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DESIGN PARAMETERS EVALUATION OF A SAP FLOW METER FOR SMALL TREES

EVALUACIÓN DE PARÁMETROS DE DISEÑO EN UN MEDIDOR DE FLUJO DE SAVIA PARA ÁRBOLES PEQUEÑOS

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RESUMEN

Se evaluó la respuesta de un medidor de flujo de savia para árboles de Eucalyptus de un año de edad en función de dos parámetros característicos de diseño del transductor. Las variables evaluadas fueron la potencia eléctrica aplicada al calefactor y la posición de las termocuplas en el medidor. En los ensayos se usaron árboles de la especie *Eucalyptus nitens* de 16 mm de diámetro colocados en maceteros. Las variables estudiadas fueron distancias de 10 a 30 mm para las termocuplas desde el borde del calefactor y potencias de 0.16 1 0.48 W para el calefactor. Se evaluó el flujo de savia y se comparó con los resultados obtenidos en paralelo mediante pesadas diferenciales de los maceteros. Los mejores resultados se obtuvieron con una potencia de calefacción de 0.40 W y una distancia de termocuplas de 20 mm desde el borde del calefactor. Aunque los resultados son válidos solamente para árboles pequeños de dimensiones similares a los utilizados, sin embargo la metodología para mejorar el diseño de un medidor de flujo de savia se puede generalizar para cualquier especie y dimensión de árbol pequeño.

Palabras clave: Flujo de savia, medidor de flujo, transpiración de plantas, transductor de flujo, termocuplas.

ABSTRACT

The response of a sap flow meter for a one year old Eucalyptus tree, as a function of two characteristic design parameters of the transducer was evaluated. The variables tested were the electric power applied to the heater and the position of the thermocouples of the flow meter. One year old potted trees of Eucalyptus nitens *with a 16 mm diameter trunk were used. In the flow meter, distances of 10 to 30 mm from the edge of the heater and heating power of 0.16 W to 0.48 W were tested. The sap flow was evaluated and compared with the results obtained in parallel by means of differential weight measurements of the potted trees. The best results were observed with heating power of 0.40 W and a thermocouple distance of 20 mm from the edge of the heater. The best results were obtained with a power of 0.40 W and a distance of 20 mm from the heater edge for the thermocouples. Even tough the results are only valid for small trees of dimensional features similar to the tested units; however the methodology to improve the design of a sap flow meter can be generalized for any particular kind of small tree.*

Key words*: Sap flow, stem flow meter, plant transpiration, flow translucer, thermocouples.*

INTRODUCTION

The modern irrigation systems try to supply the quantity of necessary water to satisfy the ideal requirements of each plant of a crop. The usage of the sap flow meter in woody stems has a great potential due to the increasing utilization of artificial irrigation in forest plantations [1], [2], [3]. The actual development of irrigation methods with efficiencies around 80% has made clear that the accuracy in the calculation of water requirements have great importance in the overall operation of every irrigation systems. There are two ways to approach the calculation; one is by means of mathematical models and the other is using direct measurements of the water consumption of the plant. Mathematical models have difficulties to reproduce the complex phenomenon of transpiration being sometimes necessary to have expensive instruments to feed these equations like the case of

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the Penman-Monteith methodology. Other models require fewer data, but they have a limited use to specific circumstances and sometimes also they need calibration. Some of the methodologies used to estimate the water consumed through direct measurements, imply to measure the soil water content (gravimetric, tensiometer, neutrometer, TDR, etc.), and others measure the evaporation from a surface of water [4]. The sap flow meter overcomes most of these complications since measures the sap flow trough the plant stem by means of a partial stem heat balance, and this measurement can be associated to transpiration. The sap flow meter is able to measure water requirements of plants in individually being capable of adapting easily to visible or exposed stems which makes it appropriate for agricultural irrigation research mainly in row crops [5], [6], [7], [8]. Also stem flow gauges can be used as data source to feed mathematical models for integrated management of basins. The main difficulty arises when this technique is applied in woody stems due to lack of information in some variety of trees. Even though some general information related to the architecture of these instruments have been reported, there is not enough data available to predict its performance when some of its design features are changed. A few number of papers are available, where the configuration of the sap flow meter is shown with some small differences either for the thermocouples number and their position or in the amount of heating power applied to the plant. One of those was used by Steinberg et al [9], were the applied power was 0.9 W for *Ficus benjamina* with a diameter of 45.2 mm, obtaining errors smaller than 4%. Also Steinberg et al. [10], obtained errors smaller than 5 % for *Taxodium distichum* and *Ficus retusa* where the diameter of the trunk varied from 32 to 45 mm, and the electric power employed was 0.4 W.

The configuration of the instrument used in the present research followed the same general design characteristics of flow meters used for herbaceous plants. The main differences are related to the architecture outlined by Steimberg et al. [1-4], where the heater had a tubular form and it was inserted into the trunk, while in our case a thin ribbon shaped resistance placed outside and surrounding the trunk was used. As for the thermocouples number, they used a serial set (thermopiles), with the aim of achieving a more representative value for temperature differentials, while in our instrument we used single thermocouples. Hinckley et al. [11] used the same design in *Populus* growing 11 to 15 meters high and 8.3 to 15 cm in trunk diameter. Devitt et al. [12] found sap flow estimation errors between 8% and 20% with the same kind of sap flow meter in three ornamental species for short periods of measurement, which was due to the uncertainty of the instrument at dawn and evening. These values are bigger than those exposed by a number of authors Steinberg [10], [13], [14], [15], whose error always was smaller than 10% for long measurement trials. In our evaluation of the sap flow meter, the main objective was to study the behavior of the transducer in terms of accuracy when testing two design parameters: one related with the distance from the thermocouples position to the edge of the heater and the other one related with the amount of thermal power supplied to the trunk of the tree by the heater.

THEORY

The method of heat balance is based on a steady state flow of water passing through the trunk. By means of its system of roots, the tree takes the water and mineral substances from the ground; this sap is then transported by the xylem towards the upper section of the tree. Not all the water transported by the xylem became stomatic transpiration, since part of it corresponds to cuticular transpiration. Cuticular transpiration is only important, in plants with a very thin cuticle, but in general it supposes less than 10% of total transpiration. Also, the sap flow in the phloem is several times minor that in the xylem [16], reason why it has a reduced effect in the heat balance. Therefore, almost the entire sap flow that travels inside a section of the trunk of a tree is transpired through the leaves; this is why the sap flow meter is an appropriate instrument to estimate transpiration of trees. The method of heat balance adapted for trunks of trees [9], [17], [18], consists on applying heat to a section of the trunk and to quantify the losses that take place. The instrument incorporates a heater, thermocouples, an insulating envelope from radial conduction losses and insulation from solar radiation (Figure 1). The heat is transferred upstream and downstream for conduction. On the other hand, the movement of the sap in the xylem produces losses for convection and also there are radial losses through the insulating jacket. Since we are in a steady state system there is not accumulated energy, and the balance of heat can be written:

$$Q_f = Q_H - Q_r - Q_u - Q_d \qquad (1)$$

where Q_H is the flow of heat supplied by the heater, Q_f represents the convective flow of heat transported by the sap, Q_u and Q_d they represent the flows of heat lost by convection toward the inferior and superior section of the trunk respectively and Q_r represents the flow of radial heat from the heater toward the exterior, all expressed in Js^{-1}. Replacing the appropriate theoretical expressions to estimate each flow of heat in the balance of the equation (1), the following equation to estimate the sap flow F (gh^{-1}) in trees is obtained:

$$F = \frac{\left(\frac{V^2}{R} - KA\frac{\left(\Delta T_d + \Delta T_u\right)}{\Delta L} - K_r \Delta T_r \right)}{4.19\Delta T_{ud}} \times 3600 \qquad (2)$$

Where V is the voltage applied to the heater (V), R is the resistance of the heater (Ω), K is the thermal conductivity of the trunk, ($Js^{-1}m^{-1}°C^{-1}$), A is the cross area of the trunk (m^2), ΔT_u is the difference of temperature between heater and upstream thermocouple (°C), ΔT_d is the difference of temperature between heater and downstream thermocouple (°C), ΔT_{ud} is the difference of temperature between upstream and down stream thermocouples (°C), ΔL is the distance from the heater edge to the upstream and to the downstream thermocouple (m), K_r is the radial conductance ($Js^{-1}°C^{-1}$), ΔT_r is the difference of radial temperature (°C), 4.19 is the specific heat of the water ($Jg^{-1}°C^{-1}$) and 3600 is the number of seconds in one hour.

The thermal conductivity (K) it is calculated with the method described by Sakuratani [19], adapted for trees:

$$K = K_t V_t + K_w V_w + K_a V_a \qquad (3)$$

where K_t, K_w and K_a are the thermal conductivity of the wood, water and air respectively in $Js^{-1}m^{-1}°C^{-1}$, and V_t, V_w and V_a correspond to the volumetric fraction of wood, water and air on the total volume respectively in m^3/m^3. The radial

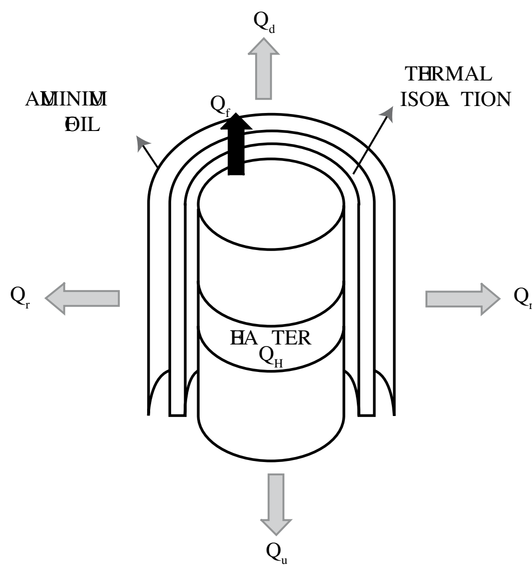

Figure 1. Sap flow meter thermal balance.

conductance K_r, can be estimated using the Ec. (2) when the sap flow is approximately zero, which can be achieve by means of one of the following methodologies: 1) taking among the lowest values in sap flow the minor and to assume that the sap flow is zero, 2) using the lowest values of the flow F when the tree is covered with a non transparent plastic simulating a dark day, and then assuming that the transpiration is zero [9], and 3) with the average of the estimates of sap flow measured among 24:00 h and 05:00 h for every day [13].

METHODOLOGY

The experiences were carried out in the facilities of the Agricultural Engineering Faculty, University of Concepción-Chile, Chillán Campus, during the month of March of 2000 and the months of October and December of 2001. Three small eucalyptus of 1 year-old with diameter of trunk of 16 mm, growing in containers, were tested with a sap flow meter system whose components are shown in the Figure 2.

The differences of temperature were measured and stored in a data acquisition data logger (Campbell Scientific, Inc. Model 21XL), every 1 minute throughout a multiplexer (Campbell Scientific, Inc. Model AM416) to be collected later from a Notebook computer. The results were compared with losses of weight of the trees, measured with a scale of 1 g

Figure 2. Experimental set up A) Eucalyptus tree, B) Power supply, C) Scale, D) Data logger.

of precision and maximum reading of 30 kg. These measurementss were carried out each 20 min. The exposed surface of soil in the containers was covered with plastic to avoid the evaporation from ground; and make sure that losses of weight would be due only to transpiration. The sap flow meter used in this research involves some differences with regard to the one reported by Steimberg et al [4] for woody trunks who used a tubular heater inserted in the trunk. In our case, we used a ribbon-shaped heater wrapped up to the trunk sector that required to be warmed up. Other difference was with regards to the number of thermocouples used, since we placed one junction instead of two junctions in the center of the heater. The single center junction works as a common reference for the estimate of the differences of temperature upstream and downstream. A diagram of the device is shown in the Figure 3. The parameters studied were the electric power applied to the heater and the distance from the upstream and downstream thermocouples to the edge of the heater. Four voltages of 3.6, 4.8, 5.6, and 6.2 volt, with a heater resistance of 79 Ω, were used. Those voltages generated four levels of electric power of 0.16, 0.29, 0.40, and 0.49 W, respectively. With respect to the placement of thermocouples, three positions were used: 10, 20 and 30 mm, from upstream and downstream thermocouples to the border of the heater. The thermocouple junctions used were type E copper-constantan of 0.13 mm of diameter, (Omega Engineering Inc), due to its high linearity in the range of working temperatures of the meter. A small wire diameter was chosen to diminish the thermal inertia of the union and, consequently, the constant of time of sensor response.

Upstream and downstream thermocouples were inserted 2 mm to the interior of the trunk. In the case of thermocouples to measure the difference of radial temperature, one was inserted in the middle of the insulating layer (polyurethane), of 20 mm of thickness, and the other one was settled on the external surface of the heater. The heater width was 20 mm. and its length allowed wrapping the entirety of the heated sector, without superposition in any place, in order to maintain a uniform heating of the trunk. As shown in Figure 4, the voltage was controlled with a power supply of selectable voltage and measured with the data logger. Since the maximum data logger reading limit is 5 V, it

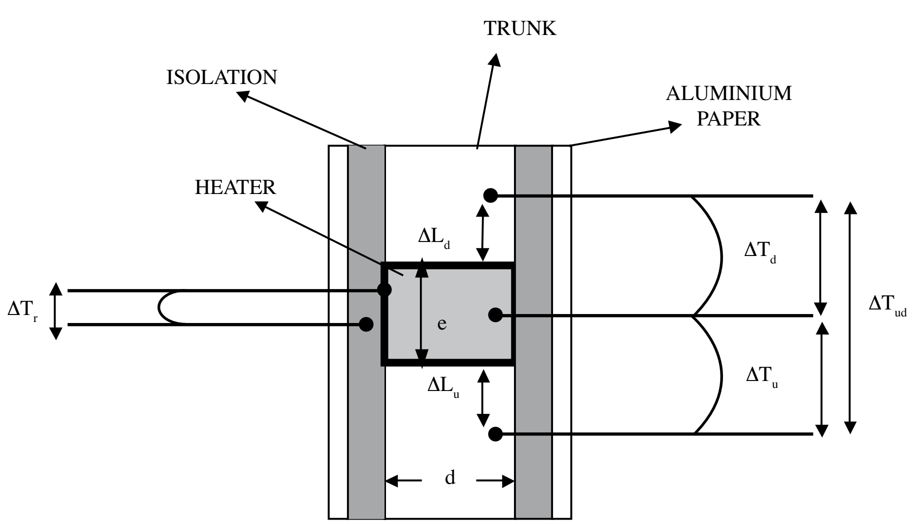

Figure 3. Configuration of the sap flow transducer.

was necessary to use a half voltage divider with 2 kΩ resistances, in order to keep voltage input to data logger below 5 V. The instrument included an external insulating (aluminum paper) for protection against the incidence of solar radiation, covering the entirety of the sap flow meter so that to avoid additional heat input.

The thermal conductivity was estimated as a weighted combination of each one of the components using the equation (3). To simplify the calculation, it was assumed that the contained air was negligible, therefore only the volume of water and wood was considered. The relative volume occupied by the wood (V_t) was determined according to the methodology proposed by Kramer et al. [20]. Also, with this methodology, the relative volume of water was obtained (V_w), being the remainder the relative volume of air (V_a). To determine the fraction that corresponds to each one of them a portion of the trunk was dehydrated in an oven at 70 °C, until a constant weight was reached. The mass of water was determined by difference of weight, and then divided by its density to obtain the volume of water. Finally, by difference, the volume of wood was obtained. Thermal conductivity of water and eucalyptus wood were extracted from standard charts of thermodynamic and physical properties of the wood. For water, a value of 0.6 $Js^{-1}m^{-1}°C^{-1}$ at 20 °C was used and for eucalyptus wood a value of 0.23 $Js^{-1}m^{-1}°C^{-1}$ was considered. The thermal conductivity of the dry wood of eucalyptus has been considered as an average of the values given for wood with similar density to that of the evaluated tree. The estimated thermal conductivity for the trunk was 0.422 $Js^{-1}m^{-1}°C^{-1}$; value that is used by most of the authors that work with sap flow meters in trees, but it is necessary to remember that the different species of trees have different contents of humidity, which influences their physical characteristics.

The radial conductance K_r, was obtained from the Ec. (2), when the sap flow approaches to zero which occurs between the 03:00 and 06:00 h. This fact can be confirmed by comparing temperature differences between upstream and downstream thermocouples and the central thermocouple (ΔT_u with T_d), which should be the same or quite similar. Once the data was generated, an analysis to establish the impact of heater electric power and the position of upstream and downstream thermocouples on the accuracy of the instrument was carried out. Testing results of the meter are mainly presented as sap flow data plots and by means of a meter performance index called relative difference (RD), used by Kjelgaard et al [13]:

$$RD = \frac{\sqrt{\frac{\sum_{i=1}^{i=n}\left(D_o - D_e\right)^2}{n}}}{\overline{D_o}} \times 100 \tag{4}$$

Where D_o is the ith observed accumulated transpiration measured with a scale, D_e is the ith estimated accumulated transpiration measured with the flow meter, $\overline{D_o}$ is the average of n values of D_o and n is the total number of data values.

One of the main objectives of this investigation is evaluating the effect of two design parameters in the operational behavior of the meter of flow. A value of Specific power Pe in Wcm^{-3} was defined as the applied electric power by unit of volume of the heated trunk portion and it is expressed as:

$$P_e = \frac{4V^2}{\pi d^2 eR} \tag{5}$$

where V in Volt and R in Ω correspond to the voltage and resistance of the heater, d in cm is the diameter of the trunk and e in cm is the width of the heating tape (in this case 20 mm), just as it is shown in the Figure 3.

A second parameter which stands for the dimensionless distance L_D in mm^3/mm^3 which is the radio between the distance ΔL from the heater edge to the upstream and downstream thermocouples and the diameter d of the trunk:

$$L_D = \frac{\Delta L}{d} \tag{6}$$

RESULTS AND DISCUSSION

The accuracy of the data given by the sap flow meter for different values of electric power and thermocouple position was evaluated by means of comparison in graphic 1:1 between transpiration (measured with a scale) and accumulated sap flow (measured with the flow meter). Measurements were done during a period of high transpiration, in clear days, from 11:00 h to 15:00 h, every 20 minutes (Figure 4). The obtained results indicate that with 0.16 W (3.6 V) applied to the heater a progressive overestimation of the tree transpiration occurs. However, for the other levels of electric power applied, a good agreement is observed.

A second Figure depicts the results obtained with a distance of 30 mm between the heater edge and the thermocouples which indicate a similar behavior to the previous case (Figure 5) where again the application of the smallest electric power overestimates transpiration. This fact indicates that the thermocouple located at a distance of 30 mm of the heater edge is in a point where is not affected by the transference of heat to the sap; in other words, it is in an area where the thermal balance was already reached. In both analyzed distances the different amount of electric power applied to the heater 0.29, 0.40, 0.49 W (obtained respectively with 4.8, 5.6, and 6.2 V) allowed to obtain a good agreement between the measured and estimated transpiration. However, it should be considered the damage generated on the trunk by effect of the local temperature that is reached. In this particular case a power of 0.49 W caused damages on the trunk surface were the heater was located. With up to 0.4 W of heating power applied to the heater no damage on the trunk was detected.

When adding a third distance of 10 mm between the heater and the thermocouples located upstream and downstream, only measurement with power of 0.4 W were made (Figure 6), which exhibited the better response. With this combination a value *RD*=11.9% is obtained. It is evident from Figures 4 , 5 and 6, that for every heating power tested with a thermocouple distance of 20 mm; the results are better than with distances of 10 and 30 mm. The relative differences obtained with 20 mm are between

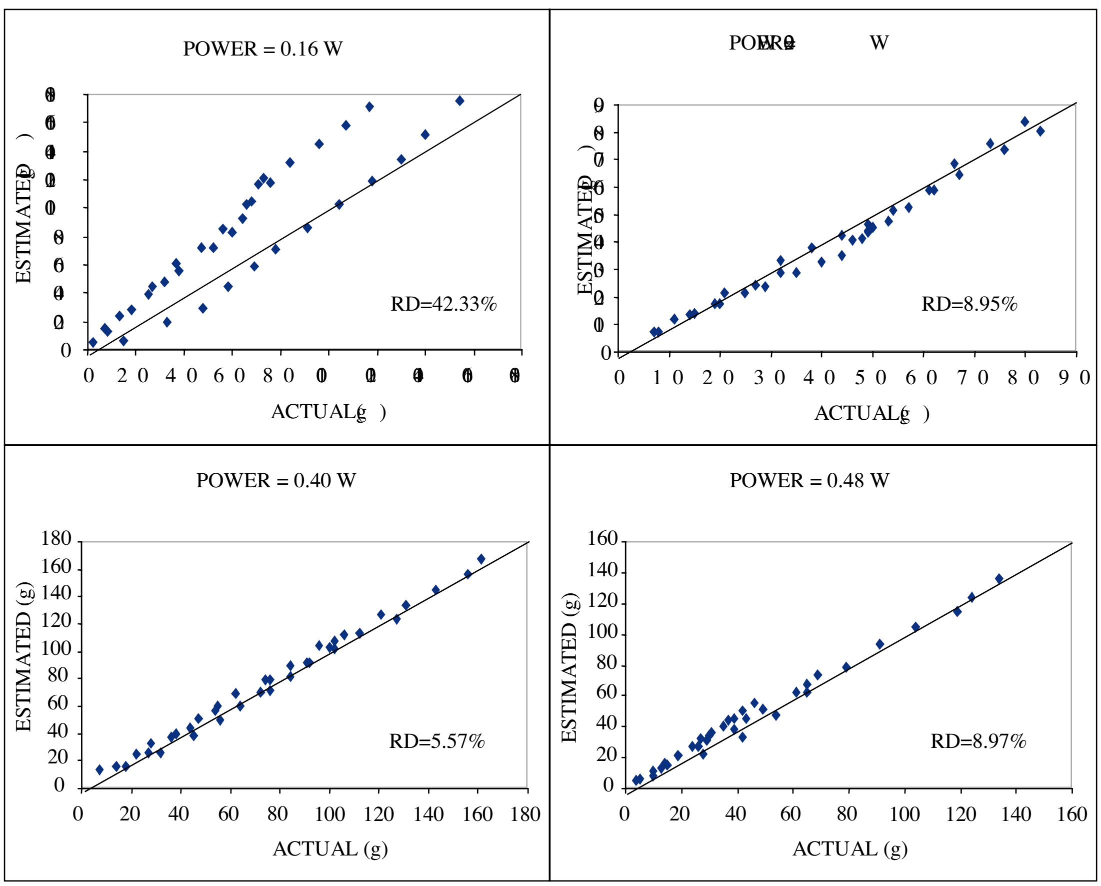

Figure 4. Comparison between actual and estimated accumulated transpiration with thermocouples located at 20 mm and different heating power.

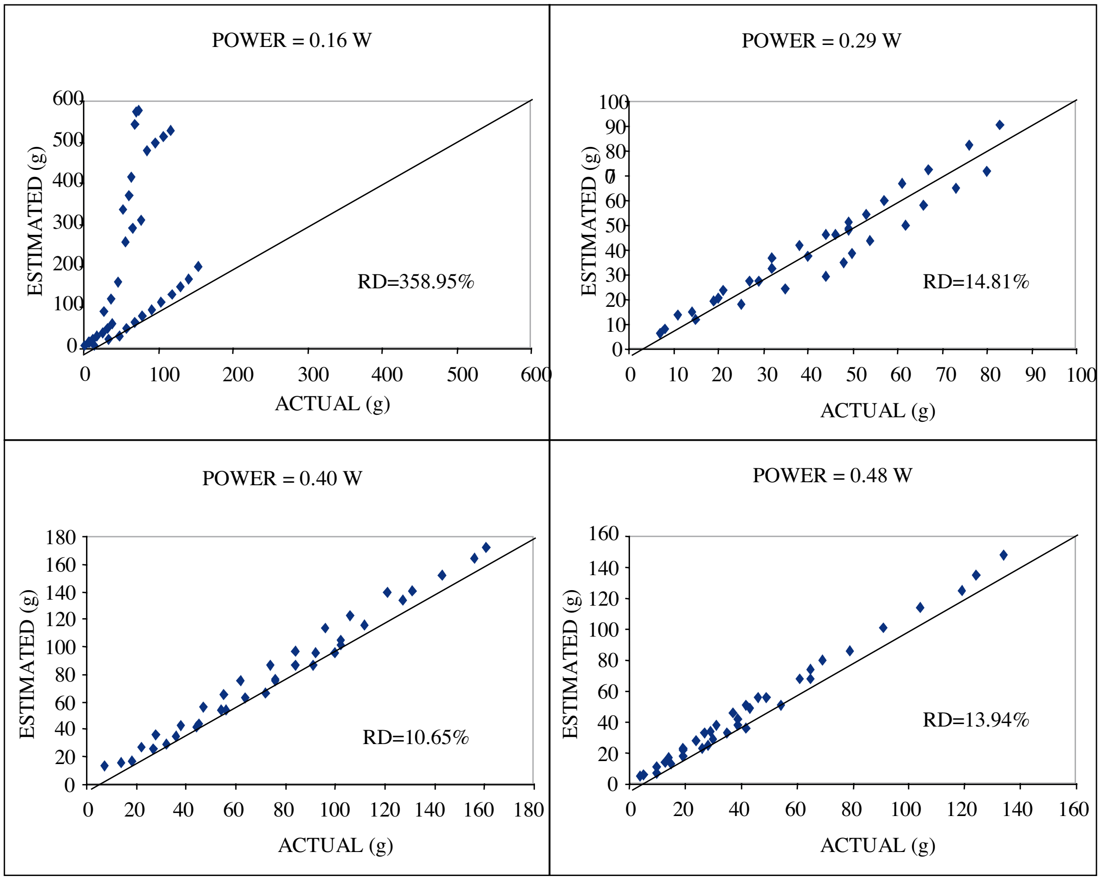

Figure 5. Comparison between actual and estimated accumulated transpiration with thermocouples located at 30 mm and different heating power.

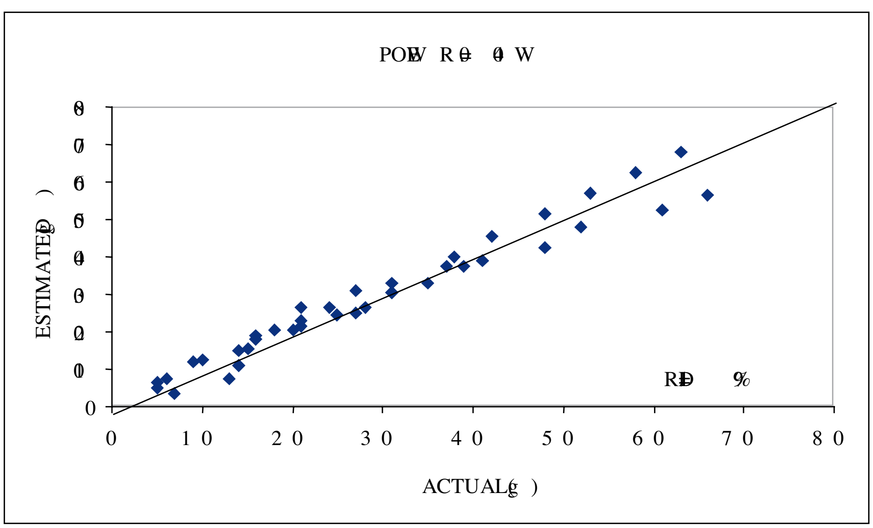

Figure 6. Comparison between actual and estimated accumulated transpiration with thermocouples located at 10 mm and heating power of 0.40 W.

the 5 and 9%, and with 30 mm are between the 10 and 15%. In spite of the increase of power, for a thermocouple distance of 30 mm it is not possible to achieve a relative difference smaller than 10%. In the case of a distance of 20 mm, when the heating power smaller than 0.29 W is used, relative difference of sap flow estimation increases considerably. However, an increase of power not always diminish the relative difference, meaning that beyond a certain power (in this case aproximatively 0.4 W), increasing the heating power causes an increment of the flow estimation error expressed as *RD*.

In Figure 7, daily temperature profiles of the sap flow transducer have been plotted for the best combination of power and thermocouple distance (0.4 W and 20 mm). When analyzing temperatures between 6:00 h and 21:00 h which is the period of more plant transpiration, we observe that the difference of temperature between the heater and upstream thermocouple (ΔT_u) it is similar to the temperature difference between upstream and downstream thermocouples (ΔT_{ud}). It is also evident that likewise the temperature difference between the heater and downstream thermocouple (ΔT_d) is near to zero as shown in the mentioned figure, which agrees with the results obtained by Steinberg et. al. [9]. The average upstream temperature difference (ΔT_u) was 7.2 °C during the same period. This behavior is due to the fact that when the sap flow increases, the energy captured by the sap is registered by the downstream thermocouple together with the energy that is transferred to by conduction, therefore increasing the temperature in the area. An increase in transpiration even cools more the heater because of bigger circulation of the sap, what agrees with the sap flow values shown in Figure 8 for the period between the 10:00 h and 11:00 h, when the sap flow is maximum. During the night the differences of temperatures stay stable without appreciable variations, which is explained because the sap flow in that period is near to zero. The difference of radial temperature has some variations during the day due to the cooling of the heater taking place by sap circulation; meaning that when the sap flow increases the difference of radial temperature diminishes. In this period radial difference of temperature is mainly due to the reading of the thermocouple that is on the heater and not to the thermocouple located on the insulating layer.

The response in accuracy of the flow meter *RD* is presented in Table 1 for every combination of the proposed design parameters P_e and L_D of Ec. (5) and (6). Since P_e=0.1 provides the best estimation results either for L_D=1.875 (thermocouples located at 30 mm from heater edge) or L_D=1.250 (thermocouples at 20 mm); the test for the third thermocouple location L_D=0.625 (thermocouples at 10 mm), was only carried out with a specific power value of P_e=0.1 that originated the best RD results. From Table 1, it is obvious that the best parameters combinations for the flow meter is P_e=0.1 (W/cm^3) and L_D=1.25 (cm/cm).

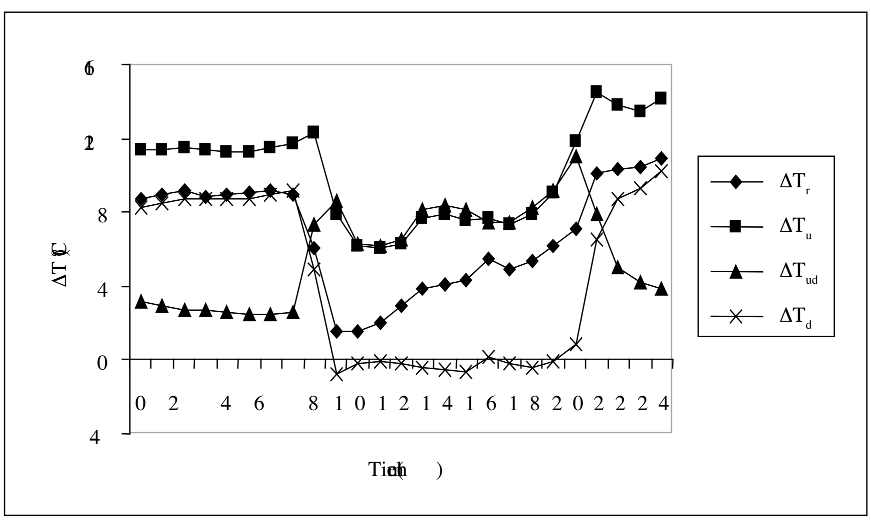

Figure 7. Profiles of temperature differences in the flow meter with P=0.4 W and ΔL=20 mm.

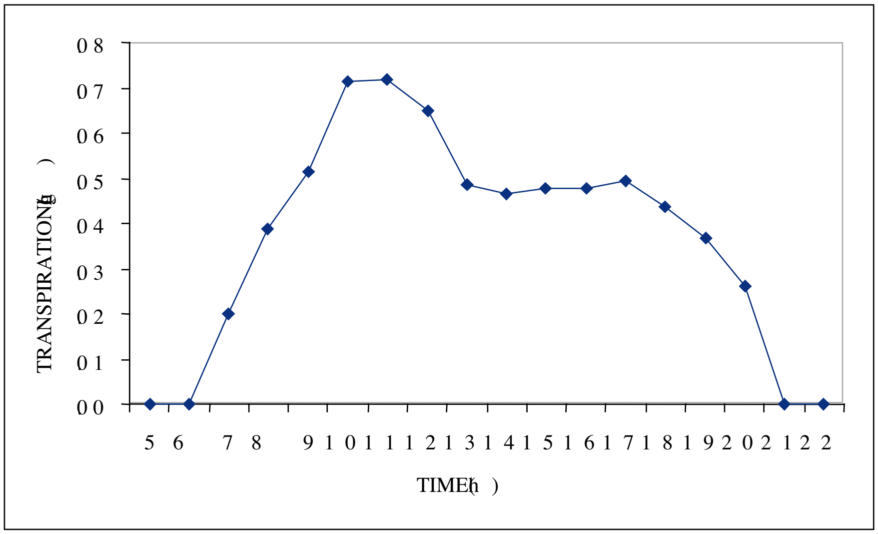

Figure 8. Estimation of transpiration with flow meter for P=0.4 W and ΔL=20 mm.

Table 1. Error of accumulated transpiration *RD* (%) for tested combinations of Dimensionless Distance L_D and Specific Power P_e

	P_e (W/cm^3)			
L_D (cm/cm)	0.040	0.073	0.100	0.120
1.875	358.95	14.81	10.65	13.94
1.250	42.33	8.95	5.57*	8.97
0.625	ne	ne	11.90	ne

*: best response of the flow meter
ne: not evaluated

CONCLUSIONS

The sap flow meter is an efficient instrument to estimate transpiration in young trees; however, big errors in sap flow estimation may be introduced if its design is inappropriate. It is possible to measure sap flow in small trees of Eucaliptus nitens with diameter of trunk near to 16 mm, and obtain a maximum relative difference of RD=5.6%, using a tape heater with a power of 0.40 W and differential thermocouples with distance of 20 mm from the heater edge to upstream and downstream junctions. Estimation errors of sap flow diminish drastically from 0.29 W to higher levels of heating power, which implies the necessity to apply a minimum power so that the sap flow meter is able to detect the influence of the heat transferred to the sap. There is an allowed maximum power that depends on the maximum temperature that the trunk can support without producing considerable damage. In the case of the trees similar to ones tested, a heating power of 0.49 W can cause serious damage to the trunk and the later death of the trees. The distance to which the thermocouples are located from the heater border also affects the accuracy of the instrument. From three thermocouple positions employees (10, 20 and 30 mm), the one that yields the best results is 20 mm. It is recommended to use the parameters of specific power P_e=0.1 (W/cm^3), an non dimensional distance L_D=1.25 (mm/mm) and the Ec. (6) and (7) to calculate the voltage required for the heater V (V) and the distance from the heater to the upstream and downstream thermocouples ΔL (mm), when designing sap flow meters for Eucaliptus nitens or other similar species, with diameter of trunk near to 16 mm.

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