COMPARISON OF TECHNIQUES FOR MEASURING LEAF DIFFUSION RESISTANCE

by

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ABSTRACT

Two methods currently used for leaf diffusion resistance measurement were studied. One of them, the Leaf Resistance Meter (van Bavel et al. 1965), had both the apparatus and the calibration technique modified. The other, the Air Flow System (Bierhuizen and Slatyer, 1964) was simplified in order to make it suitable for field use.

Leaf resistance of Red Kidney Bean (Phaseolus vulgaris L.) plants, growing in a greenhouse for a salt tolerance experiment, was measured simultaneously by the two methods. The two sets of data were not highly correlated but gave some qualitative indications of differences in behavior among three different bean plants. However, the experimental data have been considered insufficient to draw any definitive conclusion.

The Leaf Resistance Meter has been recommended for use in field conditions because it is portable, simple and inexpensive.

The Air Flow System is recommended for use under controlled conditions, at least until more and better data are available for the analysis of its behavior in field conditions.

CHAPTER 1

INTRODUCTION

The need of water in the world is increasing year after year. The "population explosion" brings about a greater need for water and foods. People use water directly. On the other hand, we may say that all the food people eat is the result of plant metabolic processes. These facts lead us to conclude that the "population explosion" means more and more need for water.

Precipitation is the main source of water for the land, and about 71% of this water goes back to the atmosphere through evapotranspiration from the soil-plant system (Waggoner and Zelitch, 1965). This amount of water exceeds the requirements of the plant metabolic processes. Hydrologists classify this excessive evapotranspiration as a "Loss" (Lee, 1967).

In the last few years a great effort has been made attempting to decrease plant transpiration; see, for example, Waggoner and Zelitch (1965), Slatyer and Bierhuizen (1964b).

Transpiration is part of a physical process in which the critical step is the transfer of water vapor from the mesophyll to the atmosphere over the leaf surface, through

the leaf stomata (van den Honert, 1948). Waggoner and Zelitch (1965) point out that most of the variations in transpiration may be linearly correlated with stomatal behavior, the reciprocal of the transpiration being directly proportional to stomatal resistance.

Transpiration also takes place through the cuticle, but stomatal resistance is much smaller than cuticular resistance (Slatyer and Bierhuizen, 1964a). Cuticular and stomatal resistances to transpiration are connected in parallel, and the reciprocal of the leaf resistance is the sum of the reciprocals of its two components, with the leaf resistance slightly smaller than the stomatal resistance (Slatyer and Bierhuizen, 1964a).

Leaf resistance may be calculated from the degree of stomatal aperture, but this does not give an exact estimate (van Bavel, Nakayama, and Ehrler, 1965).

For direct measurement of leaf resistance, two different approaches have been used. Gaastra (1959) and van Bavel et al. (1965) used techniques based upon measurement of vapor flow from the leaf to the atmosphere. Raschke (1960) used a technique in which heat flow from the leaf to the atmosphere was measured. Using these methods, the measured leaf resistance is the integrated result of the transpiration control by all of the anatomical and morphological characteristics of the leaf.

Raschke's method is not simple, nor always practical (van Bavel et al., 1965). Gaastra's method requires control of the environmental conditions. Thus, van Bavel's method is the only one reliable for field work.

The objective of the present research is to introduce some modifications both in the van Bavel et al. (1965) and Bierhuizen and Slatyer (1964) methods and, finally, to compare their performances for leaf resistance measurement in field conditions.

CHAPTER 2

THE LEAF RESISTANCE METER (LRM)

The use of relative humidity sensors for estimating stomatal apertures originated with Wallihan (1964). Van Bavel et al. (1965) improved the Wallihan system introducing changes in the apparatus and in the calibration procedures. The present paper describes additional modifications that have been made on the leaf resistance meter as described by van Bavel et al. (1965). The leaf resistance is calculated by comparing the transpiration rate from a leaf with the evaporation rate from a blotter at the same temperature. The reduction in the vapor transport observed over the leaf is attributed to the resistance the leaf offers to water vapor diffusion.

2.1 The van Bavel Leaf Resistance Meter Construction

The sensor of the van Bavel et al. (1965) Leaf Resistance Meter (Figure 1) is enclosed in a sensing chamber made of plexiglas tubing which has a cross sectional area of 2.84 cm^2. The cup is held against the leaf by a spring clamp (0.75 psi of pressure) which operates in a similar manner to a clothes pin. Sponge rubber around the cup and on the other side of the clamp insures an air-tight fit against the

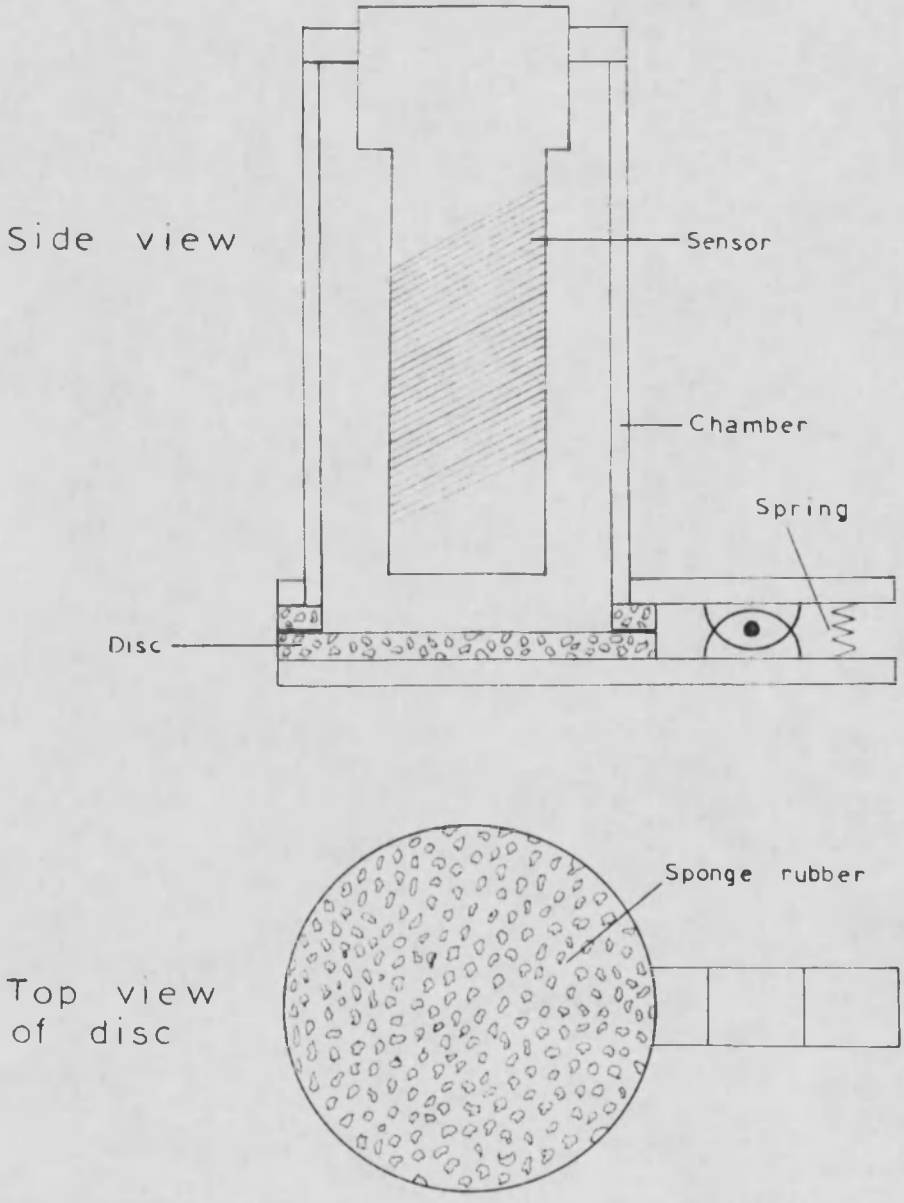


Figure 1. Diagram of van Bavel et al. (1965) Leaf Resistance Meter.

leaf. The sensor element is a narrow range lithium chloride humidity sensor manufactured by Amico-Dunmore (#4-4817) which is connected in series with a power supply and ohmmeter. Changes in the ambient relative humidity produce condensation or evaporation from the thin lithium chloride film which in turn causes the resistance of the element to change in a predictable manner. The sensing unit is placed in contact with an evaporating or transpiring surface, and the time required for the meter reading to change from .20 to .60 of full scale is recorded. This value is called the transit time (Δt).

2.2 Modified Leaf Resistance Meter Construction

The van Bavel et al. (1965) Leaf Resistance Meter has a foam rubber disc which, in field use, covers the top surface of the leaf opposite the surface exposed to the sensor. This covering of the leaf promotes cooling during the time of the observation. Ansari and Loomis (1959) showed that leaf temperature can drop as much as 8°C in less than a minute after shading. Therefore, the sensor was modified so that the portion of the leaf opposite the sensor was not shaded. The disc holding the leaf against the sensor was changed to a ring. The temperature of the sensor is measured by a thermistor inside the cup, close to the sensing unit. The leaf temperature is measured by a

Fenwal GA55P2 thermistor. This thermistor is insulated as recommended by Lange (1965) and inserted into the sensing unit tubing. The sensitive tip of the thermistor is held against the leaf by the pressure of a foam sponge ring.

2.3 Theoretical Considerations

The evaporation rate of water vapor from a surface where the primary mechanism for the removal of vapor is molecular diffusion is described by:

$$E = D \frac{\Delta \rho}{\Delta z} \tag{1}$$

Where E = Evaporation rate (g cm^{-2} sec^{-1}).

ρ = Water vapor density (g cm^{-3}).

Δz = Vertical distance above the surface (cm).

D = Molecular diffusivity of water vapor in air (cm^2 sec^{-1}).

The ratio $\frac{\Delta z}{D}$ is defined as the resistance of the air to the diffusion of water vapor and is denoted by R_A (sec cm^{-1}). Equation (1) can be rewritten as:

$$E = \frac{\Delta \rho}{R_A} \tag{2}$$

When the water vapor transpired by a leaf is primarily being removed by molecular diffusion, it is possible to write an equation similar to equation (2). However, it is necessary to add the resistance the leaf offers to water vapor

diffusion, which is called the leaf resistance and is denoted by R_L. The equation describing transpiration rate, T, can be written:

$$T = \frac{\Delta\rho}{R_A + R_L} \tag{3}$$

The sum of $R_A + R_L$ is referred to as the total resistance and is denoted by R_T. Thus:

$$R_T = R_A + R_L \tag{4}$$

It is possible to combine equations (2) and (3) for an evaporating surface and a leaf at the same temperature and environmental conditions to solve for R_L. But, to calculate the leaf resistance in this manner, it is necessary to know the vapor density at the surface and at a distance, z, above the surface, the transpiration rate, and the evaporation rate. Since all of these parameters are seldom known simultaneously, it is usually necessary to calculate the leaf resistance by another method.

2.4 Calibration Techniques

A. van Bavel et al. Technique

The method employed by van Bavel et al. (1965) is based on equation (4). If equation (4) is solved for R_L and if both sides of the equation are multiplied and divided by D, we obtain:

$$R_L = R_T - R_A = \frac{L_T - L_A}{D} \quad (5)$$

where L_T = Total resistance expressed in units of length of diffusion path (cm).

L_A = Air resistance expressed in units of length of diffusion path (cm).

Using the apparatus previously described, the transit time, Δt(sec), is recorded when the sensing cup is exposed to a wet blotter. The diffusion path, L, is lengthened by imposing cylinders of increasing lengths between the surface and the bottom of the sensing cup. The results are similar to those shown in Figure 2.

The relationship between transit time and diffusion path length is determined for a series of temperatures. Thus, when the sensing unit is exposed to leaves of a given temperature, the transit time observed can be converted to equivalent diffusion path length units. This is usually done by defining S as the reciprocal of the slope of the line, Δt vs. L. When S is multiplied by Δt, the observed transit time, the total resistance in diffusion path length units is obtained. By extrapolating the line till it intersects the abscissa, one can obtain the diffusion path length corresponding to a transit time of zero. The distance between the zero on the abscissa scale and the point of intersection is

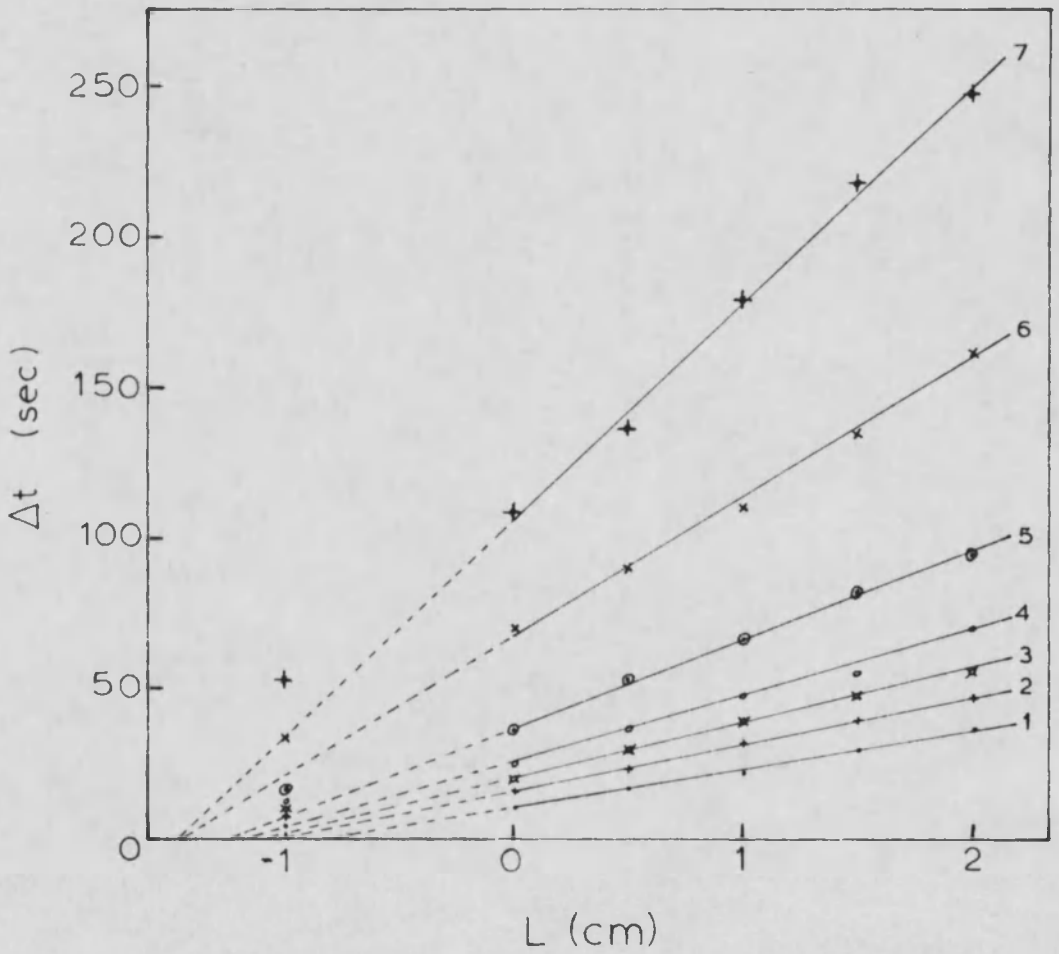


Figure 2. Regression Lines for LRM Calibration. (L is Length of Spacer and Δt is the Transit Time).

denoted by L_o. The equation of this straight line can be written as:

$$L = S\Delta t - L_o \tag{6}$$

When the transit time is obtained by exposing the sensor to a leaf, L is equal to L_T. From Figure 2 one can see that when the sensor is exposed to a blotter paper with no spacer inserted, $L = L_A = 0$. This means that the air diffusion resistance is equal to zero. Since we are only interested in the difference between L_T and L_A, this is permissible. Therefore, the equation used by van Bavel to calculate leaf resistance is:

$$R_L = \frac{S\Delta t - L_o}{D} \tag{7}$$

In practice, the transit time is recorded with the sensor exposed to the bottom of the leaf. L_o was found to be a constant by van Bavel et al. (1965) and equal to 0.72 cm. The appropriate values of S and D are determined by the air temperature. When these values are substituted into equation (7), the leaf resistance can be calculated.

B. Modified Calibration Procedure

The use of the Leaf Resistance Meter system calibrated according to the procedure described in the preceding section is limited to those cases when the leaf temperature is equal to the air and sensor temperature. This limitation is not

as inhibiting to the original system as it might first seem, since the leaf surface opposite the sensing cup is shaded and thus will have a temperature near the ambient temperature. However, in the modified system, the leaf surface is not covered; therefore, it may have a temperature different than the ambient air or sensor temperature. Thus, it was necessary to calibrate the modified Leaf Resistance Meter for several combinations of surface and sensor temperatures. The evaporating surface was an analytical filter paper held over a screen and in contact with the surface of the water in a water bath. The meter was calibrated from seven combinations of surface and sensor temperatures. More than sixty trials were run. The surface temperature was varied between 18.2° and 42.4°C, and the sensor temperature changed between 23.6 and 25.8°C. The transit time was measured for each temperature combination with cylinders from 1.0 to 3.0 cm long imposed between the surface and the top of the sensor cup. From these data regression lines were drawn for the five combinations of surface and sensor temperatures. The results are shown in Figure 2 and Table I. The data for points below 1.0 cm were eliminated in the calculation of the regression line, since the 1.0 cm spacer was permanently attached to the cup.

TABLE I

Experimental and Calculated Data for the LRM Calibration

Regression line	Surface temp. °C	Sensor temp. °C	r	$D \cdot \Delta\rho \times 10^{-6}$ (g cm^{-1} sec^{-1})	$S/D \times 10^{-3}$ (cm^{-1})	Δt_o (sec)
1	42.4	25.8	0.984	15.2	261.7	9.4
2	38.5	24.5	0.996	12.2	235.4	16.1
3	33.4	24.9	0.991	9.1	193.5	19.6
4	29.6	24.6	0.986	7.2	166.6	24.4
5	24.6	24.2	0.988	5.1	123.0	37.2
6	20.0	23.7	0.990	3.6	77.0	67.2
7	18.2	23.6	0.983	3.2	49.1	105.4

The parameters needed to calculate R_L could not be specified by a single temperature. Therefore, it was necessary to develop another way to use the calibration for field determinations of leaf resistance. The most useful relationships after exploring many possibilities were obtained when the system was specified by the product between the diffusivity (D) at the sensor temperature and the vapor concentration gradient, $\Delta\rho$ calculated from the sensor temperature, the surface temperature, and the average relative humidity in the chamber during the transit time reading. For the latter, the relative humidity corresponding to a reading of .40 full scale of the ohmmeter was used, taking into account the temperature of the sensor by using Figure 3.

2.5 Measuring Leaf Resistance with the Modified LRM

For taking measurements of leaf resistance, the sensing cup is attached to the leaf with the open end on the lower surface. Then the following steps are taken:

a. The sensor is dried by passing dried air through the side vent. A piece of dry filter paper is clamped into position over the end of the cup to prevent ambient air from entering.

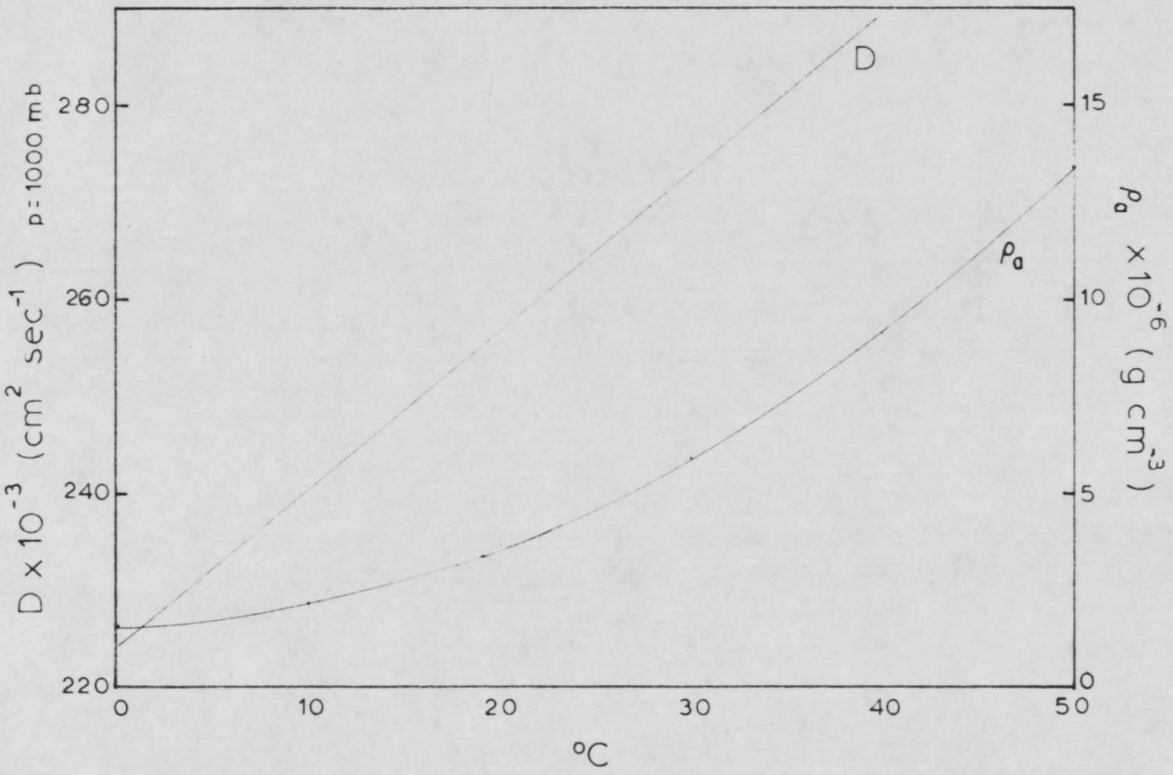


Figure 3. Water Vapor Diffusivity (D) and Actual Vapor Concentration (ρ_a) as a Function of the Air Temperature (°C).

b. The filter paper is removed and replaced by an undetached leaf.

c. The transit time is recorded.

d. Immediately the leaf and sensor temperatures are read.

The method of utilizing these data to calculate the leaf resistance has also been revised. Referring back to Equation (6) one can see that the value of the air resistance for a particular environment, specified by $\Delta\rho$, is found when the observed transit time, Δt_o, over the blotter paper is substituted into equation (6). Thus:

$$L_A = S\Delta t_o - L_o \tag{8}$$

Similarly when the transit time measured over a leaf, Δt_m, also under the same environmental conditions, is substituted into equation (6) one obtains the L value corresponding to the total resistance (air + leaf). Thus:

$$L_T = S\Delta t_M - L_o \tag{9}$$

Subtracting (8) from (9) and dividing by D we obtain:

$$R_L = \frac{L_T - L_A}{D} = \frac{S(\Delta t_M - \Delta t_o)}{D} \tag{10}$$

Equation 10 was used to calculate the leaf resistance values shown in Table II in the following manner:

TABLE II

Experimental R_L and Leaf Temperature (°C) Values for Red Kidney Plants (Phaseolus vulgaris L.) - December 7, 1967

MST	RL LRM	RL AFS	Leaf Temp. LRM	Leaf Temp. AFS	MST	RL LRM	RL AFS	Leaf Temp. LRM	Leaf Temp. AFS
7:15	4.4	8.4	14.7	15.6	13:37	14.8	9.9	27.9	26.5
7:30	6.5	5.7	15.8	14.1	13:50	8.9	10.4	26.5	25.3
7:45	9.3	15.7	17.4	16.0	14:00	9.1	8.3	26.0	25.7
8:50	12.7	11.8	18.6	17.4	14:43	14.4	18.4	26.0	26.9
9:05	9.7	7.7	21.7	18.2	14:55	10.9	10.8	27.9	26.8
9:20	10.9	13.6	20.9	21.1	15:06	7.5	9.5	27.9	26.2
10:20	8.0	17.0	31.7	28.0	15:45	13.6	14.9	34.3	26.9
10:30	7.7	22.3	29.9	30.8	15:56	9.4	5.4	29.7	27.2
10:45	5.0	7.7	29.9	30.5	16:10	10.6	6.6	26.5	26.1
11:00	7.8	15.7	33.7	32.7	16:30	13.3	11.8	31.2	26.3
11:20	4.9	8.8	31.7	30.9	16:45	13.3	9.3	27.9	24.9
11:30	5.6	7.6	28.8	29.0	17:00	16.4	7.0	24.3	23.2
12:45	11.1	14.7	31.7	20.7	18:30	7.2	7.7	14.7	15.1
13:05	7.0	3.5	24.6	27.7	18:45	15.6	13.1	16.2	16.3
13:20	6.8	4.5	26.0	25.6	19:00	12.8	6.7	17.8	15.5

a. D $\Delta\rho$ was calculated through the use of Figure 3 and the value of ρ_s was taken from meteorological tables (List, 1958). The value of D from Figure 3 is corrected to the local barometric pressure.

b. From Figure 4, the appropriate values of $\frac{S}{D}$ and Δt_o were determined.

c. Substituting these values plus the measured value of the transit time over the leaf, Δt_M, into equation (10), the leaf resistance was calculated.

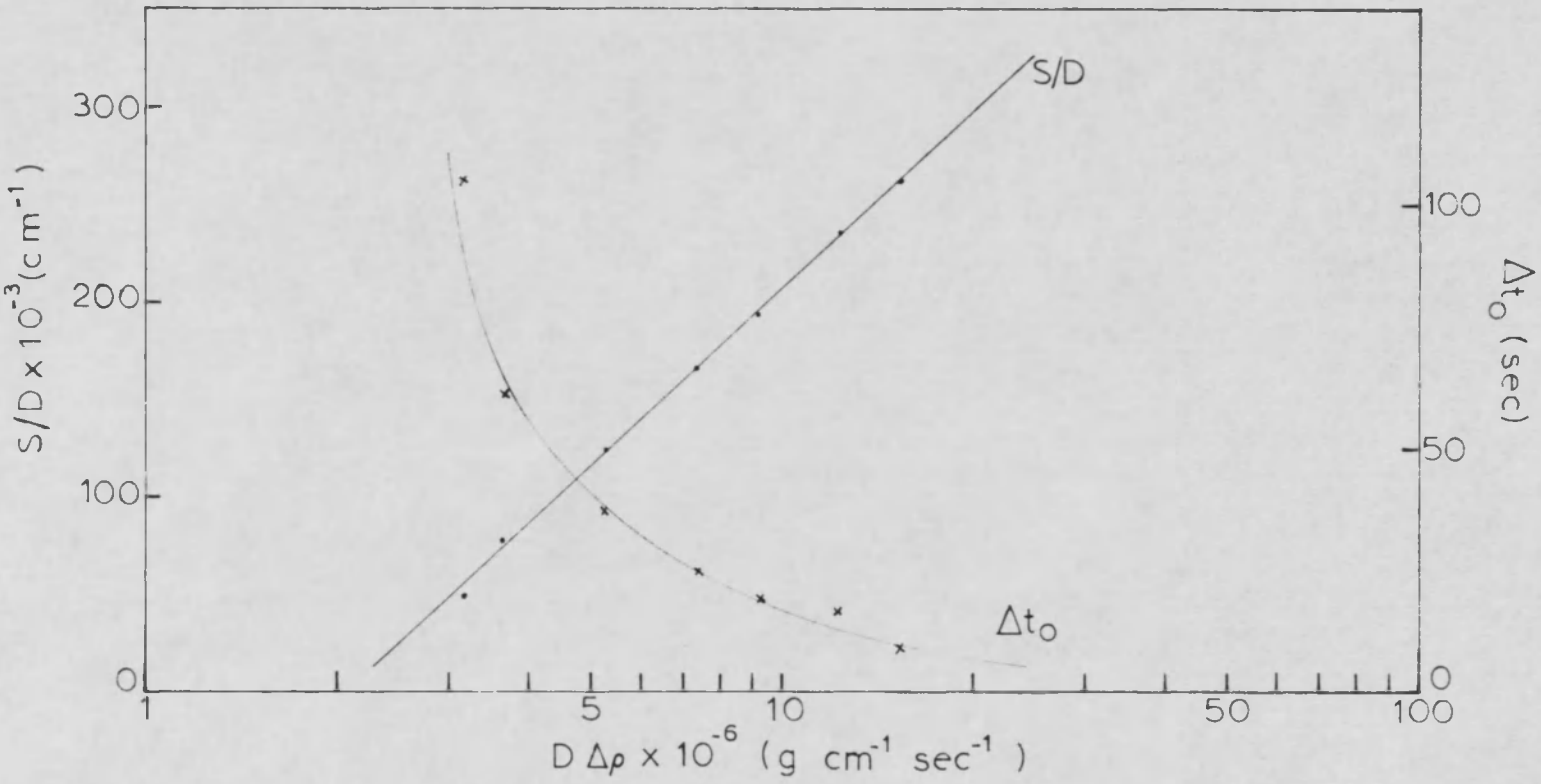


Figure 4. Graphical Aid for Calculation of R_L from LRM Data.

CHAPTER 3

THE AIR FLOW SYSTEM (AFS)

3.1 The Bierhuizen and Slatyer Apparatus

Bierhuizen and Slatyer (1964) published a paper dealing with an apparatus suitable for the continuous measurement of transpiration and photosynthesis under controlled environmental conditions. This apparatus was later used by the same authors for leaf resistance measurements (Slatyer and Bierhuizen, 1964a, 1964b).

The apparatus has five components essential for transpiration measurement.

a) Temperature control system

b) Air flow control system

c) The leaf chamber

d) Thermocouple differential psychrometers

e) Thermocouple for leaf temperature measurement

The temperature control system maintains the air temperature at the desired level. The air flow control system, composed of valves, flowmeters, dehumidifiers and humidifiers, was designed to control the air pressure and flow rate from a compressed air tank, and at the same time, to regulate the water vapor concentration in the air stream. The leaf chamber,

made of plexiglas, with inside dimensions 25x20x2 cm, has double walled upper and lower surfaces consisting of walls 1 cm apart. This results in a jacket surrounding the leaf chamber, through which water at constant temperature is circulated. The leaf is kept in the center plane position by means of a network of nylon wires on the upper and lower part of the leaf chamber. The air inlet and outlet consisted of nine pairs of holes, 0.5 cm in diameter, in each of the two end walls of the chamber. Each hole of a pair is placed on one side of the nylon wire network. A slot in one of the side walls is provided for the petiole. With a flow rate of 1 and 10 ℓpm, the wind speed across the chamber is 0.25 and 2.5m/min, respectively. The leaf temperature is measured with 44-gauge copper constantan thermocouples which are cemented over cross-threads of the nylon mesh and in such a way that they press against the leaf surface.

The differential thermocouple psychrometers do not contain dry bulb thermometers since the air temperature was known and maintained constant for each measurement. The wet bulb, a silver-soldered copper-constantan thermocouple 44 gauge, is covered with a small diameter cotton sleeve which serves as a wick. The internal diameter of the plexiglas tube inside of which the wet bulb is placed is 6 mm and the effective cross-section of the bulb is 0.2 cm^2. With a flow rate of 5 liters per minute (ℓpm) this gives a ventilation rate of 10.4 m/sec.

To measure transpiration, air samples are taken from the air stream before and after passing through the leaf chamber and the difference between the water vapor concentration, as sensed by the two differential psychrometers, is used for further calculations. To calculate the resistances to water vapor diffusion, Slatyer and Bierhuizen (1964a, 1964b) make use of the equation

$$T = \frac{\Delta\rho}{R_T} \tag{11}$$

$\Delta\rho$ is calculated as the difference between the saturation vapor concentration at the leaf temperature and the actual vapor concentration in the air after passing through the leaf chamber. R_L is calculated from equation (4),

$$R_T = R_A + R_L ,$$

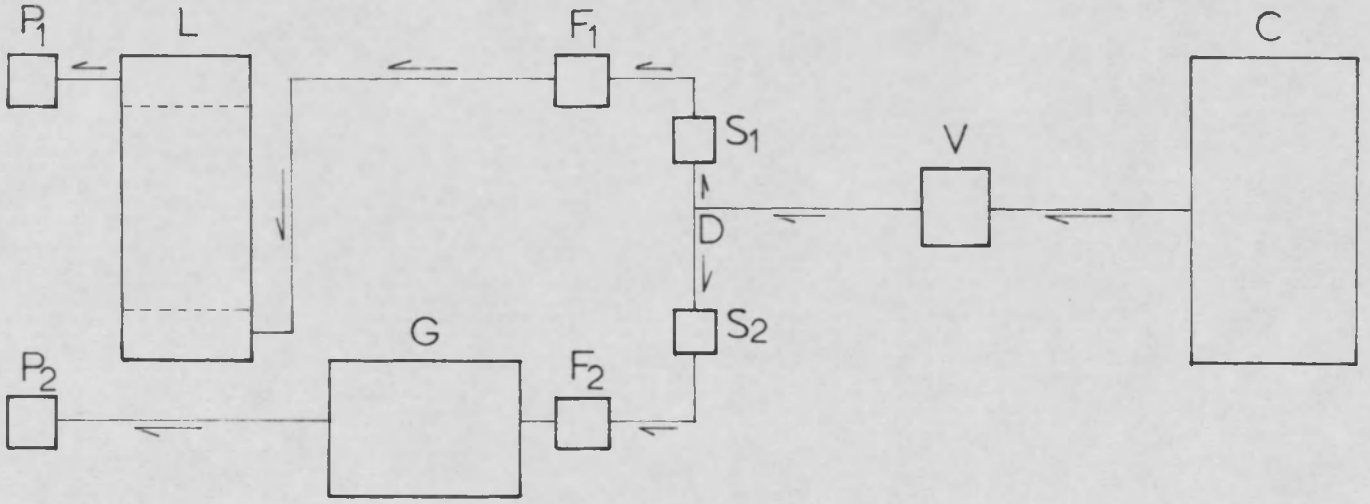
where R_A is the resistance measured when the leaf is replaced by a wet blotter paper similar in shape and size to the leaf. Evaporation values measured in this way are plotted against the vapor pressure gradient (Δe) between the blotter paper and the outgoing air. The relation $E/\Delta e$ is calculated for each wind speed, and a general equation is derived. By knowing E, Δe, T and R_T, it is possible to calculate R_L.

3.2 The Modified Air Flow System (AFS)

The objective of the present study was to modify the Bierhuizen and Slatyer (1964) system to make it suitable for field use.

The temperature control system has been eliminated; the air flow control system has been simplified; the leaf chamber has been built without the water jackets and with a different system for leaf temperature measurement; and the millivolt-recording component has been replaced by a manually operated millivoltmeter.

A diagram of the gas circuit is shown in Figure 5. The air source is a compressor tank (C). The reducing and regulating valve V reduces the pressure and regulates the flow. After valve V, the air stream is divided at point D and passes through stopcocks S_1 and S_2 where the flow rate is regulated to the desired level as measured by flowmeters F_1 and F_2. From flowmeter F_1 the air goes into the leaf chamber, and from the leaf chamber, through psychrometer P_1. From flowmeter F_2 the air passes through flask G before it goes through psychrometer P_2. Flask G approximates the same volume as the leaf chamber, and its function is to provide psychrometer F_2 with a sample of the same air as was taken at point D and is passing through psychrometer P_1.



C = Air Compressor
V = Regulating Valve
S = Stopcock
F = Flowmeter

G = Glass Flask
L = Leaf Chamber
P = Psychrometer

Figure 5. Flow Diagram of the Air Circuit for the Air Flow System (AFS).

The leaf chamber, as used by Bierhuizen and Slatyer (1964), has been modified slightly, but the dimensions (25x20x2 cm), the air distribution and collecting system, and the nylon wires network to hold the leaf, remained the same. The new chamber lacks the water jacket and the upper and lower surfaces are made of 0.1 mm transparent Teflon film. This material is more resistant than polyethylene and is as transparent to radiation in the visible and infrared wavelengths as polyethylene (Thompson, 1967).

The leaf temperature is measured by a 24-gauge copper-constantan thermocouple. This thermocouple is insulated as shown by Lange (1965) and is held by means of a plexiglas support adjustable to the leaf size and screwed to the lower part of the chamber. The junction is 0.5 mm above the nylon screen and stays in close contact with the dorsal leaf surface when inside the chamber.

The design of the thermocouple differential psychrometers is the same as the Bierhuizen and Slatyer (1964) psychrometer. Dimensions, geometry, and gas circuit are the same, but 24-gauge copper-constantan thermocouples are used both for dry and wet bulb thermometers. We also included in our psychrometers a dry bulb thermometer since we do not control the temperature of the system. The dry bulb thermometer is put in the center of a plexiglas tubing chamber which has a cross sectional area of 2.84 cm^2, 2 cm behind the wet bulb thermometer.

3.3 Calibration Technique

Equation (4) can be solved for R_L as follows:

$$R_L = R_T - R_A \tag{12}$$

where R_L is the leaf resistance, R_A is the resistance of the air in the boundary layer to water vapor diffusion, and $R_T = R_L + R_A$. The AFS provides a way to compute R_T, since:

$$R_T = \frac{\Delta\rho}{T} \tag{13}$$

where $\Delta\rho$ is the vapor concentration gradient between the leaf surface and the air after passing through the leaf chamber; T is the transpiration rate, measured as the difference in vapor concentration in the air before and after passing over the leaf inside the leaf chamber.

The AFS, when used to measure the evaporation from a wet blotter paper, also provides a way to calculate R_A, by using the equation:

$$R_A = \frac{\Delta\rho}{E} \tag{14}$$

where $\Delta\rho$ is the same as above and E is the evaporation rate calculated by the same method as the one used to calculate transpiration.

Thus, R_L will be, by combining equations (12), (13) and (14):

$$R_L = \frac{\Delta\rho}{T} - \frac{\Delta\rho}{E} \tag{15}$$

a. The accuracy of the psychrometer for measuring the vapor concentration of the air was determined. This was accomplished by checking the psychrometers against a mercury-in-glass thermometer psychrometer. From the point D on the gas circuit a bypass was taken to ventilate the new psychrometer. At a point between V and D a bottle containing distilled water was introduced in the air circuit. By putting this bottle into a water bath it was possible to obtain air streams with different water contents.

The wind speed at the wet bulb fulfilled the requirements of a value not less than 4 m/sec or greater than 10 m/sec (List, 1958) with air flows between 3 and 5 ℓpm. We selected 5 ℓpm for all of our measurements because it promoted faster circulation of the air through the leaf chamber. This allows a better estimation of the vapor concentration around the leaf, when this estimation is based upon the measurements made by using both of the psychrometers or even only one of them.

For a flow rate of 5 ℓpm, the wind speed is 1.25 m/min (or 2.08 cm/sec) across the leaf chamber and 6.7 m/sec across the wet bulb thermometer tubing.

An analysis of variance of the readings from the three psychrometers showed that the difference was not significant, as measured by the F-test.

b. The next step was to derive an equation for calculating an evaporation value (potential evaporation E^0) which

could be used in equation (14) to estimate R_A. To determine the E' values used in Figure 6, we measured the evaporation from a wet blotter paper 100 cm^2 in area. The blotter was put inside the chamber, the air turned on at 5 ℓpm and, starting from the third minute, dry and wet bulbs as well as evaporating surface temperatures were read for 5 minutes, at one minute intervals.

To compute the evaporation the following equation was used:

$$\rho_a = \rho_w \left(\frac{e}{e_w}\right) \tag{16}$$

where:

ρ_a = vapor concentration in the air (g/l)

ρ_w = saturation vapor concentration of the air, at the air temperature (g/l)

e = actual vapor pressure in the air (mb)

e_w = saturation vapor pressure in the air, at the air temperature (mb)

ρ_w and e_w were taken from tables (List, 1958), and the e values were computed by using the equation (List, 1958)

$$e = e' - [0.000660(1+0.00115t')]\ p\ (t-t') \tag{17}$$

where:

t = dry-bulb temperature (°C)

t' = wet-bulb temperature (°C)

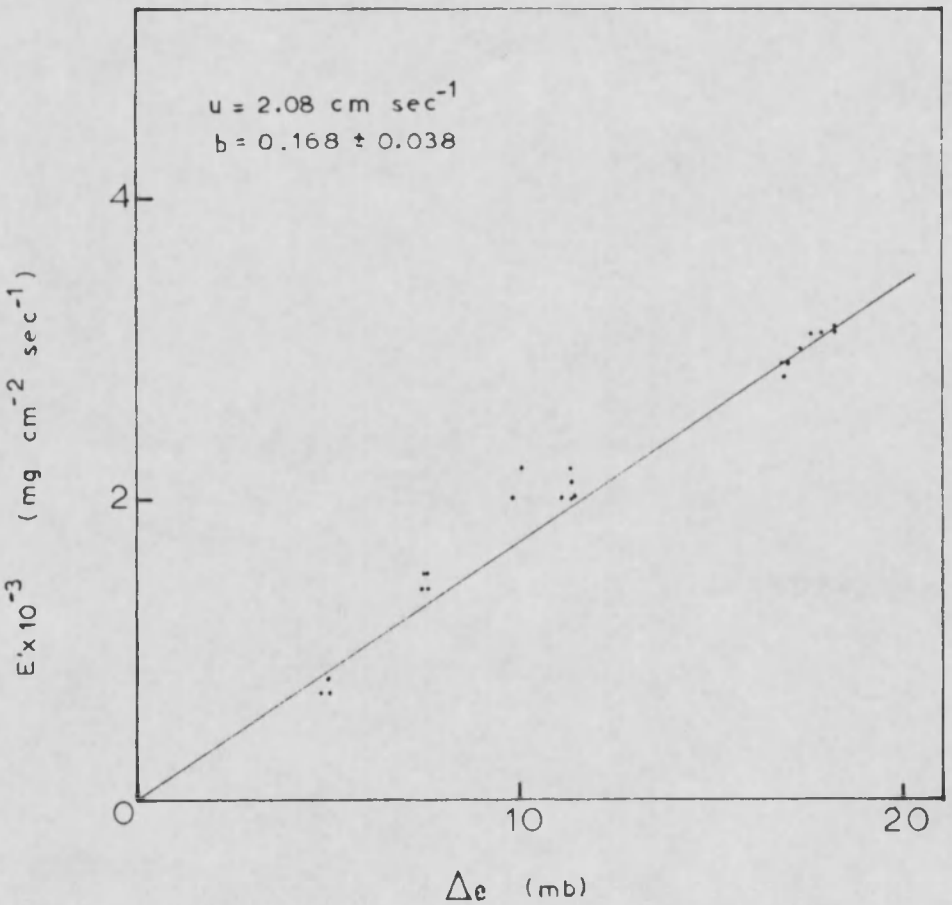


Figure 6. Evaporation (E') as a Function of Vapor Pressure Gradient (Δe).

p = barometric pressure (mb) (925 for Tucson)

e' = saturation vapor pressure at temperature t' (mb)

The difference between the values of ρ_a for incoming and outgoing air streams after multiplied by 5 ℓpm is the evaporation value in g cm^{-2} min^{-1}. This value is reduced to mg cm^{-2} sec^{-1} before going into figure 6.

Δe is computed as the difference between the saturation vapor pressure at the evaporating surface temperature and the actual vapor pressure of the outlet air stream.

From the values of E' and Δe used to plot figure 6, the following equation was derived:

$$E' = 0.168\Delta e \qquad (18)$$

This equation has been used for all further calculations of E' to compute R_A.

3.4 Measuring Leaf Resistance with the AFS

For taking measurements with the AFS, the leaf is enclosed in the leaf chamber, dorsal surface down. The leaf surface must be in contact with the thermocouple used for leaf temperature measurement. The air flow is started and, after the third minute, dry and wet as well as leaf temperatures are read for 5 minutes at one minute intervals. After the end of the experimental period the leaf surface area is determined, and only the area enclosed by the leaf outline

must be considered, or in other words, only the area of one of the leaf surfaces must be considered.

To compute R_L the following steps are involved for each individual reading:

a) e', e_w, e_s, ρ_w and ρ_s are taken from Meteorological Tables, while p is the local average barometric pressure (925 mb for Tucson).

b) e and ρ_a are calculated from equations (16) and (17).

c) Δe and $\Delta \rho$ are computed as the differences between e_s, ρ_s and e, and ρ_a for the outlet air stream, respectively.

d) T is calculated as the difference between ρ_a values for the air stream before and after passing through the leaf chamber. This difference is multiplied by 5 (flow rate = 5 ℓpm) and the result, after considering the leaf surface as described above, is reduced to g cm^{-2} sec^{-1}.

e) R_T is computed from the calculated $\Delta \rho$ and T using equation (13).

f) E' is computed from the calculated Δe and equation (18).

g) R_A is computed from equation (14).

h) R_L will be the difference between R_T and R_a, as calculated above.

The R_L values, as shown in Table II, are the average of the five individual readings taken at each time, at 1 minute intervals.

CHAPTER 4

SIMULTANEOUS MEASUREMENT OF LEAF RESISTANCE BY THE TWO METHODS

4.1 Experimental

Red kidney bean (Phaseolus vulgaris, L.) was used in comparing the two methods. The measurements were carried out on three bean plants growing in a greenhouse at the Environmental Research Laboratory of the Institute of Atmospheric Physics of the University of Arizona. These plants are numbered 1, 2 and 3 for our experiment and had been used for another experiment on salt tolerance, but were growing in a complete nutrient solution. Plant 1 is the control, plant 2 had received 2 atmospheres of salt and plant 3, 4 atm, for a period of time.

Readings were taken from 7:15 through 19:00 MST on December 7, 1967. A leaf was selected for each plant. The mid leaflet was used for the AFS and a side one for the LRM and the readings were taken simultaneously. Thirty points were determined at different times using the techniques described in sections 2.5 and 3.4 of this paper.

The results are presented in table II and figures 7 and 8.

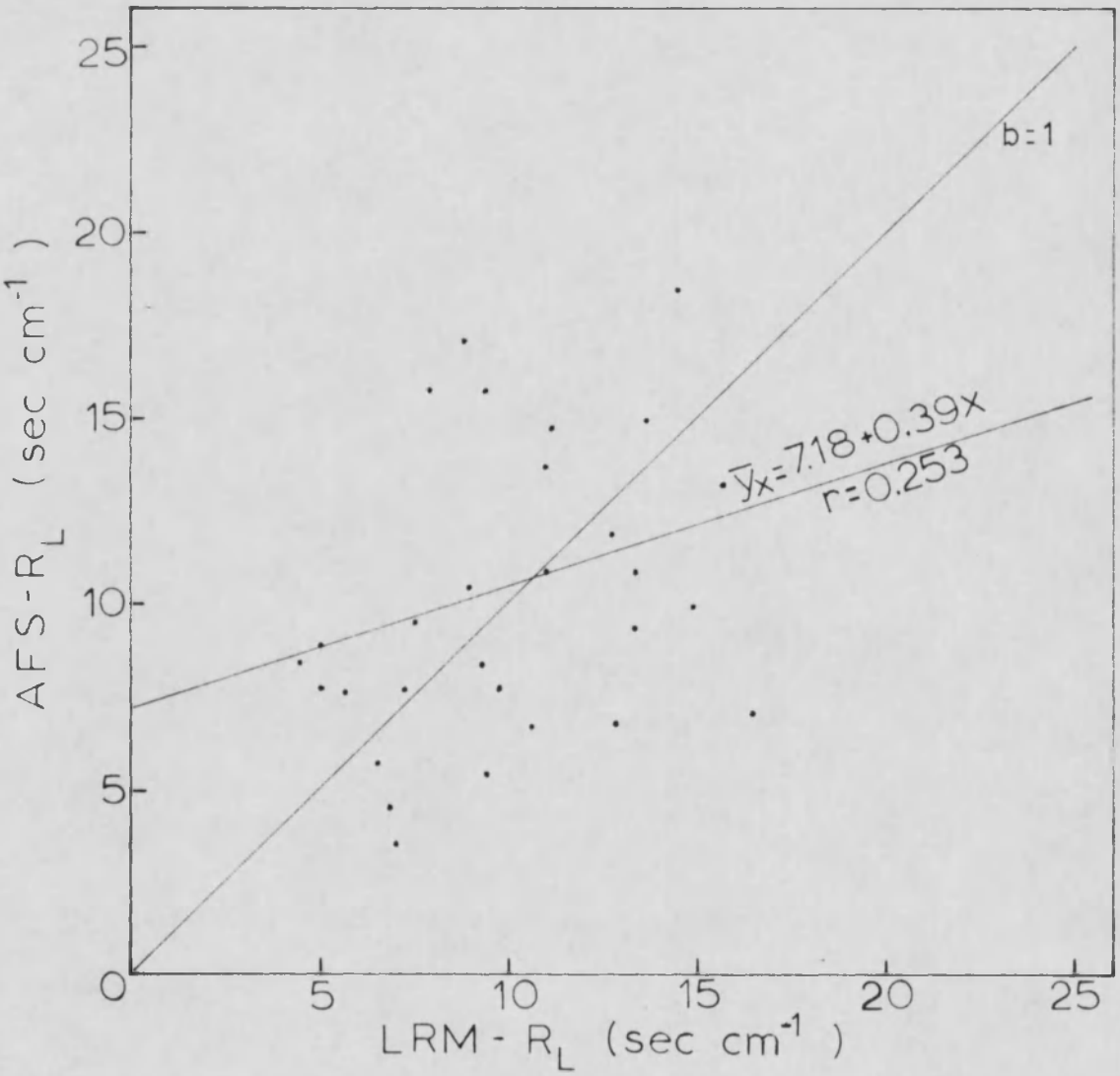
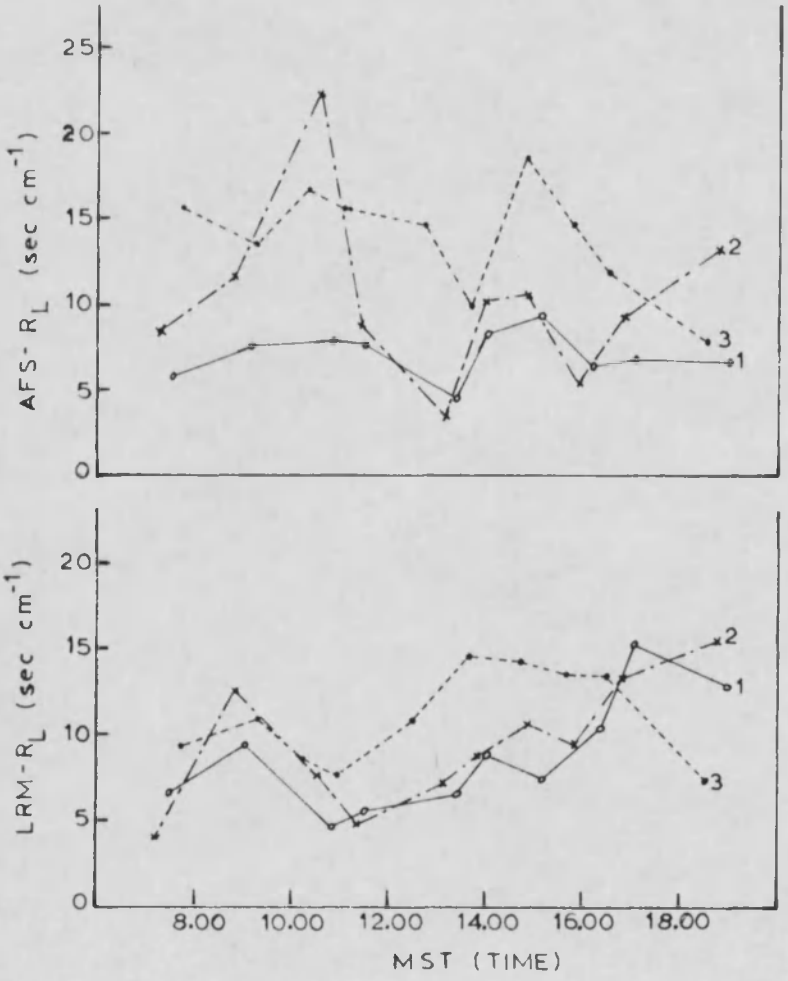


Figure 7. Linear Regression of Data in Table II.



1 - 2 Atm Salt Treated Plant

2 - Control

3 - 4 Atm Plant

Figure 8. R_L Data for Three Red Kidney Bean Plants, as Simultaneously Measured by the Two Methods.

4.2 Discussion

Table II shows for LRM-R_L a range of values between 4.4 and 16.4 sec cm^{-1}, which are within the range found for cotton by van Bavel et al. (1965). AFS-R_L values, ranged between 3.5 and 22.3 sec cm^{-1}, comparable only to those found by Slatyer and Bierhuizen (1964b) for cotton plants treated with 10^{-2}M phenyl mercuric acetate, a transpiration suppressant. The values they found for nontreated cotton plants ranged from 0.6 to 1.0 sec cm^{-1}.

Comparing our data for the two methods, the calculated correlation coefficient for the linear regression (figure 7) was 0.253, which indicates that the two sets of data are not highly correlated, for our experiment. This means that the R_L values as measured by the two systems cannot be compared, at least quantitatively. However, Figure 8 shows that:

a) Qualitatively the two methods seem to be showing the same kind of relationship among the three plants, mainly between 11:00 and 16:00 MST, the time at which the transpiration rate is expected to be greater.

b) Between 11:00 and 16:00 MST for both methods, plants 1 and 2 (control and 2 atm) show the same range of values for each method, while plant 3 (4 atm) has an average greater leaf resistance.

c) Before 11:00 LRM readings do not show any apparent differences among the three plants, and for the same period of time, AFS readings are difficult to understand or explain.

d) After 16:00 the general pattern is the same for both methods, except for plant 1.

Data from table III clearly indicate that $\Delta\rho$ is more dependent upon the leaf surface than upon the air temperature. Comparable variation of leaf and air temperatures causes larger variation of saturation vapor concentration at the surface (ρ_s) than of actual vapor concentration in the air (ρ_a).

$\Delta\rho$ is used directly to compute R_L by the AFS and is used to plot S/D and Δt_o for the LRM.

Table II shows that in about two thirds of the observations the LRM-R_L differed from the AFS-R_L in the same sense as the LRM leaf temperature differed from the AFS leaf temperature. Our data, however, were not sufficient to show if these differences in leaf temperature are the real causes of the differences between the R_L values. Further research will give more complete data and may lead to a better understanding of the differences we found. These observations, associated with the high AFS-R_L values we found, as compared with those found by Bierhuizen and Slatyer (1964) seem to indicate that the AFS works better under controlled environmental conditions.

TABLE III

Experimental Variation of Some Parameters Involved on the Computation of R_L

Parameter	Range of Variation LRM	AFS
Leaf temperature °C	14.7-34.3	14.1-32.3
Air temperature °C	14.8-27.6	14.9-29.9
ρ_a g m^{-3}	2.8- 5.4	3.0- 8.9
ρ_s g m^{-3}	12.6-38.2	14.1-34.4
$\Delta\rho$ g m^{-3}	9.7-32.8	9.5-28.3
D cm^2 sec^{-1}	0.269-0.291	---

Other points to be considered are:

1. The time required for data analysis: the AFS data requires more time to analyze than the LRM.

2. Volume and weight of the components: the LRM is a lot more portable than the AFS.

3. Cost: while the LRM costs about $100.00, the AFS, even with a portable air tank and a manual pump does not cost less than $500.00.

All these facts seem to indicate that the LRM is more suitable for routine work in field conditions, while the AFS is more suited for the kind of work in which simultaneous measurements of transpiration, photosynthesis and leaf resistance are required.

4.3 Conclusion

From the analysis of the data, we conclude:

1. At least until more data are collected, a comparison between leaf resistance to transpiration, as measured by the Leaf Resistance Meter and the Air Flow System must be qualitative rather than quantitative.

2. The simplicity of the Leaf Resistance Meter, as compared with the Air Flow System, makes the former method better for routine measurements in field conditions.

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