

Construction and calibration of thermal transducers for the measurement of water content of soils

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The knowledge of the soil characteristics and properties are fundamental for agriculture and engineering. The present water in the soil influences those properties strongly and for that, the accurate, fast and of low cost measurement of the water content is a necessity in projects of scientific research, irrigation, constructions of dams and highways. The working principle of the thermal transducer to measure the water content, proposed in this work, is the variation of the thermal diffusivity in function of the soil water content. The diffusivity was estimated through the heat transfer inverse problem. The direct problem was modeled using the energy equation in cylindrical coordinates, with first kind boundary conditions, determined experimentally. The inverse problem was solved by the Search in Net Modified Method. Calibration curves were built with the diffusivity data in function of the water content, using no linear adjusts of a sigmoid function, for each soil type. The precision of the transducer was analyzed calculating the standard deviation of the diffusivity measures. The mistake of a double standard deviation in diffusivity estimation results in a mistake smaller than 10% in the calculation of the water content. The thermal transducers can be used in situations where they are installed in the same position for all measures, such as in the irrigation by aspersion or by dripping and laboratory experiments.

Keywords: Soil Water Content, Thermal Transducers, Soil Thermal Properties, Calibration Curves, Inverse Problems

O conhecimento das características e propriedades do solo são fundamentais para a agricultura e engenharia. A água presente no solo influencia fortemente essas propriedades e, por isso, a medida do teor de água rápido, preciso e de baixo custo é uma necessidade em projetos de investigação científica, irrigação, construção de represas e rodovias. O princípio de funcionamento do transdutor térmico para medir o teor de água, proposto neste trabalho, é a variação da difusividade térmica em função do teor de água no solo. A difusividade foi estimada através do problema inverso da transferência do calor. O problema direto foi modelado usando a equação da energia em coordenadas cilíndricas, com condições de contorno de primeiro tipo, determinadas experimentalmente. O problema inverso foi resolvido pelo método de procura em rede modificado. Curvas de calibração foram construídas com os dados da difusividade em função do teor de água, usando o ajuste não linear de uma função sigmóide, para cada tipo de solo. A precisão do transdutor foi analisada com o cálculo do desvio-padrão das medidas de difusividade. O erro de um desvio padrão duplo na estimativa da difusividade resultaram em um erro menos que 10% nos cálculos do teor de água. Os transdutores térmicos podem ser usados em situações onde eles estão instalados na mesma posição para todas as medidas, como na irrigação por aspersão ou por gotejamento em experimentos de laboratório.

Palavras-chave: Teor de água do solo; Transdutores Térmicos; Propriedades Térmicas do Solo; Curvas de Calibração; Problema Inverso.

1. INTRODUCTION

The measure of the soil water content is an essential technical information for a range of economical activities of the agriculture area, ecology and civil engineering, including activities in the scientific area, as in soils physics. There are two types of methods to measure the soil water content: the direct and indirect methods. The direct methods use some form of removing water of the soil matrix, which can be obtained by heating, pressure or chemical reaction, obtaining the mass of the removed water by gravimetry. The gravimetric method consists of the

measurement of the moist and dry soil masses, using a scale and a stove. Although it is an accurate method, it is difficult, not punctual, destructive and slow (Gilberto Jr., 2003). The indirect methods that use reflectometry of microwaves gained importance, as it is the case of the TDR (Time Domain Reflectometry) and WCR (Water Content Reflectometry) sensors, whose calibration was researched by Tommaselli and Bacchi (2001) and Seyfried and Murdorck (2001), among others. The advantage of these sensors is the possibility to measure the water content in several points with the same sensor and the disadvantages are the need of calibration for each soil type, the influence of salts in the reading and the high cost of the equipment. The tensiometers are also used to measure the water content, since the soil characteristic curve is known.

Relationship the methods of measurement, directly or indirectly to the knowledge of the soil water content, Coelho, 2003, highlights that is best depends on the purpose want to get availability, accuracy and other factors that may indicate it. Indirect methods, however, require calibration with respect to water content of soils, since the characteristics of this vary by the water content present.

The thermal transducers are dispositives that use the measurement of the temperature in function of the time associated with the soil water content. The advantages of these transducers are the easy construction, the low cost in comparison to TDR, WCR and tensiometers, the portability, the additional reading of the temperature of the soil and the independence of the influence of the salts in the reading of the water content. The working principle is the variation of a thermal property (conductivity or diffusivity) in function of the water content. In Shiozawa and Campbell (1990) they present a transducer whose operation depends on the hydraulic balance of a ceramic block and the soil. As that balance is a competition between the block and soil potential matrix, that type of thermal sensor measures the water content through the measure of the potential matrix (Reece, 1996), implicating sensibility problems, mainly for dry soils.

In evaporation, irrigation and evapo-transpiration experiments it is necessary to monitor the water content in soil profile, using several sensors (more than 50); that elevates the cost of the researches and motivates the construction of a low cost sensor. The objective of the present study is to describe and to calibrate a thermal transducer to measure the water content of soils, whose operation does not depend on a porous block, presents low cost and is relatively accurate, which has show large application in the science of soils.

The transdutor built seek to meet the necessity of development devices cheaper than those currently available on market, allowing, thus, that it can be widely used, since the other techniques already discussed have a high production cost.

2. MATERIALS AND WORKING PRINCIPLE OF THE HEAT TRANSDUCER

The built thermal transducer consists of a copper cylinder of 0.01m of diameter and 0.02m of height, with a thermocouple (TC) and an electric resistance (R) of 2.5 Ω installed internally. The empty spaces are filled with dry sand in order to prevent the displacement of the electronic devices and currents of air, resultants of the heating of the resistance. The extremities are sealed with epoxy, preventing the passage of soil water inside the transducer. The inferior extremity is molded in a conical shape so the transducer penetrates the soil more easily and with more adherence. The cost of the materials is approximately US\$ 10.

The electric resistance is connected to a tension source (1.5V) and the thermo-couple is connected to analogic/digital plates of data acquisition that are connected to the computer. The outline of the transducer is illustrated in Fig. (1), whereas the beginning of the transducer operation is illustrated in Fig. (2).

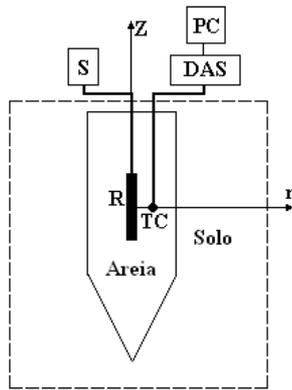


Figure 1 – Outline of the transducer: S = Electric source, TC = thermo-couple, R = Electric resistance, DAS = Data Acquisition System (analogic/digital plates), PC = Personal Computers

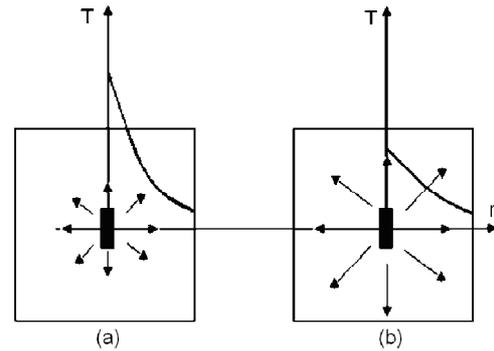


Figure 2 – (a) Residual soil, low diffusivity. (b) Saturated soil, high diffusivity.

The impossibility of water exchange between the soil and the interior of the cylinder makes the thermal properties of the materials that compose the transducer (sand and copper) stay unaffected in relation to the variation of soil water. Supposing that these properties are constant in relation to the temperature variation, the heat transfer in the system will only depend on the variation of the soil thermal properties, and these depend on the soil water content.

The soil water content based on volume was calculated using Eq. (1)

$$\theta = V_1/V_T \tag{1}$$

where, V_1 is volume occupied by water (cm^3) and V_T is the total volume of the sample (cm^3).

The water content of the sample, after being dried in the stove at $104\text{ }^\circ\text{C}$ during 24 h, is denominated residual water content (θ_r). The saturation water content (θ_s) happens when the pores are completely filled with water. The variation of the amount of water strongly modifies the soil thermal properties, making such properties to be used as calibration variables. Particularly, as the soil moistens, the thermal diffusivity increases, because the diffusivity of the water is larger than the one of the air. The water content was made dimensionless through Eq. (2)

$$\Theta = (\theta - \theta_r)/(\theta_s - \theta_r) \tag{2}$$

where, Θ is the dimensionless water content, θ is the volumetric water content, θ_r is the residual water content and θ_s is the saturated water content.

In Fig. 2 two states of the soil are illustrated: In Fig. (2a) the soil is dry, near to the residual state, therefore of smaller thermal diffusivity than the saturated one; in Fig. (2b) the soil is moist, near to the saturated state, more thermally diffusive than the residual. Where the thermal diffusivity is low, the soil acts as an insulator, hampering the propagation of the heat in the soil and quickly elevating the temperature next to the source of heat. Where the diffusivity is higher, the temperature registered next to the heat source is smaller, because the heat spreads more easily through the soil. Therefore, the higher the soil thermal diffusivity (moist soils), the lower the temperature variation next to the source, as illustrate the curves $T \times r$ of Fig. (2). The thermal diffusivity also depends on chemical constitution, texture, porosity and soil compacting. Such variables were not considered in this work, and that limits the application of the transducer to those soils and compacting conditions where calibration was accomplished.

The calibration experiments were performed with 4 soils collected in the northwest area of the state of Rio Grande do Sul, with different amounts of sand, clay and silt amongst themselves (to see Tab. 1). The structure of the soils was destroyed and sieved to eliminate organic and dry residues in the stove at $105\text{ }^\circ\text{C}$ for 24 hours. The samples were prepared in iron cylinders of same radius (0.025m) and same height (0.1m).

The inferior extremity of these cylinders was sealed with tow, allowing the gradual and uniform moistening of the soil, bottom-up by suction.

Table 1. Composition of the soils

Soils	% Clay	% Sand	% Silte
Soil A	53.5	8.6	37.9
Soil B	51.5	9	39.5
Soil C	30	29	41
Soil D	19.5	32.4	48.1

The thermal transducer was installed in the central axis of the soil cylinder (Fig. 1). The temperature data in function of time was collected for 10 different water contents, and the first and the last correspond to the residual and saturated soil state, respectively. The water contents among the residual and saturated states were obtained by putting the samples in contact with the water, during different intervals of time. The measures of the soil water content were made using the gravimetric method.

2.1. TRANSIENT CALIBRATION

The calibration curve of the thermal transducer cannot only depend on the temperature variation (ΔT), because this depends on the boundary conditions of the heat transfer problem. For the same soil, just the thermal properties remain (particularly the diffusivity) in the calibration conditions and in the measurement conditions of the water content.

Heat transfer in the cylinder-soil-transducer system (direct problem)

The calibration variable proposed in this work is the soil thermal diffusivity, estimated by the inverse problem method, for different water contents. To calculate this variable, it is necessary to solve, previously, the heat transfer problem in the system cylinder-soil-transducer (Direct Problem) with the geometry presented in the Fig. 1. The known energy equation (whose deduction is found in Özisik (1993)) was written for the conditions of the problem, in cylindrical coordinates, for the case of symmetrical axis (null derivatives in function of the rotation angle around the longitudinal axis of the cylinder), given by Eq. (3)

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \left(\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{1}{k} g \quad \text{for } 0 < r < R, 0 < z < H, t > 0 \quad (3)$$

where T is the temperature ($^{\circ}\text{C}$), z and r are the space variables (m), t is the time (s), α is the thermal diffusivity (m^2/s), k is the thermal conductivity ($\text{W}/\text{m } ^{\circ}\text{C}$), g is the heat source (W/m^3), R and H are the radius and the height of the soil cylinder, respectively (m).

The boundary conditions are expressed by Eq. (4)

$$\begin{aligned} T(r,0,t) &= T_a, \text{ to } 0 < r < R \text{ e } t > 0 \\ T(R,z,t) &= T_a, \text{ to } 0 < z < H \text{ e } t > 0 \\ T(r,H,t) &= T_a, \text{ to } 0 < r < R \text{ e } t > 0 \\ T(r,z,0) &= T_0, \text{ to } 0 < r < R \text{ e } 0 < z < H. \end{aligned} \quad (4)$$

where T_a and T_0 are the environment and initial soil temperature, respectively ($^{\circ}\text{C}$).

The heat source g was calculated using $g=V^2/R_e$, where V is the applied tension (V) and R_e is the electrical resistance (Ω) for unit of volume of the resistance.

The values of α and k vary according to the position in the integration domain in agreement with the type of material of each point (sand, copper and soil). The values of conductivity and diffusivity of the sand and copper were obtained from the literature.

The Eq. (3) with the boundary conditions (4) was solved using the finite differences method, by the explicit temporary scheme, using experimental data of the source and the boundary conditions. A computational program that calculates the temperature in points of the domain in function of time was elaborated. Particularly, only the temperature values in the position of the termo-couple (see Fig. (1)) are important for the calibration. The knowledge of the thermal conductivity of the soil is not necessary, because the heat source is zero in the out points of the sensor, annulling the source term (g) of Eq. (3).

Calculation of the thermal diffusivity (Inverse Problem)

The unknown quantity of the Inverse Problem (PI) is the soil thermal diffusivity and it was obtained based on the experimental data of temperature in function of time, measured by the thermocouple installed in the transducer (Fig.1) for each water content Θ . The estimation method used in the PI was the Search in Net Modified Method (Silva Neto and Moura Neto (2005) and Borges et al. (2008)) whose steps, adapted to the present problem, are described below:

Step 1: estimate an interval of diffusivity values $I_p = [\alpha_{p\min}, \alpha_{p\max}]$, where $p=1,2,3,\dots,n$ (number of parameters) that contain the optimum value of α_p (α_{ot}).

Step 2: build a partition of s points $\alpha_{pk} = \alpha_{p\min} + (k-1)\Delta\alpha_p$, with $k=1,2,3,\dots,s$ and $\Delta\alpha_p = (\alpha_{p\max} - \alpha_{p\min})/(s-1)$

Step 3: For each value (α_k), for $k=1,2,3,\dots, s$ the Direct Problem is solved using the numeric solution.

Step 4: the differences d_i are calculated between the estimated solutions and the experimental data using Eq. (5)

$$d_K = \sum_{t=0}^{tf} (T_{est}(t) - T_{exp}(t))^2 \tag{5}$$

where $T_{exp}(t)$ are the experimental data and tf is the final time.

Step 5: Identify the smallest value of d_k (d_{\min}) and the correspondent value of the diffusivity, α_{ot} .

Step 6: refinement of the solution: new interval is defined, $I_p = [\alpha_{p\min}, \alpha_{p\max}]$ so that $\alpha_{p\min} = \alpha_{pot} - \Delta\alpha_p$ and $\alpha_{p\max} = \alpha_{pot} + \Delta\alpha_p$

Step 7: repeat the steps 2 to 6, estimating several intervals I_{pm} , $m=1,2,\dots,nr$ (number of refinements) until $|d_{\min}^{i+1} - d_{\min}^i| < \epsilon$

Calibration curves and measurement of the water content using the transducer

The calibration curve was obtained making an adjustment of parameters of Eq. (6) using the values of thermal diffusivity estimated by PI and the correspondents water content, for each soil type.

$$\alpha(\Theta) = A(1 - e^{-n\Theta})^m + \alpha_r \tag{6}$$

where A is an adjustment parameter (m^2/s), n and m are adjustment parameters (dimensionless) and α_r is the thermal diffusivity of the residual soil (m^2/s).

Adjustments were tested with the lineal function and with the sigmoid function Eq. (6). The choice of the sigmoid function is due to the disposition of the points in a shape similar to an "S" (see Fig. 3) and to a better correlation coefficient, in relation to the lineal function. The Tab. 2 presents the values of the parameters of Eq. (3) and the correlation coefficients for the calibration curve for each soil.

With the parameters of the curves of each soil (Tab. 2) and Eq. (6) solved for the water content (Θ) Eq. (7), the soil water content was calculated, with the following procedures:

1. Set the transducer in the position of the measure of the water content.
2. Turn on the system, leaving it on for three minutes. Data of T x t.
3. The thermal diffusivity is calculated using the PI with the experimental data of T x t and the numeric solution of PD with the boundary conditions of the situation which the measure was made.
4. The water content is calculated using Eq. (7)

$$\Theta(\alpha_e) = -\frac{1}{n} \ln \left(1 - m \sqrt{\frac{\alpha_e - \alpha_r}{A}} \right) \quad (7)$$

where α_e is the estimated thermal diffusivity by PI (m²/s).

The use of Eq. (7) in evaporation experiments showed that, for dry soils, some measures of the diffusivity were located out of the interval of this variable, resulting in incorrect values of the water content.

3. RESULTS AND DISCUSSION

The Figure 3 presents the calibration curves for the different soils, where it can be observed that:

1. The calibration curves have similar lines for all soils;
2. The clay soils (A and B) present smaller variation of diffusivity for dry soils than the sandiest soils (C and D);
3. Even with similar lines, the curves of each soil present different steepness in function of the water content, raising difficulty to propose a dimensionless curve that could be used for any soil type.

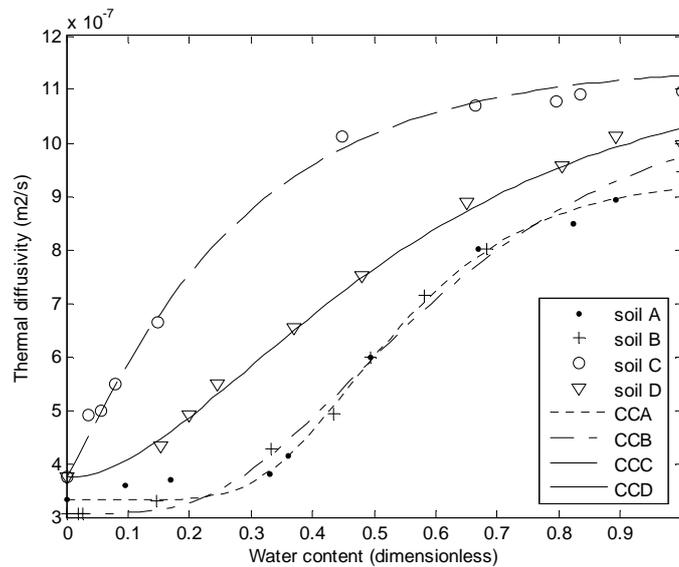


Figure 3 – Calibration curves of the soils A,B,C and D

Table 2: Parameters of calibration curves and correlation coefficient for the different soil types.

Soil	$A (10^{-7})$	N	M	R^2	$2 \sigma_a (10^{-7})$	Effect in Θ
A	6.0377	6.509	17.3245	0.9948	0.3595	± 0.0152
B	7.7170	3.6415	5.5038	0.9939	0.3627	± 0.0148
C	7.7170	3.7736	1.1132	0.9949	0.4301	± 0.0420
D	7.7170	2.5849	2.1264	0.9954	0.3289	± 0.0182

The choice of the sigmoid function for adjustment is knowingly a bad choice, because the derivatives in the extremities tend to zero, significantly increasing error in the calculation of the water content. The choice of the straight line would be more appropriate; however this correlation was very low. Thus, the proposed method presents significant imprecision for the measurement of the water content of soils, near to the residual and saturated states. That problem is more significant for the clay soils (A and B) for $\Theta < 0,25$ (see Fig. 3).

Considering the previous observations, the analysis of the transducer's precision was only performed for the $0.25 < \Theta < 0.85$ interval. Calculating the standard deviation of the diffusivity in each soil and considering two standard deviations ($2 \sigma_a$) around the estimated value of the diffusivity, it was verified that: 1) the medium error in the measure of the water content is smaller than 10% (the last column of Tab. 2 present the effects of those errors for each soil); and 2) approximately 96% of the measures of the water content will have that maximum level of imprecision.

4. CONCLUSION

The proposed transducer is easily constructed, has low cost, reduced size and it is easy to operate. The implementation of the measurement process depends on computer programs that use the experimental data supplied by the transducer to calculate the soil water content. A alternative to improve the transdutor would use thermobattery, which is the association of themocouples in series or in parallel, allowing measurement of lot small temperatures compared to those obtained in the experiments.

The impossibility to use a calibration curve for any soil demands the knowledge of the residual and saturated water content from the soil to be measured, and the previous experiments of determination of the specific calibration curve. That limitation restricts the application to situations where the transducer remains installed in the same position, for all the measures of water content, such as irrigation by aspersion or by dripping and in laboratory experiments to measure the water content in function of the time in columns of soil. In that sense, the research of a relationship between the proportion clay/sand, as well as the influence of the variation of the specific mass of the temperature and of the texture of the soil in the parameters of the calibration curve can be investigated.

The transducer's precision can be improved with the improvement of the prototype, increasing the application interval for soils near to reduced and saturated states.

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