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CONTROL OF THERMAL AND MOISTURE REGIME IN SOIL

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A b s t r a c t. The paper presents a method, a theory, and a measurement-control system permitting the control of the thermal and moisture conditions in the soil on the basis of measured basic physical properties of the soil and its thermal characteristics determined according to the method and theory presented herein. The characteristics of thermal diffusivity of soil in the function of moisture and soil density are of fundamental importance in the control of the thermal and moisture relations in the soil. Practical utilization of such characteristics allows soil moisture control at various soil densities so as to maintain optimum, for plant growth, thermal-moisture-air relations in the soil and in the ground layer of the atmosphere.

The method and the measurement-control system presented here create the foundations for rational utilization of water and thermal energy in the atmosphere-plant-soil system.

K e y w o r d s: soil, thermal regime, moisture regime

INTRODUCTION

Effective control of the thermal and moisture relations in the soil, and consequently of its air relations, for a given field and climate prevailing there, may be achieved through suitable agrotechnical, ameliorative and agrometeorological measures. The development of an optimum plan of such measures depends primarily on acquiring knowledge on the basic processes of mass and energy exchange in the soil, and on the factors determining such exchange.

In the control of the thermal and moisture relations in the soil we are going to make use of the close relations between heat and water in the soil, and correspondingly between temperature and soil water potential, and the thermal and moisture physical properties of the soil. All the measures leading to changes in the energy relations of plants in the ground layer of the atmosphere and in the root zone of the soil bring about changes in the moisture and air relations of those layers. In most cases we have no influence on the amount of solar energy reaching the plants, and thus we cannot exercise direct control over that energy. We can, however, control its distribution on the active surface. The main element of the soil which permits control of the distribution of the balance of energy on the active surface is the soil moisture. Water is also the main nutrient in plant production. These facts, and the possibility of controlling the amount of water supplied to the soil, allow for the creation, in a given period of time, of thermal-moisture relations in the soil which are favourable for plant growth. In this case the process of soil moistening will be reduced to the object of water amelioration, while values of thermal diffusivity of soil determined in measurements and adopted as reference by the user will be the source of control signals for the amelioration system.

The objective of the study was to provide theoretical and practical foundations for the development of a measurement control system permitting rational utilization of water and heat resources in the soil-plant-atmosphere system.

METHODS

To acquire detailed knowledge on the laws of mass and energy transfer in the soil in order to be able to affect that transfer, first of all we must get to know the factors determining that transfer and have at our disposal measurement-control systems which can bring a given system to a specific status. Therefore, on one hand the thermal balance, moisture balance, and their components, the laws of mass and energy transfer in the soil and its thermal-moisture characteristics permit the assessment and the selection of thermal-moisture relations which are optimum for the life and growth of plants, and on the other - the application of specific control measures permits the analysis and quantitative assessment of the effect of such measures on the thermal and moisture properties of the soil and of the field atmosphere, with plant cover or without. The thermal properties of soil are among the significant factors determining the processes of mass and energy transfer, and therefore they will be the subject of consideration in this paper.

The basic thermal properties of soil, characterizing the soil with respect to its ability to conduct and accumulate heat, are the thermal conductivity and the thermal capacity of the soil. The thermal diffusivity of soil, which is the quotient of thermal conductivity and thermal capacity per unit of soil volume, is a secondary value which determines the ability of the soil to equalize temperature at all the points within the soil.

For the determination of the thermal properties of soil the author used an empirical formula for thermal capacity and a statistical-physical model of thermal conductivity of soil [1,3,4,6]. The empirical formula was obtained by matching a specific mathematical function to the measurement data. The statistical-physical model was constructed on the basis of the concepts of thermal resistance and polynomial distribution, in such a way that a unit volume of soil, composed of solid particles, water and air, was presented as a system consisting of elementary geometrical figures (spheres of specific physical properties were adopted for the purpose) which form overlapping layers. It was assumed that connections between spheres within a layer and between layers will be represented by parallel connections of thermal resistors (spheres within a layer) and series connections of resistors (between layers). A comparison of the resultant resistance of the parallel-series system of resistors, which resistance takes into account all possible configurations of particle connections with the mean thermal resistance related to the unit volume of soil, permits an assessment of the thermal conductivity of the soil. It was found that, with changing physical properties of soil, in the model presented the number of parallel-series connections of thermal resistors is modified. Therefore, determination of the resultant resistance of the parallel-series system requires the determination of the parameters of the model, i.e., the model identification. The model was identified as a model which modifies the number of parallel connections of thermal resistors with changes in the ratio of water content in a unit of soil volume to its porosity, and modifies the radius of the spheres with changes in the type of the soil (mineral, organic).

The volumetric thermal capacity - C_v (J m^{-3} K^{-1}) was calculated according to the formula [1]:

$$C_v = (2.0x_m + 2.51x_o + 4.19\,\theta_v)\cdot 10^6 \qquad (1)$$

where x_m, x_o, θ_v (m^{3}m^{-3}) are content of mineral part, organic part, and water in a unit of soil volume, respectively.

The thermal conductivity of soil - $\bar{\lambda}$(W m^{-1}K^{-1}) was calculated from the model mentioned above, through the following mathematic formula [3,4]:

$$\bar{\lambda} = \frac{4\pi}{\bar{m}(\theta_v, \varphi, T, r, u)u} \tag{2}$$

where θ_v (m^3m^{-3}) - water content in a unit of soil volume, φ (m^3m^{-3}) - total porosity of the soil, T(°C) - soil temperature, r - equivalent radius of soil particles considered as spheres, u - number of parallel connections between soil particles considered as thermal resistors, $\bar{m}$ - expected value calculated from the formula:

$$\bar{m} = \sum_{j=1}^{K} \frac{P(x_{1\alpha}, x_{2\alpha}, \dots x_{k\omega})}{x_{1j}\lambda_{1j}(T)r_{1j} + \dots + x_{kj}\lambda_{kj}(T)r_{kj}} \tag{3}$$

where K is the number of all possible combinations of particle arrangement, P - probability of occurrence of a given combination of soil particle configuration, with $\sum_{j=1}^{K} P=1$, $x_1,\dots,x_k$ - number of particles of particular soil components of thermal conductivity $\lambda_1,\dots,\lambda_k$ and particle radius $r_1,\dots,r_k$, while $x_1+\dots+x_k=u$.

The probability of occurrence of all possible configurations of particles x_{ij} participating in thermal conductivity ($i=1,\dots,k$, $j=\alpha,\dots,\omega$, where $\alpha,\dots,\omega$, assume values from the range of $0,1,\dots,u$) is calculated from the polynomial distribution:

$$P(x_{1\alpha}, x_{2\beta}, \dots, x_{k\omega}) = \frac{u!}{x_{1\alpha}! \cdot x_{2\beta}! \cdot \dots \cdot x_{k\omega}!} f_1^{x_{1\alpha}} \cdot f_2^{x_{2\beta}} \cdot \dots \cdot f_k^{x_{k\omega}} . \tag{4}$$

where $f_1, f_2, \dots, f_k$ is the content of particular minerals, organic matter, water and air in a unit of soil volume and is considered as the probability of obtaining a type i result in a single test.

In the calculation of thermal conductivity, model identification is performed using the empirically determined characteristics of the number of parallel connections between the soil particles with relation to the degree of the soil saturation with water, as well as the empirically determined values of the equivalent radii of particle spheres for mineral soils (0.044) and for organic soils (0.08) [3,4].

In data pertaining to a specific soil, five main components were distinguished, of the following values of thermal conductivity: quartz (λ_q), other minerals (λ_m), organic matter (λ_o), water (λ_w), and air (λ_a); (Note - the mineralogical composition is simplified to a division into two classes - quartz and other minerals, meaning all the other minerals occurring in a given soil). These thermal conductivity values are used in practice in the calculation of the thermal conductivity of the soil. The values of coefficients of thermal conductivity of the above soil components and their relation to temperature (T), pressure (P) and soil water potential (ψ) are presented in Table 1. For a soil non-saturated with water and with a high soil temperature gradient the coefficient of air thermal conductivity is replaced by aggregate thermal conductivity (λ_{app}) composed of the air thermal conductivity (λ_a) and the thermal conductivity of water vapour (λ_v).

The theory presented in the paper permits the determination of all the basic thermal characteristics of the soil with relation to soil moisture (θ_v), soil density (ρ), soil temperature (T), mineralogical composition (f_i), soil water potential (ψ), and barometric pressure (P).

Practical realization of the theoretical foundations of the determination of the thermal properties of soil consists in the measurement of the basic physical properties of the soil and performing calculations according to the algorithm representing the statistical-physical model of thermal conductivity of the soil, and the mathematical formula for the thermal capacity and diffusivity of the soil [5].

Table 1. Values and expressions for parameters used in calculating the thermal conductivity of soils, T in ^oC

Source[a]	Parameters	Value/expression
	λ_q, W, $^{-1}$ K^{-1}	9.103 - 0.028 T
2	λ_m, W m^{-1} K^{-1}	2.93
2	λ_o, W m^{-1} K^{-1}	0.25
	λ_w, W m^{-1} K^{-1}	$0.551 + 2.76 \cdot 10^{-3}$ T - $1.8 \cdot 10^{-5}$ T^2
	λ_a, W m^{-1} K^{-1}	$0.0243 + 7.76 \cdot 10^{-5}$ T
2	λ_v, W m^{-1} K^{-1}	$hLD_a \nu (d\rho_o/dT)$
2	h	$\exp(\psi M_w/\rho_w R (T + 273))$
1	L, J kg^{-1}	2490317 - 2259.4 T
1	D_a, m^2 s^{-1}	$0.0000229 \cdot [(T + 273) / 273]1.75$
2	D_a, m^2 s^{-1}	$21.7 \cdot 10\text{-}6 (101.325/P) ((T+237)/273)^{1.88}$
1	ν, dimensionless	$P/[P-(h\rho_o R (T + 273)/1000 M_w)]$
1	ρ_o, kg m^{-3}	P - barometric pressure, kPa 10-3 exp [19.819 - 4975.9/(T+273)]
1	$d\rho_o$/dT, kg m^{-3} K^{-1}	$4975.9 \rho_o/(T + 273)2$

[a] 1. Kimball et al. [2]; 2. de Vries [1]

Symbols used: h - relative humidity; ψ - soil water pressure, kPa; M_w - molecular weight of water (0.018, kg mol^{-1}); ρ_ω - density of water (1 Mg m^{-3}); R - universal gas constant (8.3143, J mol^{-1}K^{-1}); L - latent heat of vapourization; D_a - diffusion coefficient for water vapour in air; T - temperature, ^oC; ν - mass flow factor; ρ_o - saturated vapour density.

SYSTEM FOR THE CONTROL OF THE THERMAL-MOISTURE RELATIONS IN SOIL*

The obtaining of required thermal-moisture relations in soil under given meteorological conditions and with a given soil density will consist in supplying the soil with, or removing from the soil, within a given period of time, a specific amount of water, and in maintaining the moisture of the soil at a specific level. In closed objects (e.g. greenhouses) it is also possible to control the influx of energy. In view of the fact that the greatest part of agricultural production takes place in the field and that amelioration is the major measure applied, what we are going to present here is a measurement-control system for the control of amelioration.

The measurement-control system for the control of amelioration system (Fig. 1)

* Patent pending.

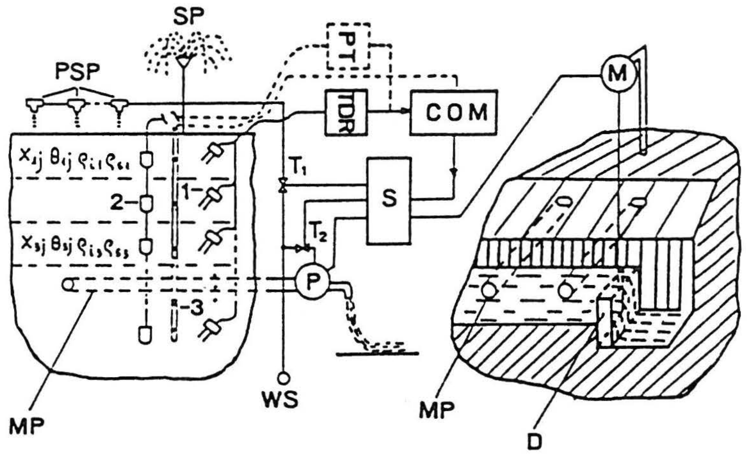

Fig. 1. The measurement-control system for the control of the soil amelioration system. MP - melioration pipe; PSP - point sprinkler; SP - sprinkler; PT - pressure transducer; TDR - meter of water content; COM - computer; S - control unit; P - pump; T_1, T_2 - valves; WS - water supply; M - motor; D - water gate.

incorporates multisensor gauges of volumetric moisture - probes 1, and a TDR, meter of water potential - sensors 2, a pressure transducer PT, temperature gauges - thermometers 3, a computer COM, a control unit S, valves (taps) T1 and T2 shutting off water supply to the sprinkler SP and point sprinklers PSP, pump P, supplying water to, and drawing water from the amelioration pipes MP, and motor M controlling the amelioration water gates D. The operation of the system consists in automatic measurement of moisture, potential, and temperature in selected layers, computer calculation, on the basis of the values measured, of the thermal diffusivity of the soil and comparison of the value calculated with preset values, and then, depending on the sign and difference, generating an appropriate signal to the control unit, providing information by how much the soil moisture is to be increased or decreased. As a rule, this will involve the opening or closing of the sprinkler valve before or after a required amount of water has been supplied to the soil, or the adjustment of the water level in an amelioration system utilizing the natural geographical conditions of the area, equipped with water gates, or in an amelioration system equipped with an irrigation-drainage pump. The function of the control unit receiving direct commands from the computer is as follows: in irrigation - to open the valves and switch on the pump supplying irrigation water or to control the position of the water gates and measure the amount of water; in drainage - the control unit functions in an identical way, the water flow being reversed, i.e., water drainage takes place.

As an example, to maintain the maximum temperature wave penetration rate in a loess-like soil of a density of 1.2 Mg m^{-3}, the measurement-control system, controlling the amelioration system, had to maintain maximum thermal diffusivity of the soil. That maximum thermal diffusivity, at the given soil density, was obtained by establishing a specific level of moisture in the soil. To determine the moisture level at which the thermal diffusivity reaches its maximum, first the thermal diffusivity characteristics in the function of soil moisture and density [3] were used to determine, for the maximum values of the thermal diffusivity of the soil, the linear regression equation of soil moisture as a function of soil density (θ=0.79-0.371 ρ), and second - the equation determined, providing reference data for the measurement-control system, was fed into the computer and the amelioration system was switched on. The measurement control system, controlling the amelioration system, brought the volumetric moisture of the soil up and maintained it, with the soil density equal to 1.2 Mg m^{-3}, at the level of 34 %, m^3m^{-3}. This level of soil moisture permits the maximum rate of temperature wave penetration. Any increase or decrease in soil moisture resulted in a decrease in the temperature wave penetration rate. The example presented above is relatively simple. Of course, it is possible to determine other sections of thermal diffusivity characteristics, depending on the soil moisture and density, or to establish specific ranges of thermal diffusivity at given soil density. The control of the thermal-moisture relations in the soil can be effected not only through the control of the soil moisture, but also through the control of the soil density, though the latter method has limited application. Soil density can be altered traditionally, by the loosening (opening) or kneading (compaction) of the soil.

CONCLUSIONS

The method and the measurement-control system presented above provide the foundations for rational utilization of the water and thermal energy resources in the soil-plant-atmosphere system, and permit the creation of thermal-moisture relations in the soil, optimum for plant growth, through establishing required levels of soil moisture or density.

Specific thermal-moisture relations in the soil are established on the basis of suitably selected values of thermal diffusivity of the soil which provide reference for the measurement-control system.

The measurement-control system for the control of amelioration system, presented above, can be used in a cultivated field, in a greenhouse, or in objects of porous structure where it is necessary to establish specific thermal-moisture relations of the porous medium.

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