness which allowed for high temperature changes with respect to time.

4. The lowest chamber wind speed reduced and the highest chamber wind speed increased initial values of latent heat transfer from the leaf. These changes occurred virtually instantaneously since the change in the boundary layer thickness can occur rapidly (0.25 s which was one time step).

5. The lower chamber wind speed changed the latent heat transfer more than the higher chamber wind speed even though each was 0.5 m/s different than the initial wind speed over the leaf. The reason for this is that as wind speed increases the boundary layer resistance approaches zero leaving only the stomatal resistance (assumed constant) to control latent heat transfer.

6. After the initial resetting of the boundary layer resistance and incoming radiation, further changes in sensible and latent heat transfer resulted mainly from changes in the leaf/air vapor pressure and temperature deficits.

7. The average change in the latent heat transfer for the three wind speeds, two humidity levels and two initial air temperatures was between

5 and 15 % below initial latent heat transfer values. The decreases observed were due to the particular conditions used and we shall see in chapter 5 that large overestimations relative to initial values may also occur.

8. When the latent heat production was shown on a cumulative basis the curves appeared to be linear. Researchers have incorrectly assumed that the linear increase of vapor density within the chamber meant that the ET rate measured was the same as the ET rate that existed prior to the placement of the chamber.

From these results it appears that a leaf enclosed within a portable measurement chamber has the capacity to respond rather quickly (mainly due to its small thickness) to changes made in its microclimate and the placement of a measurement chamber over a group of plant leaves, therefore, has the potential to cause error in ET estimation.

CHAPTER 4

DESIGN, CONSTRUCTION AND TESTING OF A PORTABLE MEASUREMENT CHAMBER

In May of 1982 construction was begun on the MSU portable evapotranspiration measurement chamber and a boom structure for chamber suspension and positioning. The equipment was ready for use in mid-July of that same year. The goal of the project during that first summer was to get the system operational, to identify problems with the measurement and transport equipment, and to minimize or correct these problems.

The design used here is similar to the design used by Peters, et al.(1974) and Schulze(1978) in some respects. Both of these designs positioned the chamber over or around the crop with part of the chamber open. The chamber was then sealed shut immediately prior to the chamber measurement. In the case of Schulze(1978) little mention was made as to the reason for the removable lid. The rationale may have in part been due to the fact that the chamber was put in place manually by two people, thus breaking the chamber into two sections made it more managable. Peters, et al.(1974) required the open front and back sides of their chamber since the chamber ran on tracks through the field. In the case of the design to be discussed here, the reason for the closable top is solely for the purpose of minimizing alteration of the crop microclimate. Figure 4.1 shows the various components of the Michigan State University portable measurement chamber system positioned in the field about to obtain a measurement.

Materials and Methods

A lightweight 2.54 cm diameter tubular aluminum frame was constructed to support a film plastic material. The film formed a transparent chamber which could be set over a group of plants to trap water vapor being given off. A frame measuring 1.22x1.22x1.52 m provided the basic unit in which instruments were mounted and was used for measurements over low growing crops including potatoes, soybeans and turfgrass. Another frame measuring 1.22x1.22x1.83 m was attached to the smaller chamber to make a taller unit for use with corn. The combined chamber measured 1.22x1.22x3.35 m. Figure 4.2 shows the single smaller chamber with dimensions. By welding gusset plates to the chamber corners through which diagonal tension wire was strung, the chamber frame was kept square and rigid.

The chamber was covered with Propafilm C110 donated by ICI Americas Inc. The film plastic was attached to the chamber using double stick transparent cellophane tape.

The selection of the film was based on tests run with a Beckman BD-GT grating spectrophotometer which revealed the film's capacity to transmit long wave radiation well. Figure 4.3 shows the transmissivity of the film for wavelengths between 2.5 and 16 microns. The integrated average infrared transmissivity of the film was determined to be 75% compared to Plexiglass and Lexan which transmitted about 10%. In the range from 0.7-2.5 microns the transmission characteristics of the these materials could not be obtained as the necessary equipment could not be found to run the test.

A test was also run to determine the solar transmissivity of the film with changing beam angle (see Figure 4.4). The test was run with a Licor pironometer positioned 25 cm from a 400-watt high pressure sodium lamp. With the film plastic positioned between the sensor and the lamp, its angle was varied with respect to the light beam through 70 degrees. From 70 to 90 degrees the measurement could not physically be obtained so the curve was extrapolated to 0% transmission at 90 degrees and is represented with a dashed line.

Chamber Top Unit

The chamber top could be opened and closed. A separate unit consisting of a roller for rolling back the film and a magnetic seat for closure as the film unrolled across the top was constructed and attached to the top of the chamber frame. Figure 4.5 shows the chamber top unit.

A spring loaded aluminum roller mounted in a small chassis with a sliding door track on each end held a roll of the film plastic. A strip of 1.9 cm wide spring steel was taped onto the edges of the film. The spring steel contacted a magnetic strip mounted around the top of the frame sealing the plastic down as the roller moved across the frame and unrolled the film. The two ends of a light twisted wire cable were attached to the two sides of the roller chassis. The wire cable was double wound around a small pulley on a reversible DC motor to open and close the top. The motor rested on a bar fixed to the top frame which

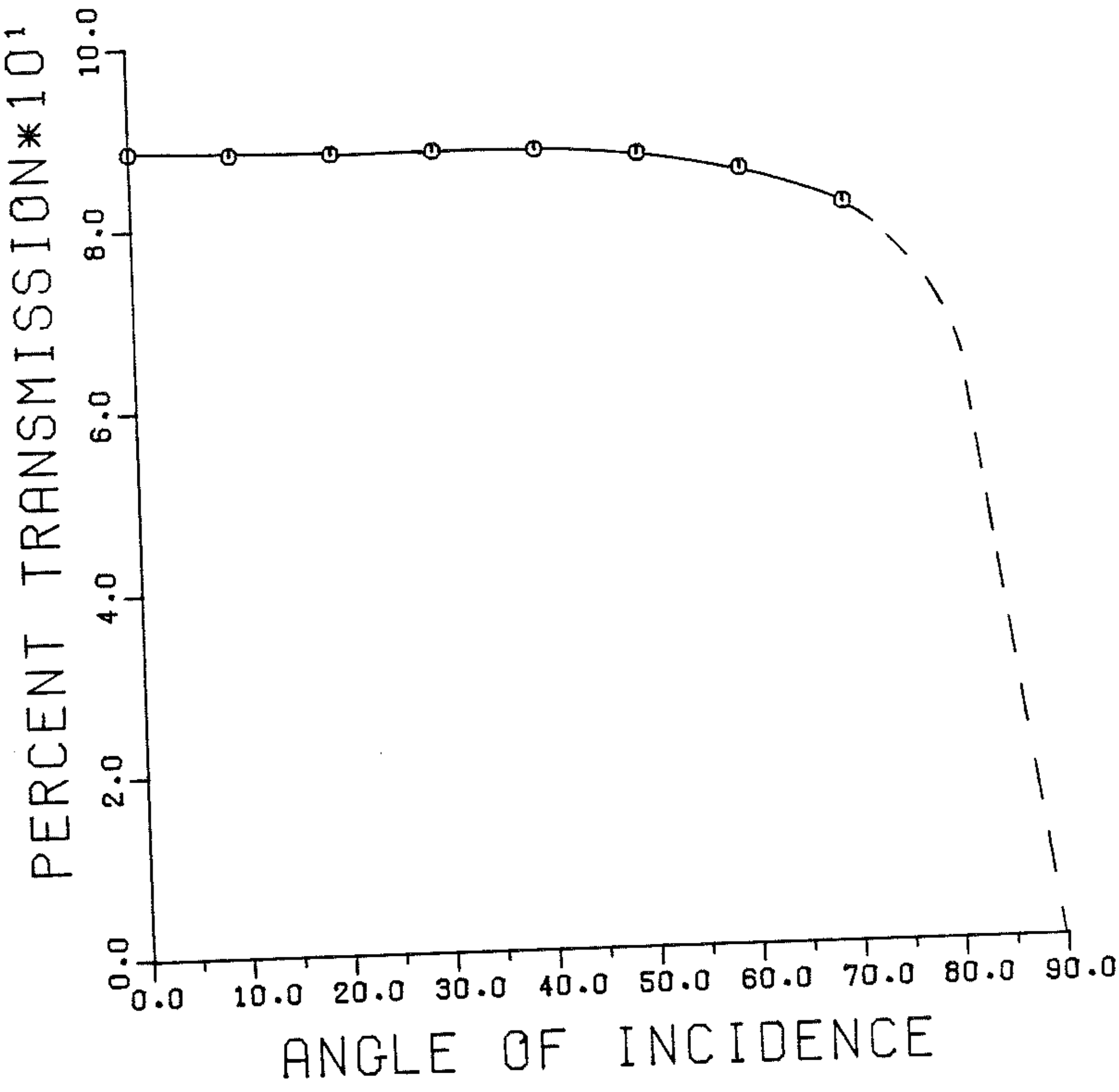


Figure 4.4 Percent transmission of visible radiation vs. angle of incidence for Propafilm C110.

also served as the mount for the cable from which the chamber was suspended for raising and lowering. Limit switches were placed at the ends of the roller chassis track to stop the travel of the roller frame.

The entire top unit was bolted to the top of the chamber frame. A switch to reverse the direction of travel and activate the roller motor was placed at the bottom of the chamber and was actuated when the chamber was lowered to or raised from the ground.

Chamber Bottom Unit

A separate bottom unit was constructed which held a 10 cm layer of foam rubber which served as a ground seal around the bottom of the chamber during the measurement. The unit was easily attached to the bottom of the chamber frame using small lag bolts and thumbnuts. Eye bolts were welded to the four corners of the unit which served as gaff pole catches to control the movement of the chamber in the field while keeping people several meters away from the point of measurement. Figure 4.6 shows the chamber bottom unit separate from the chamber.

Suspension Structure

A tractor mounted suspension structure was built to suspend the chamber above the crop and lower it into place for measurement. The suspension structure is shown in Figure 4.1, along with the chamber and farm tractor used for support and mobility. Rigid television antenna tower sections were used for the suspension tower. The tower sections could be increased in height to accommodate the tall chamber by adding additional sections. The original cross bracing was reinforced at points of critical stress. A 37.3 watt (1/20 HP) permanent magnet reversible motor was used to move the chamber laterally on a trolley set inside a heavy-duty rolling door track on the horizontal boom section. The chamber was raised from or lowered to the ground using a braided wire cable connected to a 4450 newton (1000lb.) capacity 12 volt DC winch. The winch was rigidly attached to a plate on the trolley in the door track.

The vertical portion of the tower structure rested in a steel three point hitch connected frame which prevented the tower from tipping and provided for rotation (see Figure 4.1). The bottom of the tower was positioned on a steel plate which rested on a rotation bearing. The structure was made to rotate about its vertical axis by use of a manually operated chain and sprocket attached to the lower portion of the suspension structure support frame. After the boom was rotated to the desired position, a brake could be set to avoid further rotation.

Chamber Measurement Equipment

The determination of the vapor density within the chamber was accomplished using an aspirated thermistor psychrometer. The psychrometer consisted of a 2 cm inside diameter aspiration tube with a small attached water reservoir. At the rear end of the tube the intake of a 2500 cm^3/s DC fan was attached. The resulting wind velocity over the two thermistors positioned in the tube was 8 m/s. The thermistors were rigidly placed within the tube along its central axis separated by 5 cm. The thermistor closest to the aspiration fan was enclosed in a cotton jacket shoelace which was connected to the water reservoir. The entire psychrometer was placed within a short section of Hancor Archflow white drain tile to eliminate radiation heating. A data logger was used to collect thermistor data which was subsequently written to a magnetic tape for storage.

Chamber Mixing

Two .065 m^3/s fans were used for mixing the air inside the chamber over the measurement interval. Each fan was attached to a rod located at opposite corners of the chamber by means of laboratory clamps. The clamps allowed the fans to blow in any direction and were also vertically movable along the length of the rod. The theoretical mixing rate of the 1.54 and 3.35 m chambers were 3.5 and 1 cycles per minute, respectively.

Measurement Technique

The chamber was positioned over the crop with the tractor mounted boom structure. The chamber was lowered with the top open and the fans off to prevent expelling air from the crop canopy. Upon contact with the ground the top closed automatically and the fans started when the top had completely closed. Data collection was begun upon top sealing and continued for 36 seconds while 95 paired values of wet bulb and dry bulb temperatures were logged. The data collected were transferred to a magnetic tape from computer memory after completion of data collection. The chamber was then raised above the crop, the top opened and the fans turned off after purging the chamber. Two or three runs were completed on the same plants and averaged to achieve measurement of the ET rate at that time of day. A new group of plants was usually selected for the next measurement one time increment later.

Data Interpretation

The raw data stored on the tape was transferred to a microcomputer and converted to temperature in degree centigrade via emperical formulas derived from thermistor calibration data. Each discrete sample consisted of a measurement of dry bulb temperature, wet bulb temperature and the absolute time. The vapor pressure of the air in the chamber was calculated using a rearranged form of the psychrometric equation and was given as equation 2.5. The change in the vapor pressure of the chamber air with time was then used in the ideal gas equation to obtain the slope of the vapor density increase within the chamber. Dividing the expression by the density of liquid water and multiplying by the ratio of chamber volume to the area of the chamber base, the ET rate was obtained as an equivalent depth of water per unit time. The equation used to obtain ET estimates from the chamber is given below:

$$ET = (18.0V/RT_d \rho_w A)\, de/dt \tag{4.1}$$

where

ET = chamber estimated ET (cm/hr)

e = vapor pressure of chamber air (Pa)

t = time (hr)

ρ_w = density of liquid water (g/cm^3)

T_d = dry bulb temperature of the chamber air (K)

R = universal gas constant ($Pa\text{-}cm^3/mole\text{-}K$)

V = chamber volume (cm^3)

A = area of chamber base (cm^2)

de/dt = vapor pressure slope over chamber measurement (Pa/hr)

The computed water depth-time data pairs were curve-fitted using a linear least squares approximation. The result is a slope of a line (given by ET in equation 4.1) representing the increase in water vapor in the chamber over the measurement time in centimeters per hour. Plotting the individual slope values against the time of day and integrating allowed computation of the total daily ET as an equivalent water depth.

Chamber Performance Verification

The chamber was used in East Lansing and Montcalm County, Michigan for estimating daily water use for corn, soybeans and potatoes. The data collected were, however, not reliable since a complete chamber calibration had not been performed. It was felt then that the most important goal that first season, after attaining operational status, was to test the chamber against a reliable control. On August 29, 1982 the chamber was tested against a corn covered weighing lysimeter at the

ARS Experiment Station at Coshocton, Ohio. The sky was very clear during the day of the test with a high temperature near 30 C. Figure 4.7 shows the point measured values of ET obtained from the portable chamber and average hourly ET values from the lysimeter on August 29 plotted throughout the day. By interpolation a line connecting the values was drawn and the area under the curve integrated over time. The test data obtained showed the weighing lysimeter lost 0.38 cm of water while the chamber estimated 0.43 cm of water loss. Thus the chamber overestimated the ET rate as compared to the weighing lysimeter. No attempt was made to smooth the daily ET curve; however, this may possibly be a means to improve the estimate.

Due to the late stage of growth the corn had attained, coupled with the near frost conditions ocurring nightly and several electrical and mechanical problems encountered, only the one day's data was obtained for comparison. This experience pointed out the need for a controlled experiment where statistically based information could be obtained.

The overestimation by the open top chamber measurement which converted to a 16% difference was larger than that reported by Reicosky (1981) for his closed top chamber when tested in Minnesota next to a weighing lysimeter. This indicates that there may possibly be an inherent flaw in our open top approach.

Data collected during a three hour period at Coshocton with the top closed similar to Reicosky's approach is shown in Figure 4.8 compared to the opentop chamber and lysimeter ET values for the same time period. The figure shows that the closed top approach consistently measured lower rates of ET than did the open top. From the closed top data there is reason to believe that before the measurements were taken, the chamber was not properly purged of the moist air from the preceeding runs and therefore the lower rate may be due to the lower vapor pressure deficits during the runs. In order to identify possible problems associated with the open top approach, a laboratory experiment was planned and will be discussed in the next chapter.

CHAPTER 5

LABORATORY EXPERIMENT

A laboratory experiment was desirable in which certain environmental parameters could be controlled and enough replications made to yield statistically valid information about the chamber effect on crop ET.

Questions that needed to be answered were: Does the chamber create an artificial environment which yields chamber data which is not representative of the crop? Does the succesive lowering of the chamber over the crop for a 36 second period at 15 minute intervals alter the crop physiology thereby altering the rate of transpiration? Is there a significant difference between the open top and closed top approaches as measured in chamber performance? (The initially open top approach is similar to the methods used by Peters et al. (1974) and Schulze (1978) while the top always closed approach is similar to the method used by Reicosky (1977)). Does the chamber alter ET more with respect to a control under no-wind or wind conditions? How is leaf canopy temperature affected by the chamber? If changes in the canopy temperature occur, is there a significant difference between the mean temperature changes for the open and closed top approaches? The information obtained by answering these questions is valuable and will help to determine appropriate field measurement procedures and under what conditions the chamber may or may not give reliable ET estimates.

To answer these questions two experiments were performed. The first consisted of lowering the chamber over a treatment group of potted plants which were weighed at the beginning of the replication. A control group consisting of the same number of potted plants was also weighed at the beginning of the replication. The control group was located next to the treatment group and was exposed to identical environmental conditions. During the 4 hour replication the chamber measurements were taken every 15 minutes on the treatment group. Whether an open top or a closed top was used for any one measurement depended upon a previously randomized schedule. At the end of the replications the pots were again weighed and the amount of water loss determined.

The chamber measurement system was calibrated using an independent measure of vapor introduced into the chamber. The reason for this calibration was to assure that any instrumentation error could be separated from any error due to plant and microclimate effects.

MATERIALS AND METHODS

Beginning on January 27, 1983 bean plants (Phaseolus vulgaris L., Seafarer) were grown in the Michigan State University Horticulture Greenhouse under natural and supplemental lighting. Eighty pots were seeded with density ranging from 5-8 seeds per pot and a resulting emergence of 3-5 plants per pot. The soil used was a loam soil with a 1:1 ratio of vermiculite peat and average bulk density of 1.4 g/cm^3. Supplemental lighting was used to encourage the natural bush like architecture of Seafarer found in the field. Lighting was accomplished using a high pressure sodium lamp, in combination with a metal haylide lamp both rated at 400 watts. Plants were periodically rearranged with respect to the lamp positions in order to eliminate light stratification effects.

Plants were irrigated with tap water and recieved a 200:54:187 ppm constant liquid feed fertilizer mixed with the water every several waterings. Approximately 3 weeks after emergence the plants were moved to the Agricultural Engineering Building on the Michigan State University campus. The plants were illuminated with 100% artificial light from the two aforementioned lamps.

During the experiment the plants appeared to be in good condition with respect to disease and insects although some of the lower leaves began to yellow and this became more noticeable throughout the experiment. Plants which were especially small were removed from the group of 80 during the experiment which lasted in all about two weeks. The plants left at the end of the experiment numbered about 65.

Evapotranspiration Experiment

From the total group of plants (65-80) 40 were randomly chosen for any given replication. From the 40 pots chosen 20 were randomly selected to be in a control group and the remaining 20 were put into a treatment group. One of the two groups was randomly selected for obtaining initial pot weights. After the group was finished being weighed the other group was similarly weighed.

With the completion of the weighing of the pots the chamber with top open was lowered over the treatment group. Upon ground contact the top closed automatically, fans were started and the measurement begun. Over a 36 second period 42 data points for each of 5 parameters were logged. The parameters were wet and dry bulb temperatures for a psychrometer positioned at approximatey 30 cm above the crop canopy, wet and dry bulb temperatures for a psychrometer positioned approximately 10 cm above the crop canopy and crop canopy temperature from an infrared thermometer positioned 15 cm above the crop.

Before raising the chamber the fans were switched off an the chamber top roller motor disabled so that the top would remain closed while the chamber was raised. The chamber was then lifted above the crop canopy and held until the next measuremnt 15 minutes later.

After fifteen minutes, the chamber fans were started and the chamber was purged for 30 seconds. The chamber was then lowered with the top closed and fans on. The subsequent steps were identical to the first measurement.

For statistical purposes the replication was broken up into 1/2 hour periods. Each 1/2 hour period consisted of 2 measurements with one an open top and the other a closed top run. The choice of making the first run an open top or a closed top was determined by the flip of a coin. Within any of the designated 1/2 hour periods there was always an open top and closed top run. However, when all the 1/2 hour periods were put together, which making up the 4 hour replication, new 1/2 hour periods resulted which may have contained two open top or two closed top runs. This method of randomization was seen as the best alternative to having two chambers run simultaneously side by side. The use of a second chamber and therefore a third group of plants was not a practical consideration.

At the end of the 4 hour replication, the group of pots first weighed were again weighed and recorded. Then the other group was weighed, the information recorded and this completed a single replication.

After the completion of the first experiment which consisted of 5 replications a second experiment was begun where two 45.7 cm fans were used to produce a 1.5 m/s wind velocity over the plants for the entire 4 hour replication. The second experiment also consisted of 5 replications.

EQUIPMENT AND INSTRUMENTATION

During the first 4 days of the experiment the two lamps were placed about 1.2 m from the two groups of plants such that each lamp illuminated either group approximately by an equal amount. The lights were held at a 30 degree angle from the horizontal at a position of 1.2m from the floor. Lighting for the plants therefore entered the chamber through one of its sides. On the fifth day of the experiment a 3rd lamp was employed in order to increase transpiration rates and to increase a statistical block effect within the experiment. When the chamber was lowered, radiation incident on the plants was found to decrease by 6% as measured by a model LI 200S LICOR pyronometer.

Two fans were used to stir the chamber air during a measurement. A 45.7 cm AC fan was postioned at the top of the chamber and directed air down at the crop. A 12 volt DC fan was placed in a corner of the chamber at 35 cm from the floor. The average wind speed in the chamber was found to be approximately 1 m/s. This average was obtained from horizontal and vertical wind speed measurements at 15 locations in the chamber. Wind speeds were obtained using a Weathertronics model 2440 hot wire anomometer.

Two psychrometers were used for the collection of wet and dry bulb temperatures in the chamber. The psychrometers were a redesign of the psychrometer used during the previous summer. Two water reservoirs were added. The wicks consisted of 0.3 cm cotton string which was folded over two of the four thermistors which were routed to the reservoirs. In addition to the string wicks, a piece of tissue paper was wrapped around the thermistor beads to insure complete wetting. A third order polynomial calibration equation was developed for converting the thermistor resistances to temperature. The calibrations were accomplished by submerging the thermistors in a water bath of known varied temperature. The water temperature was measured to within +/-0.05 C.

Plant canopy temperatures were collected using an infrared thermometer aimed at a selected group of plant leaves which included both shaded and nonshaded leaves. The infrared gun was held approximately 15 cm above the top of the plant canopy. A calibration was performed by aiming the gun at a flat black aluminum container filled with water of known varied temperature. The water temperature was measured to within +/-0.05 C. It was assumed that the emissivity of the container was close to that of the plant material and that the thermal conductivity of the container wall was sufficiently high so that the wall temperature was the same as the water temperature within the container.

Upon completion of the experiments the thermistors and infrared thermometor were recalibrated as a double check on the first calibration and to determine if the instrumentation experienced drift over the experimental period. The thermistors had not changed during the experiment whereas it was discovered that the infrared thermometer had been calibrated incorrecly the first time. In order to be sure that the experimental results were those due to chamber effects and not due to chamber equipment error, a calibration was run on the chamber by releasing a known amount of water vapor into the chamber air via boiling water from an insulated container placed within the chamber. The container was placed on a Mettler digital scale and the change in mass due to the vaporization of water was measured to within +/- 0.1 g. The chamber was periodically purged when humidity levels became high. It was felt that water vapor which was produced from the boiling water represented a forced vapor source which could not be controlled by the chamber environment as perhaps plants might. The calibration curve for the chamber is given in Appendix B.

RESULTS AND DISCUSSION

The laboratory experiments performed provided data which aided in answering the questions posed at the beginning of the chapter. The statistical design used for analyzing the evapotranspiration data was a randomized complete block design along with a Least Significant Difference (LSD) test for comparisons between treatments. The four treatments were:

1. The group 1 ET obtained by weighing each of the pots at the beginning and end of the replication.

2. The group 2 ET obtained by weighing each of the pots at the beginning and end of the replication.

3. The group 2 ET as measured by the chamber using the initially open top approach.

4. The group 2 ET as measured by the chamber using the top always closed approach.

For convenience the legend given below summarizes the abbreviations which will be used in referring to the treatments, and the reader may wish to refer to it from time to time while reading this chapter.

Treatment Legend

WP1 . . . . Weighed pots group 1
WP2 . . . . Weighed pots group 2
CH2OT . . . . Chamber open top group 2
CH2CT . . . . Chamber closed top group 2

The physical arrangement used in Experiments 1 and 2 is illustrated in Figure 5.1.

Experiment 1 consisted of determining the water consumption from the plant groups 1 and 2. Evapotranspiration was measured from group 1 by observing the change in mass of the potted plants over a 4 hour period(treatment WP1). Evapotranspiration from group 2 was determined by the same method as group 1(treatment WP2) and in addition ET rates were obtained by use of the chamber(treatments CH2OT and CH2CT).

Experiment 1 was run under a no-wind condition (i.e. the movement of air could not be detected by a hot wire anomometer). A summary of the test of significance and the analysis of variance (ANOVA) table for Experiment 1 are shown in Table 5.1. A block design was chosen with time as the block since from day to day the conditions in the laboratory tended to vary. Conditions which could not be controlled completely were air temperature, relative humidity, and soil moisture which varied from moist for some replications to dry to the touch for others. The block effect was found to be highly significant which confirms the appropriateness of the statistical design chosen. The values shown are means taken over 5 replications and are in grams of water. The underscore indicates no significant difference found at the 5% level.

The two psychrometers were compared by using a t-test over the 5 replications in Experiment 1 and the difference was not significant at the 5% level. The fact that the data from the two psychrometers was similar indicates that the air was not stratified with respect to vapor density. The use of two psychrometers also acted as a double check and would have revealed equipment problems if the measured temperatures had been grossly different. Since the data gave similar, results only the data from the upper psychrometer has been used in obtaining the chamber data shown in Tables 5.1 and 5.2.

In Experiment 2 the plants were exposed to an average wind speed of 1.5 m/s measured at the top of the plant canopies. The block effect was found to be significant at the 5% level over the 5 replications. A summary of the test of significance and the analysis of variance (ANOVA) for Experiment 2 are shown in Table 5.2. The values shown are means taken over the five replications and are given in grams of water. The underscore indicates no significant difference at the 5% level.

The data given in Tables 5.1 and 5.2 are shown graphically in Figures 5.2-5.5.

From Tables 5.1 and 5.2 it can be seen that no significant difference was found between treatments WP1 and WP2. From these results we may conclude that permanent or long term stomatal closure did not occur in the leaves of the group 2 plants as a result of the their successive enclosure within the measurement chamber. The implications of these findings may be important in the field where, for matters of convenience, it is desirable to obtain measurements over the same group of plants for an extended period of time rather than moving to a new group of plants after each measurement. These results should however be viewed with caution since during the experiment the plants were exposed to a very low level of visible radiation, which may have translated into high stomatal resistances. If this were the case, then the effects of the chamber to reduce the visible radiation may not have been a significant factor in altering stomatal resistance.

From the two tables we see that under the no-wind condition the chamber measurement resulted in a serious over-estimation of ET (see Figure 5.3). The results of the wind experiment on the other hand indicate that the chamber estimated the actual ET much more closely (see Figure 5.4). The gross over-estimation of ET by the chamber in Experiment 1 can be at least partly attributed to the sudden reduction in the unstirred boundary layer over the leaf surfaces caused by the chamber fans.

A large change in transpiration was confirmed theoretically by employing the computer model described in Chapter 3. By using the appropriate quantity for the solar radiation input, the average laboratory ceiling temperature for the effective sky temperature, and the actual average wet and dry bulb temperatures obtained for several of the no-wind measurements, the over estimation of transpiration for a single leaf can be determined. The data used in the simulation run were: 20.0 W/m (observed in the laboratory) for solar radiation, 28 C for the average ceiling temperature, the average wet and dry bulb air temperatures obtained during the first seven runs of the first replication of Experiment 1 (consisting of both CH2OT and CH2CT measurements), the laboratory wind speed which the leaf was initially exposed to assumed .05 m/s, a chamber wind speed of 1.0 m/s , a measurement interval of 36 seconds and a stomatal resistance of 330 s/m which is considered a upper limit by Kruiper(1961) for beans. Figure 5.6 shows the graphical comparison of the change in latent heat transfer during one of the runs from which the average temperatures were obtained.

By integrating the latent heat transfer over the measurement interval and dividing by the latent heat of vaporization the total quantity of water per unit area is found. The average calculated over estimation of leaf transpiration was 65% relative to the initial condition transpiration.

Since the model considers a single leaf and not the whole canopy, a high degree of correlation between the model and laboratory results was not expected. The use of the model here is only to show that, theoretically, altering the plant environment, the ET (or transpiration) rate can be seriously affected over the short measurement interval.

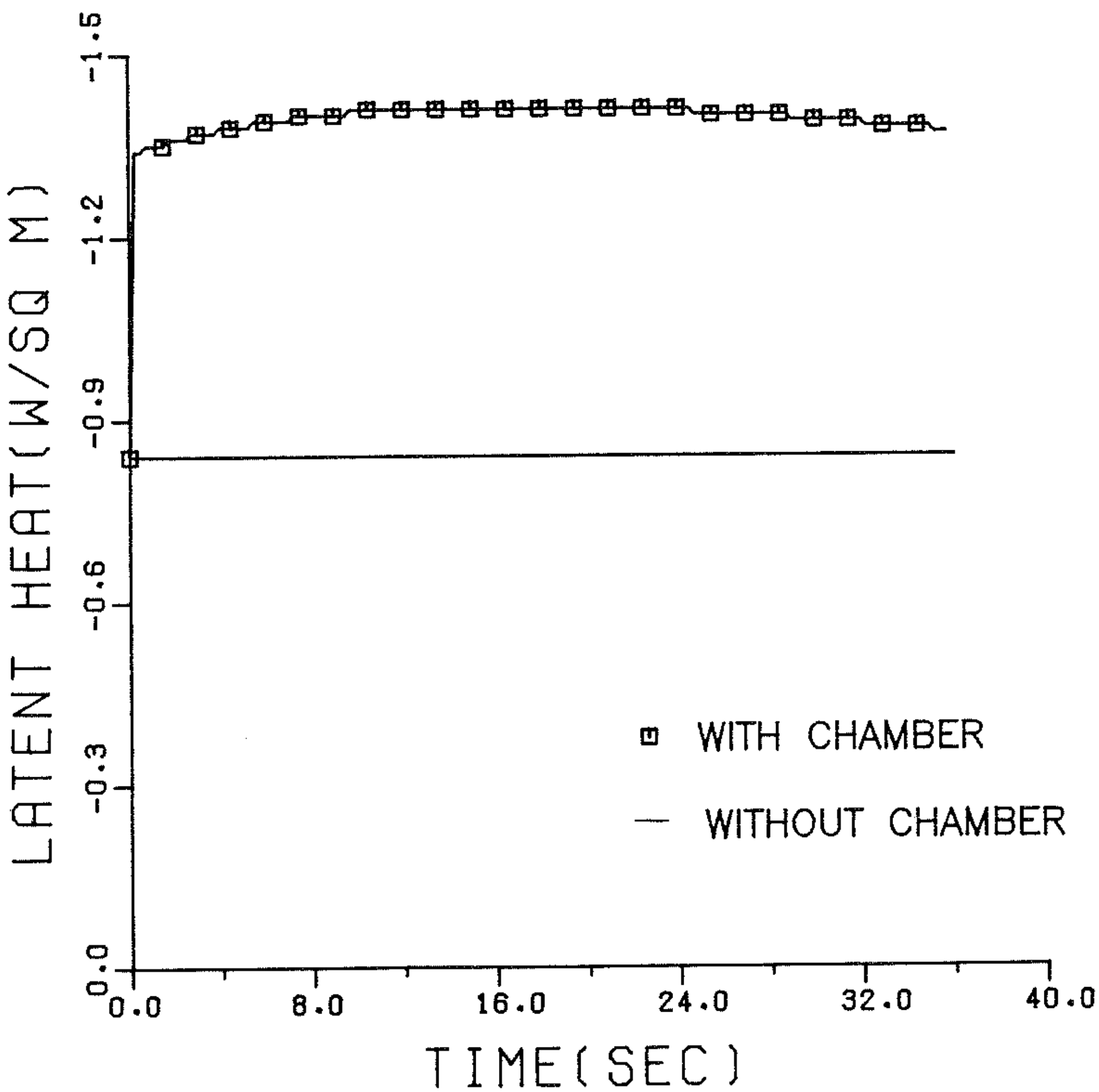
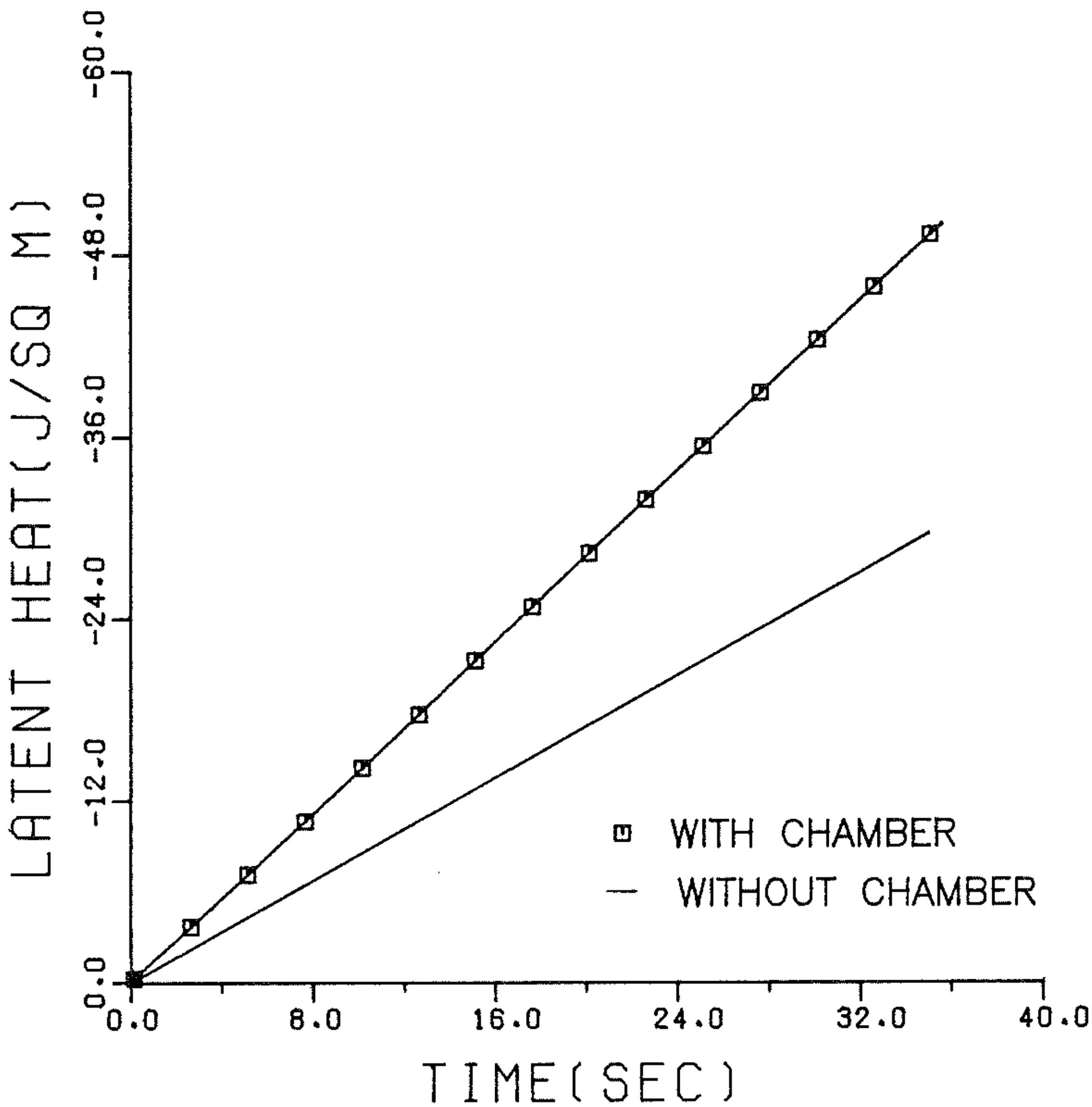


Figure 5.6 Latent heat transfer changes over simulated laboratory chamber measurement. Data is shown for a leaf inside and a leaf outside the chamber.

In Chapter 3, a nonlinear change in latent heat transfer, which was produced by the presence of the chamber, resulted in an approximately linear curve when plotted on a cumulative basis. Figure 5.7 shows the instantaneous latent heat transfer values from Figure 5.6 plotted on a cumulative basis. The slopes of the two curves shown are dramatically different and clearly illustrate the flaw in assuming that a linear increase in vapor density within the chamber implies an accurate estimate of ET.

The estimation error which might be expected in the field would probably not be as great as that found in the laboratory since the average field wind speed may, on the average, be 5 to 30 times greater than the small wind speed attainable in the laboratory. The typical average wind velocity found in a bean field might be 0.25-1.5 m/s. Using a wind velocity of 0.75m/s, 872 W/m^2 for solar radiation, 2 C for the effective sky temperature, a 36 s measurement time, a chamber wind speed of 1 m/s (observed in the 1.54 m chamber), and the initial wet and dry bulb temperatures 30 and 24 C respectively with subsequent increases of 1 C over the run, the model predicts that the transpiration produced over the chamber measurement is 6% under that of a leaf not enclosed in the chamber. This slight underestimation indicates that the chamber technique will probabaly give more accurate results under field conditions.

The fact that the wind had such a great effect on the ET rate in the laboratory is surprising in view of the fact that the stomatal resistances were probably high. As discussed in section on Chamber



5.7 Cumulative latent heat production over simulated laboratory chamber measurement. Data is shown for a leaf inside and a leaf outside the chamber.

Design Considerations, in most cases the stomatal resistance may be an order of magnitude greater than the boundary layer resistance, which means that with changes in the boundary layer resistance the total diffusion restistance should not be greatly affected. If the stomatal resistance in the laboratory was high and the sudden changing of the initial low wind condition to the high chamber wind condition did have such a dramatic effect, then we can only surmise that the effect might even be greater in the field where stomatal resistances are low during much of the day.

The ET values shown in Tables 5.1 and 5.2 also show the CH2OT values to be higher than the CH2CT values in both Experiments 1 and 2 (and this was also found in the field, see Chapter 4). The CH2OT values were on the average 100 g over the CH2CT values or roughly 10%. A reasonable explanation for this is found in the additional time required for the CH2OT treatment top closure.

The chamber top required 9 seconds to close. During this time the plants were in a still environment regardless of whether Experiment 1 or 2 is considered. This still environment is similar to the no-wind experiment which for the WP2 treatment produced an average of 410 g of water per replication. This is equivalent to 0.26 g over the 9 second closing time. Assuming that the transpiration rate can change immediately with changes in wind speed (which is supported by the laboratory and model data), then the transpiration rate of the plants during the run was controlled by the chamber wind speed. When the chamber measurement was begun, the fans were turned on and the plants were exposed to a high wind environment. From Table 5.2 the high wind condition produced an average WP2 ET of 943 g per replication or 2.4 g per chamber run. Summing the 2.4 g and the 0.26 g gives 2.66 grams of water. This value is 10.8% greater than the actual 2.4 g produced over the 36 seconds. Hence, the approximate 100 g greater estimate by the CH2OT treatment relative to the CH2CT treatment was due to the additional time required to close the chamber top.

The chamber used by Peters, et al.(1974) required 18 seconds to close and therefore may have produced similar errors. However, the chamber used was equipped with roll open sides which may have allowed a breeze to pass through the chamber and therefore may have been advantageous. The open top chamber design used here on the other hand probably experienced neglible exchange with the outside air during top closure since an unlikely down draft would be required.

Leaf canopy temperatures were also observed before and during the chamber measurements. Tables 5.3 and 5.4 summarize the average changes in leaf canopy temperatures over three time periods. The mean changes in leaf canopy temperature over the 5 replications were compared using a student t-test where the asterisk indicates significance at the 5% level. The time periods for which temperature changes were observed were: 40 seconds prior to the start of the chamber measurement to the beginning of the measurement (t=-40 s to t=0 s); from the start of the measurement to the end of the measurement (t=0 s to t=36 s); and from 40 seconds proir to the start of the measurement to the end of the measurement (t=-40 s to t=36 s).

Tables 5.3 and 5.4 show that though the CH2OT treatment tended to decrease before the run (from t=-40s to t=0s) and the CH2CT treatment temperatures tended to increase, during the run (t=0s to t=36s) opposite or small changes occurred, thus resulting in similar overall temperature changes (from t=-40s to t=36s). As expected, the leaves experienced greater initial temperature changes (from t=-40 to t=0) for the CH2CT treatment than for the CH20T treatment in the no-wind experiment. This was since, in the CH2CT treatment the fans within the chamber, which is suspended above the crop, were turned on at t=-40 and left running during chamber lowering. For the wind experiment the temperature changes for the CH2CT were small since activating the fans in the chamber did not significantly modify the plant's environment.

Once the chamber measurement was begun for each of the treatments, the environments became similar and the ultimate temperature equilibrium values were the same. The fact that the overall temperature changes were similar shows how quickly the plant leaves can adjust to a change in their environment. Figure 5.8 shows the leaf canopy temperature changes for a CH20T run and the following CH2CT run.

The overall canopy temperature changes were less for the wind experiment. This is due to the wind speed change from a 1.5 m/s to the 1.0 m/s wind speed in the chamber which is a smaller wind speed change than the plants experienced in the no-wind experiment. This may also explain why the no-wind experiment chamber ET estimates exceeded the WP1 and WP2 treatments. As the leaf temperature rises the saturated vapor pressure in the leaf stomates increases. If this increase is greater than the increase in the vapor pressure of the air, then the transpiration will increase.

To summarize the results in the laboratory:

1. No significant treatment difference was found between the WP1 and

WP2 treatments. The successive lowering of the chamber over the group 2 plants did not alter their ability to release water vapor to the air and therefore it can be assumed that stomatal apertures are not effected over relatively long time periods.

2. The CH2CT treatment compared fairly well to the WP1 and WP2 treatments in Experiment 2 (wind condition) but grossly overestimated the weighed treatments in Experiment 1. A high level of overestimation was calculated using the simulation model introduced in Chapter 3 which determines transpiration from a single leaf, thus supporting the hypothesis that the sudden increase in wind speed from near zero to 1.0 m/s was significant in causing the dramatic increase in transpiration.

3. The CH2OT treatment was found on the average to exceed the Ch2CT treatment by 10%. It was concluded that the greater amount measured was due to the additional time required in closing the chamber top.

4. Overall leaf canopy temperature changes were increased and were greater for the no-wind experiment and may have contributed slightly to the overestimated ET rates observed.

CHAPTER 6

SUMMARY AND CONCLUSIONS

1. A literature review of the use of field chambers revealed that two distinct chamber techniques exist: instantaneous and noninstantaneous.

2. The physical relationships involved in the canopy energy exchange for a crop enclosed in a portable measurement chamber and their design implications were discussed.

3. A model was developed which simulated the nonsteady state energy balance on a single leaf enclosed in a portable measurement chamber. Variation in the cumulative latent heat production (or transpiration) relative to that produced under initial conditions was shown to be as great as 65%. The nonlinearity of the latent heat transfer over the simulated chamber measurement was shown to be approximately linear when plotted on a cumulative basis. Researchers have assumed that a linear production of water vapor within the chamber meant that a negligible change in ET rate had occurred due to the chamber's presence and therefore their ET estimates were accurate. Examples were given, showing significant estimation error which can occur using this assumption.

4. A portable measurement chamber was designed, constructed and tested in the field.

   a. The design used a thin plastic film called Propafilm C which was found to be ideally suited for the chamber application.

   b. The chamber design included a closable top for the purpose of minimizing disturbance of the crop canopy during chamber placement.

   c. The chamber was tested beside a weighing lysimeter and was found to overestimate ET by 16% relative to the weighing lysimeter.

5. Laboratory experiments were conducted in which statistically based information could be obtained.

a. No significant difference was found between the two mass balance treatments (WP1 and WP2). From these findings it was concluded that stomatal closure did not occur as a result of succesive plant enclosure by the portable chamber.

b. The open top treatment gave higher ET values than did the closed top treatment. The additional build up of water vapor during top closure was hypothesized as the cause.

c. Both chamber treatments seriously overestimated ET for the no-wind experiment. The overestimation observed was found to be due to the large change in wind speed over the plants during the chamber placement.

d. No significant difference was found between the closed top chamber treatment and the mass balance treatments for the wind experiment. The results can be attributed to the similar wind speed which existed inside and outside the chamber.

6. Leaf canopy temperature changes were different just before and during the measurements for the two chamber treatments but overall temperature changes were similar.

CHAPTER 7

RECOMMENDATIONS

1. Further research is needed to determine ways in which the canopy wind velocity and profile can be simulated within the chamber. Wind speed was shown to be a very important factor in controlling the canopy ET rate and therefore wind speed studies appear to be justified.

2. Further research is needed on the open top chamber design. For those researchers who wish to apply the technique in their research, it is my opinion that the open top chamber design should not be used, since the present design tends to increase ET estimation error and also complicates the chamber design and operation.

3. Field tests should be carried out with weighing lysimeters under a variety of environmental conditions with a basic and economical chamber design. The initiation of this research could begin with a national conference with all those who have worked with portable field chambers as participants. A conference of this type might lead to a standard design with which a great deal of information could be obtained by many researchers. At present many designs exist and perforance data is often chamber specific. A standard design would make the chamber technique a practical alternative to researchers throughout the plant sciences.

APPENDIX A

COMPUTER PROGRAM

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*
*
      PROGRAM ENERGY(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C*********************************************************************
C
C       NONSTEADYSTATE ANALYSIS OF A LEAF IN AN ENCLOSED CHAMBER
C
C*********************************************************************
C
C                         GLOSSARY
C*********************************************************************
C
C    NAME          TYPE         UNITS              PURPOSE
C*********************************************************************
C   TDI       VARIABLE          C            INITIAL DRY BULB
C                                            TEMPERATURE
C
C   TWI       VARIABLE          C            INITIAL WET BULB
C                                            TEMPERATURE
C
C   TDF       VARIABLE          C            FINAL DRY BULB
C                                            TEMPERATURE
C
C   TWF       VARIABLE          C            FINAL WET BULB
C                                            TEMPERATURE
C
C   TL        VARIABLE          C            STEADY STATE LEAF
C                                            TEMPERATURE IN FIELD(OR LAB)
C
C   TD        ARRAY(200)        C            DRY BULB AIR TEMPERATURE
C                                            IN CHAMBER
C
C   TW        ARRAY(200)        C            WET BULB TEMPERATURE
C                                            IN CHAMBER
C
C   T         ARRAY(200)        C            TEMPERATURE OF LEAF
C                                            IN CHAMBER
C
C   K         VARIABLE    CAL/CM-MIN-C       THERMAL CONDUCTIVITY
C
C   YR        VARIBL.  CU CM-ATM/K-MOLE      GAS CONSTANT
C
C   L         VARIABLE         CM            LENGTH OF LEAF
C                                            IN DIRECTION OF WIND
C
C   P         VARIABLE        MBARS          ATMOSPHERIC PRESSURE
C
C   SB        VAR.  CAL/SQ CM-K**4-MIN       STEFAN BOLTZMANN CONSTANT
C
C   TCOEF     VARIABLE                       SOLAR TRANSMISSIVITY OF
C                                            CHAMBER COVER
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C
C   CVRIRT   VARIABLE                        LONGWAVE TRANSMISSIVITY
C                                            OF CHAMBER COVER
C
C   R        VARIABLE                        SOLAR REFLECTIVITY
C                                            OF LEAF
C
C   A        VARIABLE                        SOLAR ABSORPTIVITY
C                                            OF LEAF
C
C   EA       VARIABLE                         EMISSIVITY OF THE SKY(OR
C                                             CEILING)
C
C   EIR      VARIABLE                         EMISSIVITY OF THE LEAF
C
C   EIRS     VARIABLE                         EMISSIVITY OF THE
C                                             CHAMBER COVER
C
C   TSE      VARIABLE           C             EFFECTIVE SKY(OR CEILING)
C                                             TEMPERATURE
C
C   RH       VARIABLE                         RELATIVE HUMIDITY
C
C   ERH      VARIABLE                         DUMMY VARIABLE
C
C   RS       VARIABLE     CAL/SQ CM-MIN       SOLAR RADIATION
C
C   RSADJ    VARIABLE     CAL/SQ CM-MIN       SOLAR RADIATION WHICH
C                                             TRAVELS THROUGH THE
C                                             CHAMBER COVER
C
C   RSRCD    VARIABLE     CAL/SQ CM-MIN       SOLAR RAD RECEIVED BY
C                                             THE LEAF IN CHAMBER
C
C   RSRCDF   VARIABLE     CAL/SQ CM-MIN       SOLAR RADIATION RECEIVED
C                                             BY LEAF IN FIELD(OR LAB)
C
C   X        VARIABLE     CAL/SQ CM-MIN       IR COMPONENT FROM SKY(OR
C                                             CEILING)
C                                             RECEIVED BY LEAF IN
C                                             CHAMBER
C
C   XIRAF    VARIABLE     CAL/SQ CM-MIN       IR COMPONENT FROM SKY(OR
C                                             CEILING)
C                                             RECEIVED BY LEAF IN
C                                             IN FIELD(OR LAB)
C
C   XIRS     VARIABLE     CAL/SQ CM-MIN       IR COMPONENT FROM
C                                             CHAMBER COVER RECEIVED
C                                             BY LEAF
C
C  RSABS     VARIABLE     CAL/SQ CM-MIN       TOTAL RADIATION RECEIVED
C                                             BY LEAF IN CHAMBER
C
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C  RSABSF     VARIABLE     CAL/SQ CM-MIN   TOTAL RADIATION RECEIVED
C                                          BY LEAF IN FIELD(OR LAB)
C
C  VCH        VARIABLE        CM/S         AVERAGE WIND VELOCITY IN
C                                          CHAMBER MOVING OVER LEAF
C
C  VF         VARIABLE        CM/S         AVERAGE WIND VELOCITY IN
C                                          THE FIELD(OR LAB) MOVING
C                                          oVER LEAF
C
C  DEL        VARIABLE        CM           AVERAGE THICKNESS OF
C                                          BOUNDARY LAYER ON LEAF
C                                          SURFACE
C
C  DELF       VARIABLE        CM           AVERAGE THICKNESS OF
C                                          BOUNDARY LAYER ON LEAF
C                                          SURFACE IN FIELD(OR LAB)
C
C  RINT       VARIABLE        S/CM         STOMATAL RESISTANCE
C
C  RBL        VARIABLE        S/CM         BOUNDARY LAYER RESISTANCE
C
C  ITIME      VARIABLE                     INDEX FOR TIME ARRAY
C
C  TIME       ARRAY(200)      SEC          TIME
C
C  SLOPETD    VARIABLE        C/S          SLOPE OF WET AND DRY BULB
C                                          TEMPERATURE CURVES
C
C  ROA1       VARIABLE       G/CU CM       VAPOR DENSITY OF THE AIR
C                                          AT FIELD(OR LAB) CONDITIONS
C
C  ROA       ARRAY(200)      G/CU CM       VAPOR PRESSURE OF AIR
C                                          IN CHAMBER
C
C  QS1       VARIABLE      CAL/SQ CM-MIN   SENSIBLE HEAT TRANSFER
C                                          FROM LEAF UNDER
C                                          FIELD(OR LAB) CONDITIONS
C
C  QS        ARRAY(200)    CAL/SQ CM-MIN   SENSIBLE HEAT TRANSFER
C                                          FROM LEAF IN CHAMBER
C
C  QL1       VARIABLE      CAL/SQ CM-MIN   LATENT HEAT TRANSFER
C                                          FROM LEAF UNDER
C                                          FIELD(OR LAB) CONDITIONS
C
C  QL        ARRAY(200)    CAL/SQ CM-MIN   LATENT HEAT TRANSFER
C                                          FROM LEAF IN CHAMBER
C
C  ROL1      VARIABLE      CAL/SQ CM-MIN   VAPOR DENSITY IN LEAF
C                                          STOMATAL CAVITY
C
C  ROL       ARRAY(200)    CAL/SQ CM-MIN   VAPOR PRESSURE IN LEAF
C                                          STOMATAL CAVITY WITHIN
```

```
C                                          CHAMBER
C
C  ET1       VARIABLE   G/CU CM/SQ CM-MIN TRANSPIRATION RATE
C                                          FROM LEAF UNDER
C                                          FIELD(OR LAB) CONDITIONS
C
C  ET        ARRAY(200) G/CU CM/SQ CM-MIN TRANSPIRATION RATE
C                                          OF LEAF IN CHAMBER
C
C  EOL1      VARIABLE         ATM          SATURATED VAPOR
C                                          PRESSURE WITHIN LEAF
C                                          UNDER FIELD(OR LAB)
C                                          CONDITIONS
C
C  EOL       ARRAY(200)       ATM          SATURATED VAPOR PRES-
C                                          SURE WITHIN LEAF IN
C                                          CHAMBER
C
C  E1        VARIABLE         ATM          VAPOR PRESSURE OF THE
C                                          AIR UNDER FIELD(OR LAB)
C                                          CONDITIONS
C
C  E         ARRAY(200)       ATM          VAPOR PRESSURE OF THE
C                                          AIR IN CHAMBER
C
C  AIR       VARIABLE                      FLAG FOR EITHER MOIST
C                                          OR DRY AIR
C
C  F        ARRAY(200)                     DUMMY ARRAY
C
C  DIFO     VARIABLE                       DUMMY VARIABLE
C
C  DIF1     VARIABLE                       DUMMY VARIABLE
C
C
C*******************************************************************
      DIMENSION E(200),EO(200),RNET(200),EOL(200),T(200),QS(200)
      DIMENSION QL(200),ROA(200),ROL(200),TD(200),TW(200),XIRU(200)
      DIMENSION ET(200),TIME(200),F(200),EOW(200)
      DIMENSION RELH(200)
      REAL XIRAA,XIRAF X,XIRS,K,L
* INITIALIZE VARIABLES
*
      K=3.37E-3
      L=8.0
      YR=82.05
      P=1000.0
      SB=8.13E-11
      TCOEF=0.89
      R=0.22
      A=0.78
      EA=0.97
      EIR=0.97
      EIRS=0.250
```

```
      TSE=2.0
      CVRIRT=0.75
*
**********************************************************************
*               DATA INPUT SECTION
**********************************************************************
*
      PRINT*,'INTITIAL DRY BULB TEMPERATURE (C)'
      READ *,TDI
*
*
      PRINT*,'FINAL DRY BULB TEMPERATURE (C)'
      READ *,TDF
*
      PRINT*,'ENTER INITIAL WET BULB TEMPERATURE'
      READ*,TWI
      PRINT*,'ENTER FINAL WET BULB TEMPERATURE(C)'
      READ*,TWF
      PRINT*,'ENTER EFFECTIVE SKY(OR CEILING) TEMPERATURE'
      READ*,TSE

*GENERATE LINEAR EQUATIONS FOR TEMP WITH TIME
*
      SLOPETD=(TDF-TDI)/36.0
      SLOPETW=(TWF-TWI)/36.0
*
*THE INTERCEPTS FOR THE EQUATIONS ARE THE INITIAL TEMPS
*
      PRINT*,'SOLAR RADIATION'
      READ *,RS
*
**********************************************************************
*                  OPTIONAL INPUT SECTION
**********************************************************************
*
      PRINT*,'DO YOU WANT THE TOTAL INPUT OPTION?'
      READ(5,*)IN
      IF(IN.EQ.1)THEN
      PRINT*,'COVER TRANS. COEF FOR SOLAR RAD.'
      READ *,TCOEF
*
*ENTER CROP REFLECTIVITY AND ABSORPTIVITY FOR
*SOLAR RADIATION
*
      PRINT*,'REFLECTIVITY AND ABSORPTIVITY FOR SOLAR RAD'
      READ *,R,A
*
*ENTER EFFECTIVE SKY(OR CEILING) TEMPERATURE IN DEGREES C
*EMISSIVITY OF ATMOSPHERE AND IR TRANSMISSION
*COEFFICIENT FOR THE CHAMBER COVER
*
      PRINT*,'EFF SKY(OR CEILING) TEMP, EMIS OF ATM AND TRANS COEF OF CO
     +VER'
      READ *,TSE,EA,CVRIRT
```

```
*
* ENTER EMISSIVITY OF THE PLANT MATERIAL
*
      PRINT*,'PLANT EMISSIVITY '
      READ *,EIR
*
*ENTER EMISSIVITY OF THE LOCAL ENVIRONMENT
*
      PRINT*,'EMISSIVITY OF SURROUNDINGS'
      READ *,EIRS
*
*THE ABOVE CALCULATION IS BASED ON THE INITIAL
*DRY BULB TEMPERATURE
*
*ENTER AVE WIND VELOCITY AT A HEIGHT OF 1M
*IN THE FIELD(OR LAB) AND IN THE CHAMBER
*
      END IF
      PRINT*,'VFIELD(OR LAB),VCHAMBER'
      READ *,VF,VCH
*
      DO 6161 I40=1,4
*
*******************************************************************
*                    RADIATION CALCULATIONS
*******************************************************************
*
*CALCULATION OF THE SOLAR RADIATION WHICH TRAVELS
*THROUGH THE COVER
      RSADJ=RS*TCOEF
*CALCULATE SOLAR RAD RECIEVED BY THE LEAF
*IN CHAMBER
      RSRCD=RSADJ*A*(1.0+R)
*CALCULATE VALUE OF SOLAR RAD RECIEVED
*BY LEAF NOT UNDER CHAMBER
      RSRCDF=RS*A*(1.0+R)
*CALCULATION OF IR COMPONENT FROM SKY(OR CEILING)
*RECEIVED BY LEAF IN CHAMBER
      X=EA*SB*CVRIRT*((TSE+273.15)**4.0)
*CALCULATE THE IR COMPONENT FROM SKY(OR CEILING) RECIEVED
*BY A LEAF NOT UNDER THE CHAMBER
      XIRAF=X/CVRIRT
*CALCULATION OF IR FROM SURROUNDINGS
*WHERE SURROUNDING SURFACES ARE AT TDI
      XIRS=EIRS*SB*((TDI+273.15)**4.0)
*CALCULATION OF RADIATION ABSORBED BY LEAF
*IN CHAMBER
      RSABS=RSRCD+X+XIRS
*CALCULATION OF TOTAL RAD ABSORBED BY THE
*LEAF NOT UNDER THE CHAMBER
      RSABSF=RSRCDF+XIRAF
*
*******************************************************************
*THIS PORTION OF THE PROGRAM PRINTS OUT ALL DATA BEING USED
```

```
*AND THE RESULTS OF ANY CALCULATIONS
****************************************************************************
          PRINT*,' '
          PRINT*,' '
          PRINT*,' '
      PRINT*,'INITIAL DRY BULB TEMPERATURE=',TDI
      PRINT*,'FINAL DRY BULB TEMPERATURE=',TDF
      PRINT*,'INITIAL WET BULB TEMPERATURE=',TWI
      TWF=36.0*SLOPETW+TWI
      PRINT*,'FINAL WET BULB TEMPERATURE=',TWF
      PRINT*,' '
      PRINT*,'LINEAR TEMPERATURE EQUATIONS:'
      WRITE (6,26) TDI,SLOPETD
26    FORMAT ("1","TD=",F6.2,"+(",F8.5,") *TIME")
      WRITE (6,27) TWI,SLOPETW
27    FORMAT ("0","TW=",F6.2,"+(",F8.5,") *TIME")
      WRITE (6,28) RS
28    FORMAT ("0","RS=",F6.2)
      WRITE (6,29) TCOEF
29    FORMAT ("0","CHAMBER SOLAR TRANS COEF=",F6.2)
      WRITE (6,30) RSADJ
30    FORMAT ("0","RS THROUGH COVER =",F6.2)
      WRITE (6,31) A
31    FORMAT ("0","SOLAR ABSORPTIVITY OF LEAF=",F6.2)
      WRITE (6,32) R
32    FORMAT ("0","REFLECTIVITY OF PLANT MATERIAL=",F6.2)
      WRITE (6,88) RSRCDF
88    FORMAT ("0","SOLAR RAD ABSORBED BY LEAF IN FLD",F6.2)
      WRITE (6,33) RSRCD
33    FORMAT ("0","SOLAR RAD RECIEVED BY LEAF IN CHAMBER=",F6.2)
      WRITE (6,34) TSE
34    FORMAT ("0","EFFECTIVE SKY(OR CEILING) TEMP=",F6.2)
      WRITE (6,35) EA
35    FORMAT ("0","THE EMISSIVITY OF THE ATMOSPHERE=",F6.2)
      XIRAA=X/CVRIRT
      WRITE (6,36) XIRAA
36    FORMAT ("0","IR FROM SKY(OR CEILING) ABSORBED BY LEAF IN
     +FIELD (OR LAB)=",F6
     +.2)
      WRITE (6,37) CVRIRT
37    FORMAT ("0","TRANS COEF FOR THE CHAMBER COVER=",F6.2)
      WRITE (6,38) X
38    FORMAT ("0","IR RAD FROM SKY(OR CEILING) ABSORBED BY LEAF
     +IN CHAMBER =",F6.2)
      WRITE (6,39) EIRS
39    FORMAT ("0","EMISSIVITY OF CHAMBER COVER=",F6.2)
      WRITE (6,40) XIRS
40    FORMAT ("0","IR ABSORBED BY LEAF FROM CHAMBER COVER=",F6.2)
      WRITE (6,41) RSABS
41    FORMAT ("0","TOTAL RAD ABSORBED BY LEAF IN CHAMBER=",F6.2)
      WRITE (6,102) RSABSF
102   FORMAT ("0","TOT RAD ABSORBED BY LEAF IN FIELD(OR LAB)",F6.2)
      WRITE (6,42) VF
42    FORMAT ("0","AVERGE WIND VELOCITY IN FIELD(OR LAB)=",F6.2)
```

```
      WRITE(6,43)VCH
43    FORMAT("0","AVERAGE WIND VELOCITY IN CHAMBER=",F6.2)
      PRINT*,'LEAF LENGTH IN THE DIRECTION OF AIR MOVEMENT    ',L
      DEL=0.4*((L/VCH)**0.5)
      DELF=0.4*((L/VF)**0.5)
      WRITE(6,44)DELF
44    FORMAT("0","AVE BOUNDARY LAYER IN FIELD(OR LAB)=",F6.2)
      WRITE(6,45)DEL
45    FORMAT("0","AVE BOUNDARY LAYER IN CHAMBER=",F6.2)
      WRITE(6,46)
46    FORMAT("1"," ")
************************************************************************
*         DETERMINATION OF STEADYSTATE ENERGY BALANCE
*            IN FIELD(OR LAB) PRIOR TO CHAMBER PLACEMENT
************************************************************************
      CALL STEADY(TL,YR,DELF,K,D,ROA1,SB,EIR,RSABSF, QS1,QL1,
     +ROL1,RNET1,ET1,EOL1,E1,EO1,TDI,TWI,P,AIR)
      RH=E1/EO1*100.0
      ROA(1)=ROA1
      QS(1)=QS1
      QL(1)=QL1
      ROL(1)=ROL1
      RNET(1)=RNET1
      ET(1)=ET1
      E(1)=E1
      EO(1)=EO1
      TD(1)=TDI
      TW(1)=TWI
      DO 773 I=1,200
      RELH(I)=RH
      T(I)=TL
      F(I)=TL
773   CONTINUE
      ITIME=0
      TIME(1)=0.0
      DO 96 ITER=1,500
      DIFO=0.0
      DO 1 ITIME=2,144
      TIME(ITIME)=TIME(ITIME-1)+0.25
************************************************************************
*         DETERMINATION OF NONSTEADYSTATE ENERGY BALANCE
*               OVER PERIOD OF CHAMBER MEASUREMENT
************************************************************************
*CALCULATE THE TEMPERATURES AT TIME ITIME
*
      TD(ITIME)=TDI+SLOPETD*TIME(ITIME)
      TW(ITIME)=TWI+SLOPETW*TIME(ITIME)
*
*DETERMINE THE SATERATED VAPOR PRESS OF THE AIR
*
      CALL SATVP(TW(ITIME),EOW(ITIME),ITIME)
*
      EOW(ITIME)=EOW(ITIME)*(1.3329)
*DETERMINE THE VAPOR PRESSURE OF THE AIR EA
```

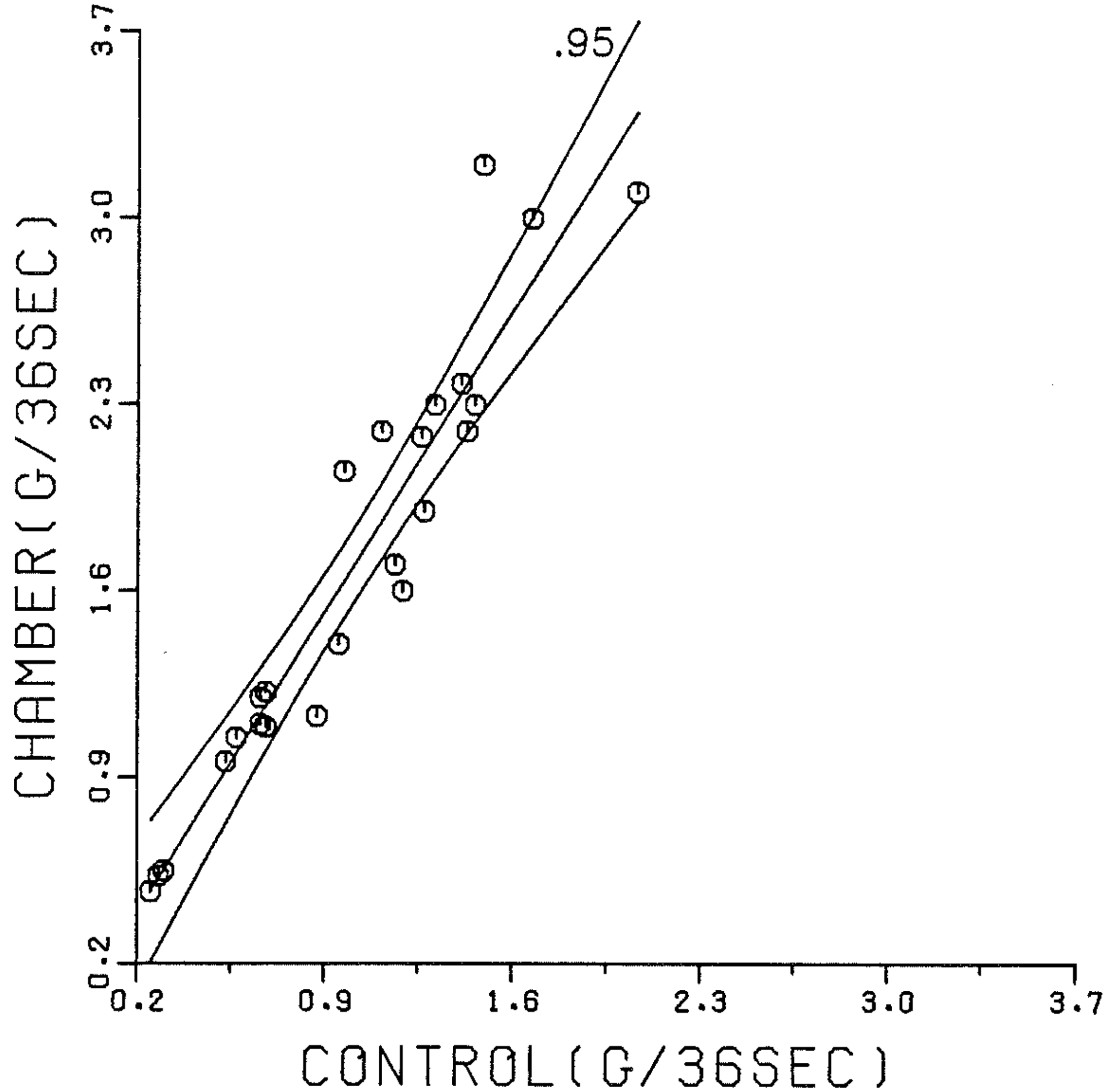
```
*
      CALL VAPRES(TD(ITIME),TW(ITIME),P,EOW(ITIME),E(ITIME))
      EOW(ITIME)=EOW(ITIME)/1013.0
      E(ITIME)=E(ITIME)/1013.0
      ROA(ITIME)=18.0*E(ITIME)/YR/(273.15+TD(ITIME))
*
      CALL SATVP(TD(ITIME),EO(ITIME))
      EO(ITIME)=EO(ITIME)/760.0
      RH=E(ITIME)/EO(ITIME)*100.0
*
      RELH(ITIME)=RH
      AIR=1.
      IF(RH.GE.50.0)THEN
      AIR=2.0
      END IF
* CALCULATION OF LATENT HEAT TRANSFER
      CALL LATENT(T,YR,DEL,K,D,ROA,SB,EIR,RSABS, QS,QL,
     +ROL,RNET,ET,EOL,E,TD,ITIME,AIR)
      DIF1=ABS(T(ITIME)-F(ITIME))
      F(ITIME)=T(ITIME)
      IF(DIF1.GT.DIFO)DIFO=DIF1
1     CONTINUE
      IF(DIFO.LT.0.01)GOTO 81
96    CONTINUE
81    CONTINUE
      PRINT*,'DIFO=',DIFO
      PRINT*,'ITER=',ITER
*********************************************************************
*                    OUTPUT ROUTINE
*********************************************************************
      WRITE(6,1919)
1919  FORMAT('0','TIME',T10,'TL',T18,'TD',T29,'TW',T39,'RNET',
     +T49,'QS',T59,'QL',T69,'RH')
      DO 11 M=1,144
      WRITE(6,1920)TIME(M),T(M),TD(M),TW(M),RNET(M),QS(M),QL(M),
     +RELH(M)
1920  FORMAT('0',F3.0,T9,F5.2,T18,F5.2,T28,F5.2,T37,
     +F6.3,T47,F6.3,T57,F6.3,T67,F5.2)
11    CONTINUE
      VCH=VCH+50.0
6161  CONTINUE
      STOP
      END
      SUBROUTINE LATENT(T,YR,DEL,K,D,ROA,SB,EIR,RSABS, QS,QL,
     +ROL,RNET,ET,EOL,E,TD,ITIME,AIR)
*********************************************************************
*
* SUBROUTINE LATENT PERFORMS AN ENERGY BALANCE ON THE LEAF
*             FOR A GIVEN POINT IN TIME
*********************************************************************
      DIMENSION EOL(200),T(200),ROA(200),QS(200),QL(200),
     +F(200),XIRU(200)
      DIMENSION ROL(200),RNET(200),TIME(200),
     +ET(200),E(200),TD(200)
```

```
      REAL K
      EOL(ITIME)=2.7182**((21.07-(5336.0/(273.15+T(ITIME)))))
      EOL(ITIME)=EOL(ITIME)*0.00131
      ROL(ITIME)=18.0*EOL(ITIME)/(YR*(T(ITIME)+273.15))
      RBL=DEL/14.4
      CALL INTERNR(T(ITIME),AIR,RINT)
      QL(ITIME)=(-2.0)*580.0*(ROA(ITIME)-ROL(ITIME))/(RBL+RINT)
      QS(ITIME)=2.0*(-K)*(TD(ITIME)-T(ITIME))/DEL
      XIRU(ITIME)=EIR*SB*((T(ITIME)+273.15)**4.0)
      RNET(ITIME)=RSABS-XIRU(ITIME)
      T(ITIME)=T(ITIME-1)+(RNET(ITIME)-QS(ITIME)-QL(ITIME)
     +)*0.0042
     +/1.025/0.956*50.0
      ET(ITIME)=QL(ITIME)/580.0
      QS(ITIME)=-QS(ITIME)
      QL(ITIME)=-QL(ITIME)
      RETURN
      END
      SUBROUTINE SATVP(TD,EO)
********************************************************************
*          SUBROUTINE SATVP CALCULATES SATURATED
*                    VAPOR PRESSURE
********************************************************************
      EO=2.7182**((21.07-(5336.0/(273.15+TD))))
      RETURN
      END
      SUBROUTINE VAPRES(TD,TW,P,EO,E)
********************************************************************
*               SUBROUTINE VAPRES CALCULATES
*                    VAPOR PRESSURE
*********************************************************************
      E=EO-(0.00066)*(P)*(TD-TW)
     +*(1.0+(0.00115*TW))
      RETURN
      END
      SUBROUTINE STEADY(TL,YR,DELF,K,D,ROA,SB,EIR,RSABSF,QS
*********************************************************************
*            SUBROUTINE STEADY PERFORMS A STEADYSTATE
*                 ENERGY BALANCE ON THE LEAF
*********************************************************************
     +,QL,ROL,RNET,ET,EOL,E,EO,TDI,TWI,P,AIR)
      REAL K
      CALL SATVP(TWI,EOW)
*
      EOW=EOW*(1.3329)
*DETERMINE THE VAPOR PRESSURE OF THE AIR EA
*
      CALL VAPRES(TDI,TWI,P,EOW,E)
      EOW=EOW/1013.0
      E=E/1013.0
      ROA=18.0*E/YR/(273.15+TDI)
*
      CALL SATVP(TDI,EO)
      EO=EO/760.0
```

```
      AIR=1.0
      RH=E/EO*100.0
      IF(RH.GE.50.0)THEN
      AIR=2.0
      END IF
      TP=5.0
      TL=5.0
*
      FUNC=1.0
      DO 321 III=1,50000
      IF(FUNC.LT.0)THEN
      TL=TL-5.0
      TP=.01
      END IF
      TL=TL+TP
      CALL LATSTED(TL,YR,DELF,K,D,ROA,SB,EIR,RSABSF, QS,QL,FUNC,
     +ROL,RNET,ET,EOL,E,TDI,TWI,P,AIR)
      IF(ABS(FUNC).LT.0.01)GOTO 345
321   CONTINUE
345   CONTINUE
      RETURN
      END
      SUBROUTINE LATSTED(T,YR,DELF,K,D,ROA,SB,EIR,RSABSF, QS,QL,FUNC,
     +ROL,RNET,ET,EOL,E,TDI,TWI,P,AIR)
      REAL K,XIRU
      EOL=2.7182**((21.07-(5336.0/(273.15+T))))
      EOL=EOL*0.001316
      ROL=18.0*EOL/(YR*(T+273.15))
      QS=(-K*2.0)*(TDI-T)/DELF
      RBL=DELF/14.4
      CALL INTERNR(T,AIR,RINT)
      QL=(-2.0)*580.0*(ROA-ROL)/(RBL+RINT)
      XIRU=EIR*SB*((T+273.15)**4.0)
      RNET=RSABSF-XIRU
      FUNC=RNET-QS-QL
      QL=-QL
      QS=-QS
      ET=QL/580.0
      RETURN
      END
      SUBROUTINE INTERNR(T,AIR,RINT)
**************************************************************************
*           SUBROUTINE INTERNR CALCULATTES THE INTERNAL
*           DIFFUSION RESISTANCE FOR A GIVEN TEMPERATURE
*
*           NOTE: THE INTERNAL DIFFUSION RESISTANCE CAN
*           BE SET EQUAL TO A CONSTANT (AS WAS THE CASE IN
*           THE RUNS MADE SHOWN IN CHAPTERS 3 AND 5) OR
*           AN EXPRESSION CAN BE USED FOR ITS CALCULATION.
*           WHICH EVER WAY IS USED MUST BE DECIDED BY THE
*           USER AND APPROPRIATE MODIFICATIONS DONE.
*           THE SUBROUTINE AS SHOWN SETS THE INTERNAL
*           DIFFUSION RESISTANCE EQUAL TO .055 MIN/CM.
**************************************************************************
```

```
      IF(AIR.EQ.2.0)THEN
*
*  THE EQUATIONS BELOW WERE GIVEN FOR XANTHIUM BY DRAKE ET AL.(1970)
*
*   FOR "WET" AIR USE THIS EQUATION
      RINT=0.292+0.1397*T-0.00342*(T**2.0)
      ELSE
*   FOR "DRY" AIR USE THIS EQUATION
      RINT=7.95-0.18*T
      END IF
      RINT=RINT/60.0
      RINT=.055
      RETURN
      END
*
*
*
```

APPENDIX B



Calibration curve for the chamber for use with experimental data from Experiments 1 and 2.

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