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Simulation of thermal field in soil

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A – koncepcja
B – zestawienie danych
C – analizy statystyczne
D – interpretacja wyników
E – przygotowanie maszynopisu
F – przegląd literatury

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Abstract

Heat energy resources from the ground may be rationally used to maintain optimal microclimate conditions inside livestock buildings. Simulation of heat and mass exchange, as factors influencing the thermal field in the ground, is extremely complicated because of the necessity of taking into consideration many different mechanisms that govern the happening phenomenae and also chemical and mineralogical properties of the very complicated, multicomponent medium of soil. The parabolic, partial differential equation was proposed as one which describes accurately enough the simulated problem. In this case soil was considered as a quasi-homogenic body for which a normal equation for heat conduction may be applied, interrelating the temperature T, time t and depth z. The simulation for climatic conditions at Zaporozhye region (Ukraine) demonstrated that the annual temperature oscillation in soils reaches 9–17 m in depth, depending of the soil type and its heat conductivity. The results of simulation may be used in technical solutions to harness the geothermal sources of heat.

Key words: soil, thermal field, soil thermal conductivity, soil thermal resources, depth

Introduction

The maintenance of optimal microclimate in animal buildings entails a significant consumption of energy and costs. It is impossible to achieve cheap and high quality livestock products in short time without keeping optimal microclimate conditions in animal buildings. The microclimatic impact consists of combined effect of the temperature, air humidity, air gaseous composition and air pollution. One of ways to increase the efficiency in livestock production is cutting down costs of maintaining these conditions, using alternative energy sources, and in particular – geothermal energy [DYJAKON, MILA 2013; KREIS-TOMCZAK 2008; ONISZK-POPŁAWSKA i in. 2011; SZULC, ŁASKA 2012].

For the rational use of potential energy of soils with the application of technical equipment, having ground heat exchangers as working elements, it is necessary to determine the temperature field formed by various factors (Fig. 1). In doing so, first and foremost we need to calculate the temperature field of soil (that is to say, in the absence of thermal action on the soil of ground heat exchange system), which will be taken into account in the simulation of technological processes and technical systems capable of using geothermal energy.

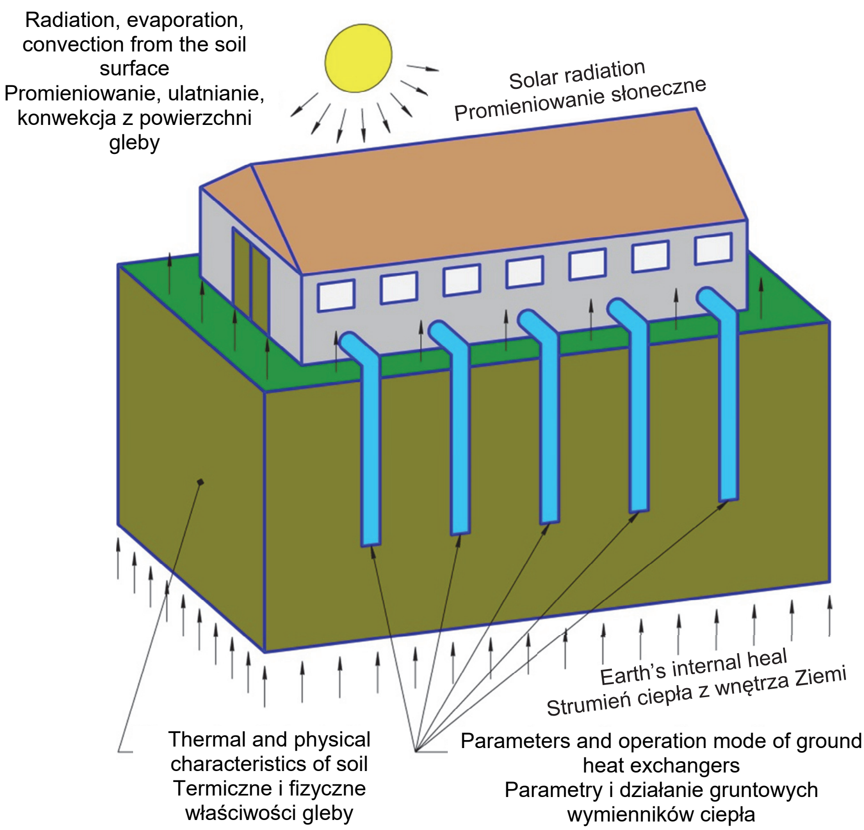

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Fig. 1. Soil thermal field forming factors
Rys. 1. Czynniki wpływające na pole rozkładu ciepła w gruncie

DENISOVA [2003], GRZYBEK, PAWLAK [2015a, b], POLJANIN [2001] and other authors provide the dependencies which can be used for determination of thermal field in soils. However, these dependencies do not consider Earth's radiogenic heat flux of 65–101 $mW \cdot m^{-2}$ [POLLACK et al. 1993] for continental regions, including Ukraine's territory, which results in the steady increase in the soil temperature of 3°C for every 100 m of depth on the average [KAVANAUGH, RAFFERTY 1997; PABIS 2011].

CHROMOV, PETROSJANC [2006] and NERPIN, CHUDNOVSKIJ [1967] provide the following expression for thermal field in soil that allows us to consider Earth's radiogenic heat flow:

$$T_g(z,t) = A_T\, e^{-z\sqrt{\frac{\pi}{a_g \Theta}}} sin\left(\frac{2\pi}{\Theta}t - z\sqrt{\frac{\pi}{a_g \Theta}}\right) + \varphi(z) \tag{1}$$

where:

$T_g(z, t)$ = the soil temperature at time t and depth z [°C];
A_T = amplitude of the soil surface temperature (at $z = 0$) [°C];
a_g = thermal conductivity of the soil [$m^2 \cdot month^{-1}$];
Θ = amplitude cycle, $\Theta = 12$ months;
$\varphi(z)$ = function describing the distribution of temperature in the ground with depth at the initial moment of time, which can be used to calculate Earth's radiogenic heat flow.

The problem was solved with given initial condition: $T_g(z, 0) = \varphi(z)$ and boundary conditions: $T_g(\infty, t) = 0$; $T_g(0,t) = A_T\, sin\left(\frac{2\pi}{\Theta}t + t_0\right)$, where t_0 is the initial phase.

However, the above reference does not provide a detailed derivation of the expression (1), and what is more, the derived expression satisfies neither the initial condition nor the boundary conditions at the soil surface, what can be proved by direct substitution.

Results of investigations

Simulation of heat and mass transfer, which is a factor of thermal field formation in such a multi-component system as soil, is a highly complicated task because of the necessity of considering mathematical description and implementation of various mechanisms: thermal conductivity of solids, heat transfer from one solid particle to another upon their contact, molecular thermal conductivity of the medium that fills the space between solid particles, convection of steam and water occupying the pore space, and so on. Strictly speaking, besides the aforesaid mechanisms, the simulation of soil thermal field requires the consideration of chemical and mineralogical characteristics of the soil skeleton, mechanical properties of solids, dispersion degree in porous medium, shape and size of solids and pores, number of phases, quantitative relationship between phases and their relative position in the porous medium and many other physical and chemical parameters of the soil. The detailed consideration of the aforesaid factors in simulation of soil thermal fields represents a serious problem [KOLPAKOV 2016; VASILEV 2006].

However, applying the model of equivalent thermal conductivity we can to describe those processes accurately enough by means of the parabolic partial differential equation using equivalent coefficients [CHUDNOVSKIJ 1976]. In this case, the soil is considered as a quasi-homogeneous body for which an ordinary heat conduction equation, relating temperature T_g, time t and depth z, can be applicable.

$$\frac{\partial T_g}{\partial t} = a_g \frac{\partial^2 T_g}{\partial z^2} \tag{2}$$

The soil thermal field can be determined based upon a solution of the basic equation (2) with preset boundaries, that is the initial and boundary conditions.

The initial condition is defined by using the function of temperature distribution with depth of the earth at the initial moment of time:

$$T_g(z, 0) = T_{g0} + k_T z \tag{3}$$

where:

T_{g0} = average annual temperature at the soil surface [°C];

k_T = the rate of temperature increase with depth depending on the rate of Earth's radiogenic heat flow, can be taken as k_T = 0,03°C·m^{-1} for thermal conditions of Ukraine.

Boundary conditions expressing the law of soil-environment interactions, should be formulated as two soil boundaries.

The boundary condition at the soil surface can be written as follows:

$$T_g(0, t) = T_{g0} + A_T \sin\left(\frac{2\pi}{\Theta} t\right) \tag{4}$$

The amplitude of temperature oscillations decay with depth, and when the value $z \geq Z$ is reached, the soil temperature remains practically unchangeable in the prescribed time interval, that allows the setting of the following boundary condition [CHUDNOVSKIJ 1976]:

$$T_g(Z, t) = T_{g0} + k_T Z = \text{const.} \tag{5}$$

According to CHROMOV and PETROSJANC [2006], annual temperature-oscillations decay in amplitude towards zero at a depth of 30 m in polar latitudes, at a depth of 15–20 m in mid-latitudes, and about 10 m in tropical latitudes (where annual amplitudes have lower values then in middle latitudes). At these depths the annual soil temperature remains constant.

Therefore, Z = 100 taken for the boundary condition (5) will guarantee the absence of temperature oscillations at this depth and lead to lower computational costs to an acceptable level.

The soil surface temperature for Zaporozhye region was determined as a function of time using "Scientific-practical handbook of SSSR climate" [Gidrometeoizdat 1990] and based on the approximation of long-term data (Fig. 2).

$$T_g(0, t) = 120 + 15.2 \sin\left(\frac{2\pi}{12} t + 4.15\right) \tag{6}$$

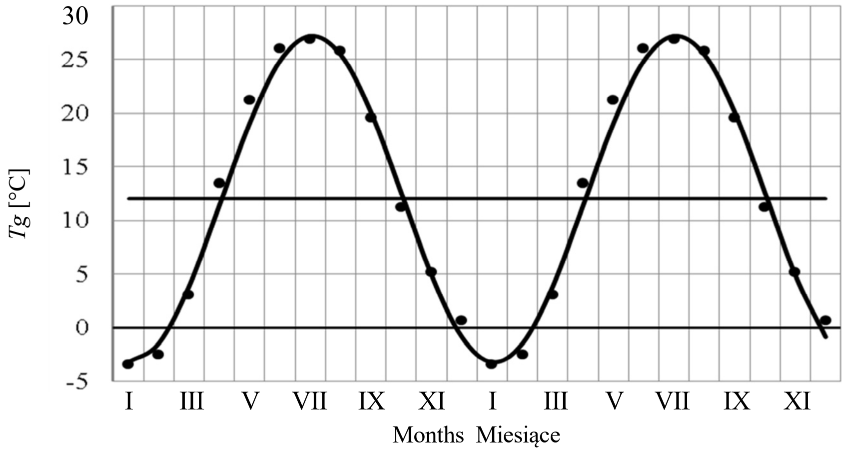

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Fig. 2. Soil surface temperature according to long-term data for Zaporozhye region
Rys. 2. Temperatura wierzchniej warstwy gleby według wieloletnich danych dla regionu Zaporozhye

The expression (6) contains the initial phase of temperature oscillations equal to 4.15 months. Therefore, in simulation of the soil thermal field with the use of the initial condition (4) not including the initial phase, we set approximately April 20 (see Fig. 2) as the process start date for Zaporozhye region (not January 15 because we only have the average monthly temperature data at soil surface). That is to say, for natural climatic conditions of Zaporozhye region the annual average temperature at soil surface is determined as of April 20.

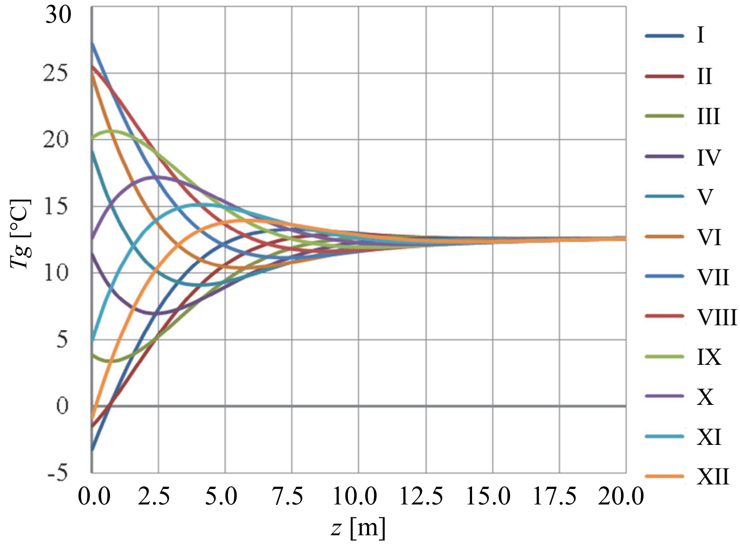
With increasing soil density and moisture content thermal conductivity increases, temperature oscillations become faster and penetrate more deeply into soil. According to SNiP [2005], soil thermal conductivity coefficient a_g = 0,76–2,67 $m^2 \cdot month^{-1}$, and at the same density and moisture content, it is also dependent upon soil type. For example, sand has the highest coefficient of thermal conductivity, sandy loam – somewhat less, and loam has the lowest value.

Having solved the equation (2) with the boundary conditions (3), (4), (5) using numerical method and taking into account the initial phase t_0, we obtained the dependence of soil temperature on time and depth as shown on the Fig. 3.

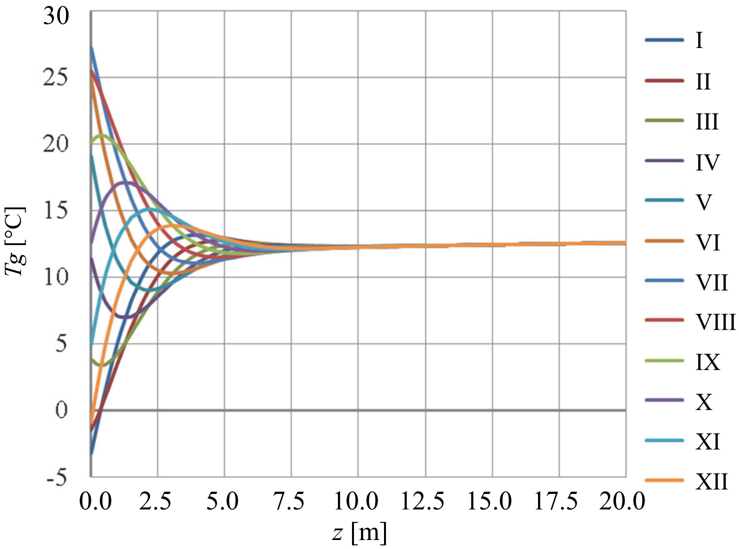
As shown in the Figure 3, annual soil temperature oscillations can penetrate to depth z = 9–17 m under natural climatic conditions of Zaporozhye region.

Therefore, there is an algorithm allowing the simulation of a soil thermal field:
1) To determine the coefficient k_T, that takes into account the increase in temperature with depth.
2) To approximate long-term records of soil surface temperature by means of the following type of function $T_g(0,t) = T_{g0} + A_T \sin\left(\frac{2\pi}{\Theta}t + t_0\right)$.

a)



b)



Source: own elaboration. Źródło: opracowanie własne.

Fig. 3. Soil temperature T_g in various months of a year, depending upon depth z with coefficient of thermal conductivity: a) $a_g = 2.67$ m^2·month^{-1}, b) $a_g = 0.76$ m^2·month^{-1}; I, II, III... XII – months

Rys. 3. Temperatura gleby T_g w poszczególnych miesiącach roku, na różnych głębokościach, gdy współczynnik przewodności cieplnej: a) $a_g = 2{,}67$ m^2·miesiąc^{-1}, b) $a_g = 0{,}76$ m^2·miesiąc^{-1}; I, II, III... XII – miesiące

3) To determine the soil thermal conductivity coefficient a_g related to the type, density and moisture of soil.
4) To solve the equation (2) with boundary conditions (3), (4), (5) taking into account the initial phase t_0.

Conclusions

The algorithm has been developed allowing the simulation of the temperature field in soils under various natural climatic conditions and in soils having different coefficients of thermal conductivity. It has been established that under climatic conditions of Zaporozhye region annual soil temperature fluctuations reach the depth *z* = 9–17 m. Obtained results will be used for simulation of technology processes with technical facilities designed for use to harness geothermal energy.

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SYMULACJA POLA ROZKŁADU TEMPERATURY W GLEBIE

Streszczenie

Zasoby energii cieplnej gruntu mogą być wykorzystane w celu zapewnienia należytego mikroklimatu w budynkach inwentarskich. Symulowanie wymiany ciepła i masy jako czynników pola rozkładu temperatury w gruncie jest wysoce skomplikowane ze względu na konieczność uwzględnienia znacznej liczby mechanizmów rządzących zachodzącymi zjawiskami, a także chemicznych i mineralogicznych własności bardzo złożonego środowiska glebowego. Zaproponowano wykorzystanie parabolicznego, cząstkowego równania różniczkowego, dostatecznie dokładnie opisującego ekwiwalentną przewodność cieplną gleby. Założono przy tym, że gleba jest quasi-homogenicznym ośrodkiem, w odniesieniu do którego może być zastosowane zwykłe równanie przewodzenia ciepła uzależniające wzajemnie temperaturę T, czas t i głębokość z. Wyniki symulacji dla warunków klimatycznych regionu Zaporoża (Ukraina) świadczą, że wahania temperatury w ciągu roku sięgają, zależnie od rodzaju gleby i jej przewodności cieplnej, do głębokości 9–17 m. Wyniki symulacji mogą być zastosowane w rozwiązaniach technologicznych służących do wykorzystania ciepła z gruntu.

Słowa kluczowe: gleba, pole rozkładu temperatury, przewodność cieplna gleby, zasobność cieplna gleby, głębokość

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