STUDYING OF THE EFFECT OF BOUNDARY CONDITIONS ON HEAT TRANSFER IN SOIL IN THE IGDIR REGION (EASTERN ANATOLIA, TURKEY)

ИЗУЧЕНИЕ ВЛИЯНИЯ ГРАНИЧНЫХ УСЛОВИЙ НА ТЕПЛОПЕРЕНОС В ПОЧВЕ В ИГДИРСКОМ РЕГИОНЕ, ВОСТОЧНОЙ АНАТОЛИИ (ТУРЦИЯ)

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Experimental investigations were carried out to establish the infl uence of boundary conditions at depth in soil on the solution of inverse problems of modeling of heat transfer in soils. Soil temperature was measured by waterproof, portable temperature sensors according to the soil profile in the field. For this purpose, 1 soil profile in the land at different depths (x=0, 5 10, 15, 20, 40, 60 cm) thermal sensors (Temperature recorder Elitech RC-4) have been installed to measure soil temperatures depending on time and depths. Based on these data, the thermal diffusivity in soils was calculated using the classical (layered) and proposed (point) methods developed for the case with one and two harmonics, and they were compared and the calculated characteristics were compared with the experimental results. It was found that the proposed point methods best reflect the movement of heat in the soil profile.

Проведены экспериментальные исследования по установлению влияния граничных условий на теплоперенос в почве. Температуру почвы измеряли водонепроницаемыми переносными датчиками температуры в соответствии с профилем почвы в поле. Для этого был установлен 1 профиль почвы на разных глубинах (x = 0, 5, 10, 15, 20, 40, 60 см), термодатчики (регистратор температуры Elitech RC-4) для измерения температуры почвы в зависимости от времени и глубины. На основании этих данных была рассчитана теплопроводность в почвах с использованием классических (слоистых) и предложенных (точечных) методов, разработанных для случая с одной и двумя гармониками. Расчетные характеристики сопоставлены с результатами эксперимента. Установлено, что предлагаемые точечные методы лучше всего отражают движение тепла в профиле почвы.

Keywords: soil, heat, modeling, boundary conditions, thermal diffusivity.

Ключевые слова: почва, тепло, моделирование, граничные условия, теплопроводность.

https://doi.org/10.46646/SAKH-2020-1-227-230

Soil temperature is one the most important factors affecting physical, chemical, and biological characteristics of soils. The main thermal characteristics of soil are the coefficients of volumetric heat capacity, thermal conductivity, thermal diffusivity, thermal absorptivity (assimilability), heat flow on the soil surface and the damping depth of diurnal temperature waves. Knowing the above characteristics of the soil can bring a solution to such a modern problem as forecasting the thermal regime of soils [1, 3-4]. Determination of these parameters is important to understand behavior of soil thermal regime and manage soil temperature at field scale. Several methods are available to model soil thermal properties, including apparent diffusivity, from observed soil temperature [1-5] . All of these researchers and others noted that most of these models are based on solutions of the one-dimensional heat equation with constant diffusion. In modeling heat-transfer processes in soil, there is a need for analysis of solution of heat-transfer equations, since for practical calculations of a thermal regime, use can be made of approximate solutions that have a simpler form and possess a sufficient accuracy, which must be, as far as possible, in fuller conformity with the physical picture of the processes of heat propagation in soil. To this end, it is expedient to make an analysis of the impact on heat transfer in soil using simplify models most frequently used in practice and to assess the influence of boundary conditions, individual terms, and coefficients of differential equations, and the effects of the dimensions of the region on the process being described.

The objective of this study was investigate the influence of boundary conditions in the soil depth under natural conditions on the development of methods to determine the soil′s thermal diffusivity based on solution of inverse problems of a heat-transfer equation.

In this case, the thermal conductivity and diffusion coefficient were predicted on the undisturbed soil profile by four different classical and two improved methods, and the results were compared.

The research was carried out by opening a profile at 2 m length and 60 cm width in the land of Iğdır University Agricultural Application and Research Center located within the borders of Melekli Municipality of Iğdır Province. The geographical location of the study area is between $39^0,1 – 39,5^0$ East longitude and 44^0 -44,2 ^{0} North latitude. Located at

850 m above sea level, the Igdir region covers approximately 3.588 (1.479) km^2 plain exhibiting a no uniform characteristic in terms of topography (Fig. 1).

Figure 1 – Location of study area

Thermal sensors used for measuring and recording soil temperature in the soil profile with the depths of 0, 5, 10, 15, 20, 40 and 60 cm. In this study, soil temperature was measured with a portable thermal Sensor (Elitech RC-4 Mini temperature data logger). The sensor registers and stores temperature measurements in its memory. Recorded temperature degrees are stored directly and can be downloaded by users via data cable (Fig. 2).

Figure 2 – Placing the thermel sensors (Elitech RC-4 Mini temperature data logger) in soil profile

Assuming that a soil is vertically homogeneous, the one-dimensional distribution of the temperature field is described by the following equation of heat conduction [3, 7]:

$$\partial T / \partial t = \kappa \cdot \partial^2 T / \partial z^2 \quad (\kappa = \lambda / C_v) \tag{1}$$

Where, κ : Thermal diffusivity, m^2/s; λ: The thermal conductivity, W/(m·°C); $C_v = P_b \cdot C_m$: Volumetric heat capacity (J/m^3·°C); P_b : The soil bulk density (kg/m^3) Cm : The specific heat capacity (J/kg·°C).

In the present work, were used the four (the so-calleds) classical algorithms and two improveds method, were used to estimate the thermal diffusivity κ, based on solving of equation (1). Below are the formulas that are used for the case when the daily temperature variation on the soil surface is represented by one and two harmonics.

These algorithms for calculating the apparent thermal diffusivity of soil κ are shown in Table 1.

Table 1 – Six algorithms to determine the Thermal Diffusivity k

No.	Name	Formula	References
Classical algorithms			
1	Amplitude algorithm	$\kappa = \frac{\pi}{\tau_0} \cdot \frac{(z_2 - z_1)}{\ln^2\left[\frac{T_{max}(z_1) - T_{min}(z_1)}{T_{max}(z_2) - T_{min}(z_2)}\right]}$	Carslaw and Jaeger, 1959
2	Phase algorithm	$\kappa = \frac{\pi}{\tau_0}\left(\frac{z_1 - z_2}{\varphi_2 - \varphi_1}\right)^2$	Nerpin and Chudnovskii,1967
3	Arctangent algorithm	$\kappa = \frac{\pi (z_2 - z_1)^2}{\tau_0 \cdot \arctan^2\left[\frac{(T_1' - T_3')(T_2'' - T_4'') - (T_2' - T_4')(T_1'' - T_3'')}{(T_1' - T_3')(T_1'' - T_3'') + (T_2' - T_4')(T_2'' - T_4'')}\right]}$	Kaganov and Chudnovsky, 1953

4	Logarithmic algorithm	$\kappa = \dfrac{4\pi\cdot(z_2-z_1)^2}{\tau_0\cdot\ln^2\left\{\dfrac{[T_1(z_1)-T_3(z_1)]^2+[T_2(z_1)-T_4(z_1)]^2}{[T_1(z_2)-T_3(z_2)]^2+[T_2(z_2)-T_4(z_2)]^2}\right\}}$	Kolmogorov, 1950
Improved algorithms			
5	Methods-1	$\kappa=\dfrac{\pi}{\tau_0}\cdot\dfrac{(2z_*)^2}{\ln^2\left\{\sum_{i=1}^{4}\left[T(z_*,t_i^*)-T(z_*,t_{i+4}^*)\right]^2/4T_a^2\right\}}$	Mikayilov and Shein, 2010
6	Methods-2	$\kappa=\dfrac{\pi}{\tau_0}\cdot\left(\dfrac{L}{b_1^*}\right)^2$	

where; $T_{min}(z)$ and $T_{max}(z)$ – are the minimum and maximum temperature values during the measurement at the depths $z=z_1$ and $z=z_2$ respectively, τ_0– period of heat wave, $T_i(z_1)$ and $T_i(z_2)$ in the furmulas (3)-(4) are the soil temperature values at the depths $z=z_1$ and $z=z_2$, respectively, at the time at the time moment (for our example $\tau_0 = 24$ h and $t_1=6$, $t_2=12$, $t_3=18$ and $t_4=24$ h).

The performance of four methods was evaluated by Pearson's Correlation Coefficient (*r*), Coefficient of Determination (R^2), Root Mean Squared Error (RMSE, σ), Mean Absolute Percentage Error (MAPE, A), and Theil's U Statistic (*UII*).

Vertical changes of soil properties in soil profile and soil column are depicted in Table 2.

Table 2 – Some physical and chemical properties of research soil

Depth (z)	Clay	Silt	Sand	BD*	OM	q	*Cv*
m	%			kg m^{-3}	%	$m^3\ m^{-3}$	kJ $m^{-3}\ {}^0C$
0-10	28.60	32.10	39.80	0.9743	1.40	0.2406	1757.5904
20-25	25.50	29.50	45.10	1.0491	2.35	0.2584	1901.3979
30-35	14.20	19.60	66.30	1.1581	3.07	0.2672	2033.1646
50-60	22.45	33.35	44.20	1.3431	1.60	0.1870	1820.3163
0-60	22.69	28.64	48.85	1.1312	2.11	0.2383	1878.1173

**BD: Bulk density; OM: Organic matter; θ: Volumetric water content; C_v: Volumetric heat capacity*

To determine the parameters of the soil′s active surface (T_0, T_i, and ε_i), we adopted one and two harmonics in condition (2). Using the measurement results for $x = 0$, that is, $T\ (x = 0,\ t_j)$ and using the least squares method, we determined the parameters of the temperature distribution of the surface of the in studied soils. Table 2 gives results of calculation of the parameters, and also statistical characteristics of approximation between – the initial data, and – the data computed from formula (2) for n = 1 and n = 2.

As can be seen from Table 3, the introduction of the second harmonic makes it possible to determine with high accuracy the parameters of the temperature distribution on the soil surface.

Table 3 – Parameters of the field soils surfaces and model performance

№	The Parameters at the soil surface	Numbers of harmonics			
		m=1		m=2	
1	Mean Temperature at soil surface (T_0), ${}^0C$	T_0	26.8488	T_0	26.8488
2	Amplitude of oscillations of the soil surface temperature (Ti), ${}^0C$	T_1	19.5764	T_2	5.5732
3	Phase shift	ε_1	2.4929	ε_2	-1.0678
№	Statistical approximation parameters				
1	Coefficient of Determination, %	R^2	91.77	R^2	99.21
2	Root Mean Squared Error (RMSE) T in t	σ	4.54	σ	1.48
3	Mean Absolute Percentage Error (MAPE), %	A	18.37	A	3.91
4	Normalized Standard Error or Theil's U Statistic	UII	0.1359	UII	0.0421

Mean values for soil thermal diffusivity (κ), thermal conductivity (λ), and damping depth (*d*), calculated by amplitude, phase, arctangent and logarithm methods, are given in Table 4.

After determining the values of the thermal diffusivity κ, using the classical and improveds formulas (1-6) listed in Table 1, the values of T (z, t) for the depths of 5, 10, 15, 20, 40, and 60 cm were calculated for the soil temperature.

Table 4 – The mean values of the thermal diffusivity (k), thermal conductivity (λ), damping depth (d), and heat absorptivity (e) of studies soils, calculated by six different methods.

№	Type of methods	C_v	$10^{-6} \cdot k$	λ	*d*	*e*
		kJ/($m^3 \cdot {}^0C$)	m^2/s	W/(m· °C)	m	$W \cdot h^{0.5}/(m^2 \cdot {}^oC)$
Classical Methods						
1	Amplitude	1878.1173	0.5416	1.0172	0.1220	23.0362
2	Phase	1878.1173	6.2780	11.7908	0.4155	78.4300
3	Arctangent	1878.1173	13.2986	24.9764	0.6048	114.1498
4	Logarithm	1878.1173	0.4889	0.9183	0.1160	21.8878
Improved Methods						
5	Methods-5	1878.1173	0.2878	0.5405	0.0890	16.7917
6	Methods-6	1878.1173	0.2701	0.5074	0.0862	16.2693

A comparison of numerical calculations revealed that improved methods 1 and 2, with a comparison with all classical methods, give satisfactory results (see Table 5). Therefore, when modeling heat transfer in soils, it is necessary to take into account conditions of the second kind on the lower boundary. And to determine the parameter thermal diffusivity it is advisable to use Method 2.

Table 5 – Values of parameters σ and A for comparing methods 1-6

z	**σ***				**A**			
depth	Numbering of methods				Numbering of methods			
m	1	4	5	6	1	4	5	6
0.05	3.876	3.836	3.940	1.560	12.534	12.196	11.876	3.841
0.10	3.927	3.780	3.448	2.068	12.301	11.661	10.980	4.645
0.15	3.728	3.610	3.408	2.603	11.727	11.717	12.284	6.175
0.20	3.364	3.279	3.168	2.457	11.667	11.721	12.006	5.745
0.40	3.151	3.160	3.158	1.640	12.586	12.657	12.664	3.739
0.60	3.992	3.993	3.993	2.219	16.596	16.596	16.597	5.302

**RMSE (σ)–Root Mean Squared Error, MAPE (A)–Mean Absolute Percentage Error.*

When modeling heat transfer in soils, it is necessary to take into account conditions of the second kind on the lower boundary. And to determine the parameter thermal diffusivity it is advisable to use Method 2.

In fact, at certain depths, convective heat transfer is absent and the heat flux is zero, so it is necessary to accept the boundary conditions of the second kind i.e., conditions (5).

If the depth of profile is relatively small, then it is advisable to use Method 1, since this method also takes into account the values of the amplitude of the soil surface.

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