Studies on development of an electrothermal method of measuring the soil thermal conductivity

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The paper presents the studies on development of a simplified electrothermal method of measuring the soil thermal conductivity, that may be used directly in the field. A measurement system has been designed and built, that is connected to measuring sensors located in the examined soil. Two types of sensors, i.e. active and passive ones were used. The passive sensors were provided with thermistors used for temperature measurement, while the active one, apart from the thermistor, was provided with a heating element of resistance type. The study has shown that the proposed method, consisting in measuring the steady heat conduction between the measuring sensor and soil, allows to determine the value of the soil thermal conductivity with satisfying accuracy. Moreover, the method is conducive to significantly smaller disturbance of the soil structure, being a reason of measurement errors occurring while using traditional methods.

Mathematical processing of the research results has been carried out with the help of STATISTICA software.

1. Introduction

Thermal properties of the ground, and first of all the value of thermal conductivity of soil, have crucial meaning for heat flow and temperature distribution in the ground. Moreover, they affect water motion in the ground [6], thus deciding the duration and intensity of vegetation of plants. Therefore, these properties are the object of studies of agrophysicists, climatologists, meteorologists, biologists, building and power engineers.

The research [1, 6] has shown that thermal properties of the ground are chiefly affected by soil water contents, soil density, soil mineralogical composition. Temperature of the ground, pressure and humidity of the air included between the ground particles do not significantly affect these properties.

Direct measurement of soil thermal properties is difficult and complicated. Therefore, more simple measurement methods are developed, that could be helpful directly in the field.

It is usually assumed during the measurement that when neither water nor air flow is observed due to the lack of any external factors, the heat exchange in the ground occurs in result of conduction. It means that the effects of radiation and convection are sufficiently small to be neglected.

Another simplifying assumption says that the ground is a homogeneous and isotropic medium.

Thermal conductivity of the soil or another loose material is measured with the help of a so-called Poensgen apparatus [3]. Theoretical basis for the measurement consists in the fact that at steady heat conduction through cylindrical wall of constant thermal conductivity, constant internal (T_w) and external (T_z) surface temperatures, the heat flows only in radial direction. In result, the conductivity equation in cylindrical coordinates simplifies to the following form [4]:

$$\frac{d^2T}{dr^2}+\frac{1}{r}\frac{dT}{dr}=0\ , \tag{1}$$

with boundary conditions: for $r = r_{\mathrm{w}}$, $T = T_{\mathrm{w}}$, and for $r = r_{\mathrm{z}}$, $T = T_{\mathrm{z}}$, where: r_z, r_w - external and internal radii of the cylindrical heat conducting wall, T_z, T_w - temperatures of the external and internal surfaces of the cylindrical wall.

Value of the heat conducted in the above system may be calculated by substitution of the result of equation (1) solution into the Fourier equation. Integration of the relationship obtained this way gives the following formula for the value of the heat conducted through a cylindrical wall of the length L within a time unit (power):

$$Q_{\mathrm{h}}=\frac{2\pi\lambda L\left(T_{\mathrm{w}}-T_{\mathrm{z}}\right)}{\ln\frac{r_{\mathrm{z}}}{r_{\mathrm{w}}}}, \tag{2}$$

Knowledge of the value (Q_h) allows to use the formula (2) for calculating the thermal conductivity λ. In order to make such measurements a so-called Poensgen apparatus [3] is designed and built. Thermal conductivity of loose material is measured with this apparatus by placing a sample of the material inside the apparatus shaped in the form of a tube made of an insulating material. The sample of the examined material makes a cylindrical wall, as inside it a main electric heater is axially placed. At both ends of the sample the screening electric heaters are located, also axially. The heaters are shaped in the form of cylinders of the radius r_{w}. The whole apparatus is then placed in ultrathermostat of the temperature T_{z}. The heaters are switched on and then the temperature of the inner surface of the sample, adjacent to the main heater, is measured (T_{w}), as well as the temperature of external surface of the sample (T_{z}). Once the temperatures stabilize, they are finally measured and the value of thermal conductivity [3] is calculated based on the formula (2). Disadvantage of the method of measuring the thermal conductivity consists in the need of sophisticated equipment composed of ultrathermostats, screening heaters, and high quality insulating materials. Possible measurement error may be the effect of the change in soil density resulting from collecting the sample and locating it in the measuring device. Therefore, the authors' research was aimed at finding a simpler measuring method of the soil thermal conductivity, that would allow to measure it directly in the ground, without disturbing the soil structure.

2. Description of the measuring stand

The research has been carried out with the use of the stand, the main part of which was a cylindrical container made of polyvinyl chloride. It has 1 m diameter and 0.4 m height. It was filled with a model soil, being a mixture of siliceous sands of the following composition and granulation: 3% sand of grain diameter below 0.15 mm, 54% of the diameter from 0.15 to 0.30 mm, 38% of the diameter from 0.30 to 0.45 mm, and 5% above 0.45 mm.

The humidity of the soil in the container was adjusted by adding distilled water or drying at a sieves and blowing with warm air.

For purposes of humidity measurement the value of soil humidity, considered as a reference to the measured value, has been determined with the dryer method.

Two types of sensors have been used in the studies – the passive and active sensors. The passive sensors have been used only for temperature measuring. Therefore, every such sensor was provided with a thermistor. On the other hand, an active sensor, besides a thermistor, was provided with an additional heating element, made of a resistance wire [5].

The sensors were shaped in the form of a cylinder of 4 mm diameter and 120 mm length. They were made of aluminum tube with electrolytically anodized surface. Inside the tube a thermistor is located. Additionally, a heating element made of a resistance wire of 0.1 mm diameter is wound on the surface of the active sensor. Resistance of the element is equal to 100 Ω. The tube with the thermistor inside was poured with epoxy resin. Surface of the resistance wire of the heating element was covered with the resin too.

During some research trials the screening heaters were located at both ends of the active cylindrical sensor in its axis, above, and below it, with a view to reduce non-uniform temperature distribution. The heaters were shaped in the form of a cylinder of 4 mm diameter and 60 mm length. They were made of aluminum tube with electrolytically anodized surface, with a resistance wire of 0.1 mm diameter wound on it. Resistance of the element was equal to 50 Ω. The tube was poured with epoxy resin. Surface of the resistance wire was covered with epoxy resin too.

During the research trials carried out with steady heat exchange the heating elements of the active sensors were supplied from a stabilized DC feeder.

Temperature was measured by means of thermistor sensors with the use of unbalanced Wheatstone bridge. Wiring diagram of the measuring systems is shown in Fig. 1. The bridge was supplied with the current of constant value of 40 μA. The current source of internal resistance exceeding 2 MΩ was used for this purpose.

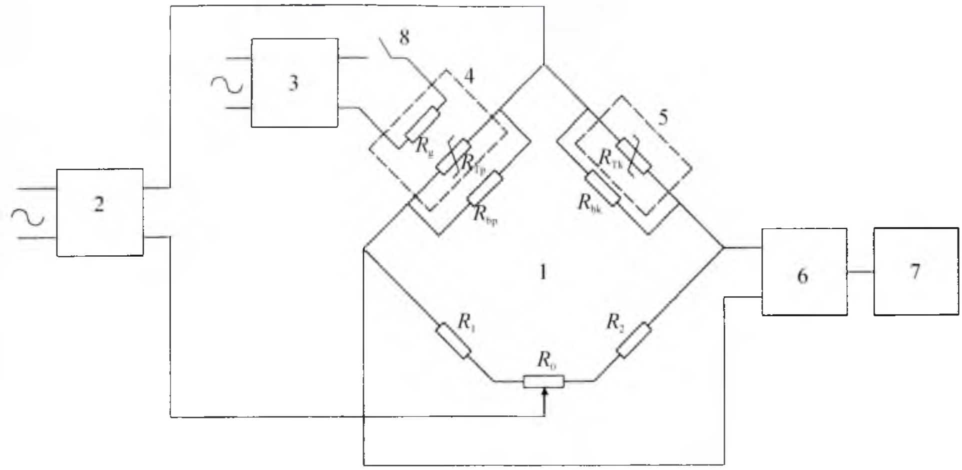

Fig. 1. Wiring diagram of the measuring systems: 1 – symmetrical Wheatstone bridge; 2 – DC feeder; 3 – the feeder generating a power pulse; 4 – active sensor; 5 – compensation sensor; 6 – digital recorder MC 101/8/20 for voltage time patterns; 7 – computer; 8 – electronic connector with adjusted switching time; R_{Tp} – resistance of the active sensor thermistor; R_g – resistance of the resistance heater of the active sensor; R_{bp} – resistance of the shunt of the active sensor thermistor; R_{Tk} – resistance of the thermistor of compensation sensor; R_{bk} – resistance of the shunt of the compensation sensor thermistor; R_1 and R_2 – resistances of the other bridge resistors; R_0 – potentiometer for zeroing of the measuring system

The role of bridge balance index was played by a voltmeter – i.e. the digital recorder MC 101/8/20 of input resistance exceeding 10 MΩ. It is connected to microcomputer (PC) designed for recording the data from the recorded voltage time patterns.

Value of the current density in the system was intentionally reduced, as the current flowing through the thermistors is conducive to heat emission and, in consequence, to temperature increase, that disturbs the measurement.

The bridge circuit (Fig. 1) has an additional potentiometer R_0 of the resistance (up to 200 Ω) low as compared to resistance of the thermistors used in the system. This potentiometer is designed for initial bridge balancing. The initial lack of balance was due to the difference between the A and B parameters of two thermistors used in the system (the measuring and compensative ones). Values of resistance in particular bridge branches were approximately equal, amounting about to 10 kΩ in the temperature 18 °C. One of the bridge branches is represented by the measuring thermistor R_{Tp} implemented in the active sensor. The same sensor was provided too with a resistance heater R_g designed for thermal energy generation.

In order to linearize the resistance-temperature characteristics the R_{Tp} thermistor was shunted with the R_{bp} resistor. In the second bridge branch the R_{Tk} thermistor was connected, as a part of the compensation sensor, the resistance-temperature characteristics of which was compensated by the R_{bk} resistor. It was located in the soil, far away from the active sensor. It was designed for compensation of possible soil temperature changes caused even by minor variations of the environment temperature in case of long-lasting research trials. In order to linearize the resistance-temperature characteristics this thermistor was shunted with the R_{bk} resistor.

The measuring R_{Tp} thermistor and compensating R_{Tk} thermistor were so selected as to ensure their similar resistance-temperature characteristics.

3. Measurement results and discussion

The studies were carried out in laboratory and in the field. During the laboratory tests carried out for steady heat exchange five measuring sensors have been used, one of them being an active sensor. As a principle it was assumed that the active sensor is located in the middle of the cylindrical container with the soil – Fig. 2.

In order to minimize disturbance of temperature distribution in one sensor caused by another, the passive sensors were so placed as to preclude location of any sensor between the active sensor and any of the passive ones, since this could change the thermal energy flux.

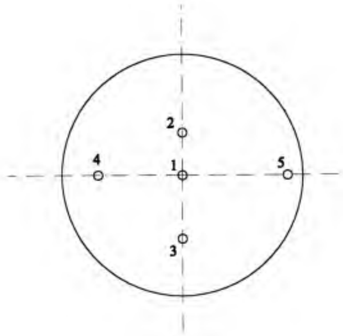

Fig. 2. Location of measuring sensors in the soil container – view from above: 1 – active sensor; 2÷5 – passive sensors; distance from the active sensor No 1 located in the middle to the passive sensor No 2 – 2 cm, No 3 – 4 cm, No 4 – 6 cm, and No 5 – 10 cm

The laboratory tests have been carried out with the use of a model soil. The measurements have been made for five different soil humidities. The power emitted by the active sensor during these tests amounted to 1 W. Cylindrical screening heaters of 0.5 W power were located at both ends of the active cylindrical sensor in its axis, above, and below it. The end of the upper screening heater was flushed with the soil surface. Once the supply of the active and screening sensors was switched on, temperature stabilized after more than ten hours.

Overall calculation results of thermal conductivity of the model soil of various humidities, obtained based on measured temperature distribution are presented in Table 1.

Table 1. Specification of calculation results of thermal conductivity of the model soil for various humidities, obtained based on measured temperature distribution; the confidence interval calculated for the confidence level α = 0.95

No	W, %	Value of thermal conductivity λ, calculated based on temperature difference between the following sensor pairs						Average value $\bar{\lambda}$, standard deviation s, and confidence interval $\bar{\lambda} \pm t_{\alpha} s$ of thermal conductivity		
		W/(m·K)						$\bar{\lambda}$	s	$\bar{\lambda} \pm t_{\alpha} s$
		2–4	2–6	2–10	4–6	4–10	6–10	W/(m·K)	W/(m·K)	W/(m·K)
1	0	0.43	0.42	0.42	0.41	0.41	0.41	0.42	0.01	0.40÷0.44
2	5.3	0.53	0.54	0.54	0.53	0.54	0.55	0.54	0.01	0.52÷0.56
3	10.7	0.82	0.84	0.84	0.87	0.85	0.83	0.84	0.02	0.79÷0.89
4	16.1	1.52	1.64	1.59	1.68	1.71	1,66	1.63	0.08	1.44÷1.82
5	21.4	2.35	2.45	2.66	2.63	2.84	2.87	2.65	0.22	2.12÷3.18

The results of temperature distribution obtained in the measurement tests have been used for calculating the values of thermal conductivity of the model soil of various humidities. Value of thermal conductivity was calculated from the formula (2) after its transformation. The confidence interval was calculated for the assumed confidence level equal to α = 0.95.

Based on the calculation results included in Table 1 the relationship between thermal conductivity of the model soil and soil humidity has been plotted. It is shown in Fig. 3.

Comparison of the measured values of the soil thermal conductivities at various values of humidity specified in Table 1 and presented in Figure 3 gives evidence that they approximate the data given in literature [1, 6].

Moreover, Table 1 and Figure 3 show that maximum deviation between the measured values of soil thermal conductivity occurred in case of the soil of the highest humidity (21.4%). It is probably due to the fact that so high soil humidity approximates the state of water saturation of the soil, i.e. so-called water field capacity. Under such condition the soil is no more homogeneous, that is conducive to heat flow disturbance. In the vicinity of the saturation state the humidity level becomes irregular and some privileged heat exchange paths appear.

The above measurement method of soil thermal conductivity was tested under field conditions. The tests were carried out in an experimental field with sandy soil with clay addition. Macroscopic estimation of the soil in accordance with the standard PN-88/B-04481 and the guidelines from the work [7] has shown that the field ground was a fine-grained low-cohesive soil. Perpendicularly to the ground surface a cylindrical active sensor was inserted with two cylindrical screening heaters located above and below, axially with respect to it. In the distance of 2 and 15 cm from the axis two cylindrical passive sensors were placed.

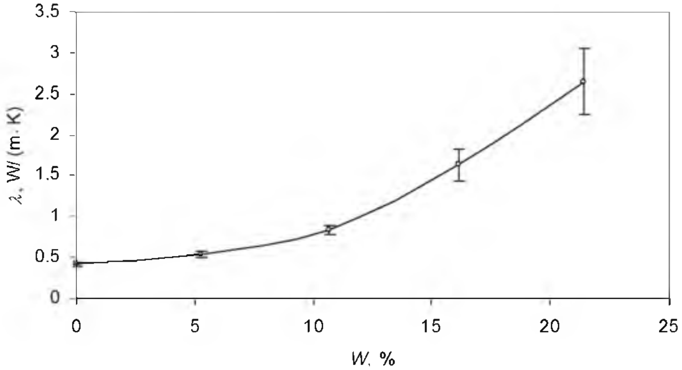

Fig. 3. Relationship between thermal conductivity of the model soil and soil humidity, with 95% confidence interval

The power emitted during the measurement by the active sensor was equal to 1 W, while the power emitted by each of the screening ones – 0.5 W.

The soil humidity varied naturally, when the test time was synchronized with weather conditions, or artificially – by sprinkling the field with water.

Temperature differences measured in steady state at the distance of 2 and 15 cm from the active sensor and the ones calculated from the formula (2) are specified in Table 2.

Based on the calculation results included in Table 2 the relationship between thermal conductivity of the model soil and soil humidity has been plotted. It is shown in Fig. 4.

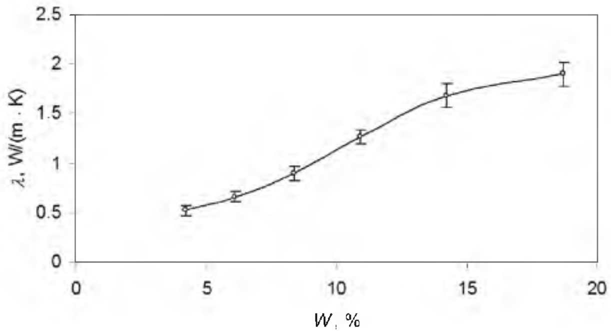

Fig. 4. Relationship between soil thermal conductivity and soil humidity

Table 2. Specification of temperature differences measured in steady state in the soils of various humidity values, at the distance of 2 and 15 cm from the active sensor and the values of soil thermal conductivity calculated from the formula (2)

No	Soil humidity W	Differences of temperatures measured in independent measurement trials ΔT					Thermal conductivity λ		
							Arithmetic mean $\bar{\lambda}$	Standard deviation s	95% confidence interval $\bar{\lambda} \pm t_{\alpha} s$
	%	K	K	K	K	K	$W/(m \cdot K)$	$W/(m \cdot K)$	$W/(m \cdot K)$
1	4.2	5.1	5,1	5.2	5.0	5.0	0.52	0.02	0.47÷0.57
2	6.1	4.1	4.0	4.0	3.9	4.1	0.62	0.02	0.57÷0.67
3	8.4	3.1	3.0	3.0	3.1	3.0	1.09	0.03	1.02÷1.16
4	10.9	2.0	2.1	2.2	2.1	2.0	1.47	0.03	1.40÷1.54
5	14.2	1.7	1.6	1.6	1.5	1.6	1.68	0.05	1.56÷1.80
6	18.7	1.3	1.4	1.5	1.4	1.4	1.90	0.05	1.78÷2.02

4. Summary and conclusions

In result of the study a new conception of measuring sensors and measuring system has been developed, that enabled measuring soil thermal conductivity directly in the field.

Our research shows that knowledge of basic physical features of the soil, i.e. its granulometric composition, density, and humidity, allows to determine with satisfying accuracy the value of soil thermal conductivity with the use of the above mentioned method. Moreover, this method causes significantly lower soil disturbance leading to measurement error, as compared to the situation occurring in case of traditional methods.

The value of soil thermal conductivity depends on soil humidity. Hence, the same method may be helpful in determining the soil humidity when the soil thermal conductivity is known.

In conclusion we would like to notice the difficulties arising during the experimental tests. They are caused by complex structure of various soil types and complicated physical processes undergoing in the ground during such measurements. Further studies on developing detailed measurement methods seem to be purposeful, particularly what concerns measuring thermal properties of the soils of high humidity. The studies should also be focused on complex determination of the effect of the type, density, humidity, and temperature of the soil on its thermal conductivity.

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