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HEAT BALANCE
OF HORIZONTAL GROUND HEAT EXCHANGERS

BILANS CIEPLNY POZIOMYCH GRUNTOWYCH WYMIENNIKÓW CIEPŁA

Abstract: This work refers to the modelling of heat transfer in horizontal ground heat exchangers. For different conditions of collecting heat from the ground and different boundary condition profiles of temperature in the ground were found, and temporal variations of heat flux transferred between the ground surface and its interior were determined. It was taken into account that this flux results from several different mechanisms of heat transfer: convective, radiative, and that connected with moisture evaporation. It was calculated that ground temperature at great depths is greater than the average annual ambient temperature.

Keywords: ground heat exchangers, heat balance

Introduction

Energy contained in the ground is used for heating purposes. The ground can also be used as the place where the excess heat can be transferred. Taking heat from the ground and transferring it to the ground occurs in heat exchangers installed in the ground. The main classification of ground heat exchangers refers to their geometrical orientation; there are vertical and horizontal exchangers. An overview of the application of ground heat exchangers and numerical models related to them was presented by Florides and Kalogirou [1]. Soni et al. [2] presented the types of ground heat exchangers and their applications.

Horizontal ground heat exchangers are installed at small depths, which causes heat to be transferred to the ground surface and the environment contributes significantly to the heat balance. Depending on the relation between net heat transferred in the exchanger and net heat transferred through the ground surface, the ground average temperature changes. The differences in ground temperatures (with heat exchanger installed) before heating seasons in successive years were determined by Adamovsky et al. [3]. In the extreme case temperature decreased of 1.54 K.

Horizontal ground heat exchangers are the subject of many studies that are both experimental and numerical [4-11].

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Determination of the magnitude of the heat fluxes on the ground surface has been the subject of analyses conducted by many researchers who described the specific heat fluxes occurring on the ground surface: convective flux, flux of solar radiation, flux of long-wave radiation, and flux caused by evaporation of water contained in the ground.

Such analyses were conducted by many authors [12-18]. The specific models differ in the form of empirical relationships describing the size of specific fluxes.

In the work by Ouzzane et al. [19], on the basis of the measurement data from different places in the world, the values of the undisturbed ground temperature were compared with the average annual ambient temperature. A linear correlation between these two temperatures was determined; it results from this correlation that the undisturbed ground temperature is on average 5 K greater than the average annual ambient temperature. For example, for Alert (Nunavut, Canada, latitude 82.5°) these temperatures are −13.7 and −18.7 °C, respectively; for Zaghreb (Croatia, latitude 45.8°): 15.5 and 10.5 °C, for Dhahran (Saudi Arabia, latitude 26.3°): 32.6 and 27.4 °C. This principle has a significant meaning for the design and modelling of ground exchangers; it should be stressed that for approximate calculations it is often assumed that these temperatures are equal to each other.

Transfer of heat in the ground occurs basically as a result of heat conduction. The equation of heat conduction for an infinite slab has the form:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} + \frac{q_v}{c_v} \tag{1}$$

where: T - temperature, t - time, x - position coordinate, q_v - rate of heat generation per unit volume, a - thermal diffusivity, c_v - volumetric heat capacity.

The model of the horizontal ground heat exchanger used in this work is based on the following assumptions [20, 21]:

1. The temperature of the working fluid at the exchanger outlet is equal to the ground temperature at the exchanger depth.
2. The heat transfer process in the ground can be described by the equation of heat conduction for an infinite slab (x-axis direction) with an internal source of heat.
3. The heat transfer resistance occurs only in the ground. That is why the model does not take into account the surface area of exchanger pipes.

Profiles of ground temperatures and magnitudes of specific heat fluxes in a ground heat exchanger were determined in this work. On the basis of the heat balance, the dependence of the average ground temperature on time for the long-term operation of the heat exchanger was determined. Cases referring to different boundary conditions for the ground surface were considered, including the condition describing cooperation with the environment, and the condition taking into account the different mechanisms of heat transfer and mass transfer. The case of the continuous and periodic taking heat from the ground and the case of the absence of heat being taken from the ground were analysed.

Heat balancing of ground exchangers based on the applied mathematical model allows one to predict the changes of the average ground temperature. Excessive reduction of this temperature can lead to reduction of the possibility of taking heat in successive heating seasons.

Conditions

Boundary condition on ground surface

The simplest form of this condition is the assumption that ground surface temperature and ambient temperature T_a are identical. This is the first-type (Dirichlet) boundary condition of the form:

$$x = 0;\ T = T_a \tag{2}$$

It is more realistic to assume that the heat transfer coefficient at the ground surface has a finite value and temperatures T and T_a are related to each other by the formula:

$$x = 0;\ -k\frac{\partial T}{\partial x} = h_0\left(T_a - T\right) \tag{3}$$

where: k - ground thermal conductivity, h_0 - convective heat transfer coefficient.

In the above condition it was assumed that the heat transfer between the ground surface and the environment occurs only as a result of convective heat transfer. The direction of the convective flux changes, which results from the relationship between the ground surface temperature and the ambient temperature. During warmer months (April-September) the convective flux is directed from the environment to the ground, while during colder months the direction of heat transfer is opposite.

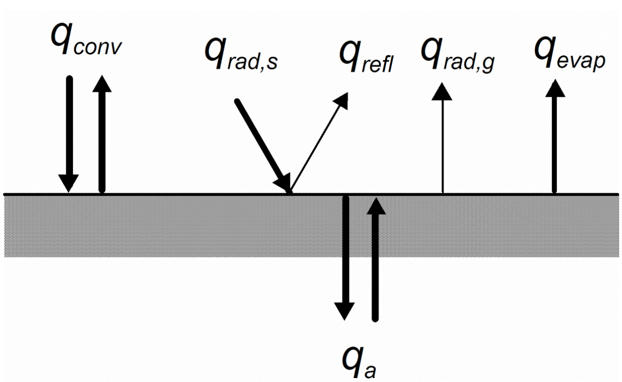

Fig. 1. Heat fluxes at the ground surface. Indexes mean: *conv* - convection, *rad,s* - solar radiation, *refl* - reflected, *rad,g* - ground radiation, *evap* - evaporative, *a* - conductive

The heat transfer coefficient between the environment and the ground depends on the hydrodynamic conditions near the surface of the ground. For the known velocity of wind u expressed in [m/s] this coefficient can be calculated from the formula [14, 16, 17]:

$$h_0 = 5.7 + 3.8u \tag{4}$$

Condition (3) does not take into account all the heat fluxes at the surface of the ground. These fluxes are presented schematically in Figure 1 [21]. The symbols denote heat fluxes expressed in [W/m^2]. The flux which results from solar radiation $q_{rad,s}$ is directed towards the ground. Some part of this flux q_{refl} is reflected from the ground surface. Regardless of the reflected flux the ground radiates heat towards the sky $q_{rad,g}$. The ground also loses heat through the evaporation of moisture contained in it. This flux q_{evap} results from the difference of water vapour's partial pressure directly above the ground surface and in the atmospheric air. Heat fluxes can be determined on the basis of appropriate formulas, mainly empirical ones.

The flux of solar radiation is highly variable over time; it occurs only during the daytime and is much greater during summer than during winter. For climate conditions in Poland the global horizontal irradiation is: for the whole year GHI_{year} = 990 kWh/m^2, while for summer GHI_{summer} = 428 kWh/m^2. On the basis of these data the relationship between solar radiation flux and time was determined. It was assumed that this relationship is a harmonic function and the maximum of radiation is on the 175$^{\text{th}}$ day of the year (June 22). It was obtained that [21]:

$$q_{rad,s} = 113 + 97 \cdot \cos\left[\frac{2\pi}{365}(t-175)\right] \qquad \left[\frac{\text{W}}{\text{m}^2}\right] \tag{5}$$

This function is presented in Figure 2. Values of $q_{rad,s}$ are averaged over 24 hours, and they take into account the whole solar radiation, direct as well as diffuse. The shaded area in Figure 2 corresponds to the amount of solar radiation incident on the surface of 1 m^2 within 3 summer months.

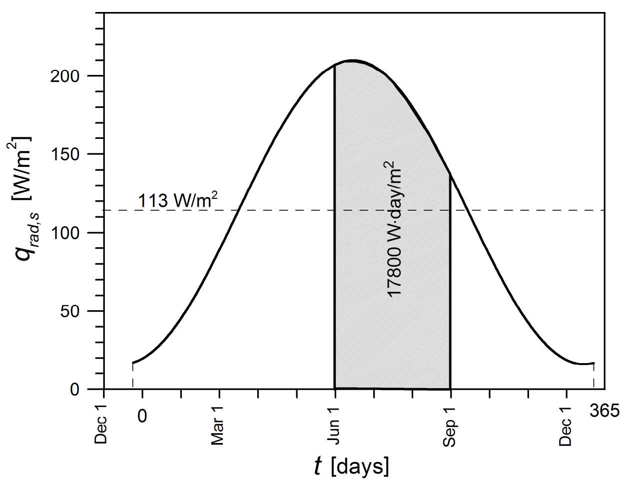

Fig. 2. Changes of solar radiation heat flux during a year

The flux of solar energy is partially reflected from the ground surface. The reflection coefficient (albedo) for the ground depends on its humidity and kind of coverage. Typical values of albedo for the ground are in the range 5-30 %.

The long-wave radiation flux depends on air temperature, its humidity, and moreover is variable during the day. The variation of this flux is not strong, and in approximate calculations it is assumed that the average long-wave radiation flux is 63 W/m^2 (towards to sky).

In addition to convective and radiative fluxes, heat is transferred between the ground and the environment as a result of the evaporation of water contained in the ground. Heat flux transferred because of the evaporation of moisture from the ground surface is:

$$q_{evap} = f k_p \left(p_i - p\right) L \tag{6}$$

where p_i and p are, respectively, partial pressure of water vapour at the surface of the ground and in atmospheric air, k_p is the mass transfer coefficient referred to the driving force expressed in partial pressures, while L is the heat of the evaporation of water. The quantity f (fraction of evaporation rate) takes into consideration that the rate of water evaporation from the ground surface is smaller than the rate of evaporation from the water surface; this coefficient is 0.1-0.2 for dry ground conditions and 0.4-0.5 for humid ground conditions. According to the heat and mass transfer Chilton-Colburn analogy, the heat and mass transfer coefficient are related to each other by the formula:

$$\frac{h_0}{\rho c_p} Pr^{2/3} = k_c\, Sc^{2/3} \tag{7}$$

where k_c is the mass transfer coefficient referenced to the driving force expressed by the differences in mass-volume concentrations $c_i - c$. The transfer coefficients k_p and k_c meet the following relation:

$$k_p = k_c \frac{c_i - c}{p_i - p} \cong k_c \frac{\rho M_w}{P M_a} \tag{8}$$

Because the ratio between the Prandtl and Schmidt numbers, Pr and Sc, is equal to the mass and thermal diffusivity ratio:

$$\frac{Pr}{Sc} = \frac{D}{a} \tag{9}$$

so it results from the combination of formulas (6)-(9) that:

$$q_{evap} = fA\left(p_i - p\right) h_0 \tag{10}$$

where A is the constant:

$$A = \frac{L M_w}{P M_a c_p} \left(\frac{D}{a}\right)^{2/3} \tag{11}$$

The value of the constant A was determined by the substitution of numerical values for molar mass of water and air, respectively, $M_w = 0.018$ kg/mol, $M_a = 0.029$ kg/mol, and physical properties at 10 °C: specific heat $c_p = 1010$ J/(kg·K), heat of evaporation $L = 2.48 \cdot 10^6$ J/kg, diffusivity in air $D = 22.5 \cdot 10^{-6}$ m^2/s and thermal diffusivity $a = 19.4 \cdot 10^{-6}$ m^2/s. For pressure $P = 1 \cdot 10^5$ Pa it was obtained that $A = 0.0168$ K/Pa, which is consistent with the value given in the literature [16, 18].

Hence, the boundary condition at the ground surface, taking into account convection, radiation and humidity evaporation, has the form:

$$x = 0; \qquad -k \frac{\partial T}{\partial x} = h_0 \left(T_a - T\right) + q_\Sigma \tag{12}$$

where:

$$q_\Sigma = q_{rad,s} \left(1 - \alpha\right) - q_{rad,g} - q_{evap} \tag{13}$$

Boundary condition at great depths of the ground

If the geothermal flux for the Earth's interior is not taken into account in calculations, this condition refers to such a depth of the ground h_{inf}, under which temperature does not change with location (undisturbed temperature). Therefore, it is:

$$x = h_{inf} \qquad T = T_{undist} \tag{14}$$

If the value of the undisturbed ground temperature is not known, the following condition can be used:

$$x = h_{inf} \qquad \frac{\partial T}{\partial x} = 0 \tag{15}$$

When the geothermal flux q_{geo} is taken into account in calculations, the suitable condition has the form:

$$x = h_{inf} \qquad \frac{\partial T}{\partial x} = G \tag{16}$$

However, in this case the depth h_{inf} is difficult to determine because ground temperature does not stabilize with depth. The average increase of ground temperature is 3 °C per each 100 m of depth, which gives approximate value of the geothermal gradient G = 0.03 K/m.

Heat balance

Heat fluxes in the ground are marked in Figure 3.

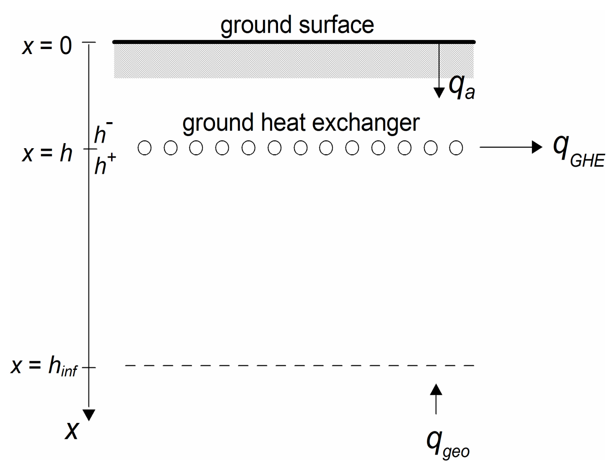

Fig. 3. Ground heat exchanger. Indexes mean: *GHE* - ground heat exchanger, *geo* - geothermal, *a* - conductive

It was assumed that while heat is transported in the direction of the arrows, then corresponding flux is positive. The heat balance of the ground exchanger has the form:

$$q_a - q_{GHE} + q_{geo} = h_{inf}\, c_v \frac{d\overline{T}}{dt} \tag{17}$$

The average temperature of the ground for the depth from 0 to h_{inf} equals:

$$\bar{T} = \frac{1}{h_{inf}} \int_{0}^{h_{inf}} T \cdot dx \tag{18}$$

The flux transferred between the ground surface and its interior q_a is determined by the Fourier equation:

$$q_a = -k \left(\frac{\partial T}{\partial x} \right)_{x=0} \tag{19}$$

An analogous relationship was also used to determine the geothermal flux:

$$q_{geo} = kG \tag{20}$$

Calculations that are based on formula (1) were conducted with the use of the finite difference method. The following values of parameters were used: k = 1.5 W/(mK), $c_v = 3 \cdot 10^6$ J/(m^{3}K), G = 0.03 K/m. It was assumed that the maximum depth of the ground taken into account in calculations (thickness of the model infinite slab) was h_{inf} = 50 m. Therefore, the geothermal flux has the value $q_{geo} = 1.5 \cdot 0.03 = 0.045$ W/m^2.

Continuous collection of heat with a constant ground surface temperature

In numerical calculations, a horizontal ground heat exchanger is an infinite slab of thickness Δx which results from digitizing the position coordinate x. Therefore, heat is transferred to/from the upper and bottom surfaces of the exchanger. The relationships between heat fluxes for the upper and bottom surfaces and their temporal variations were studied numerically. In order to obtain greater transparency of the resulting relationship it was assumed that the ground surface temperature is constant.

Calculations were conducted by solving equation (1) with conditions (2) and (16). It was assumed that the exchanger is at depth h = 1 m and the heat flux collected in the exchanger is q_{GHE} = 3.014 W/m^2. Because the ambient temperature and initial ground temperature are the same and equal to T_b = 8.5 °C, heat is transferred from the ground surface inside the ground without changes of the heat transfer direction, so $q_a > 0$. Profiles of ground temperatures are presented in Figure 4a. The profile of temperature above the exchanger stabilized fairly rapidly, while the profile in deeper layers of the ground changed even after 15 years.

The calculated values of temperature T_h of the ground at the depth where the exchanger is located, and values of the heat flux q_a are presented in Figure 4b. When heat flux q_a reaches the value of q_{GHE} = 3.014 W/m^2, then accumulation of heat in the ground reaches the zero value, so the average temperature of the ground does not change and the process becomes steady in time. It was also calculated that temperature T_h corresponding to steady heat conduction in a slab is:

$$T_h = T_b - \frac{q_{GHE} h}{k} = 8.5 - \frac{3.014 \cdot 1}{1.5} = 6.49 \text{ °C} \tag{21}$$

It can be seen in Figure 4b that both q_a and T_h tend to reach the values presented above.

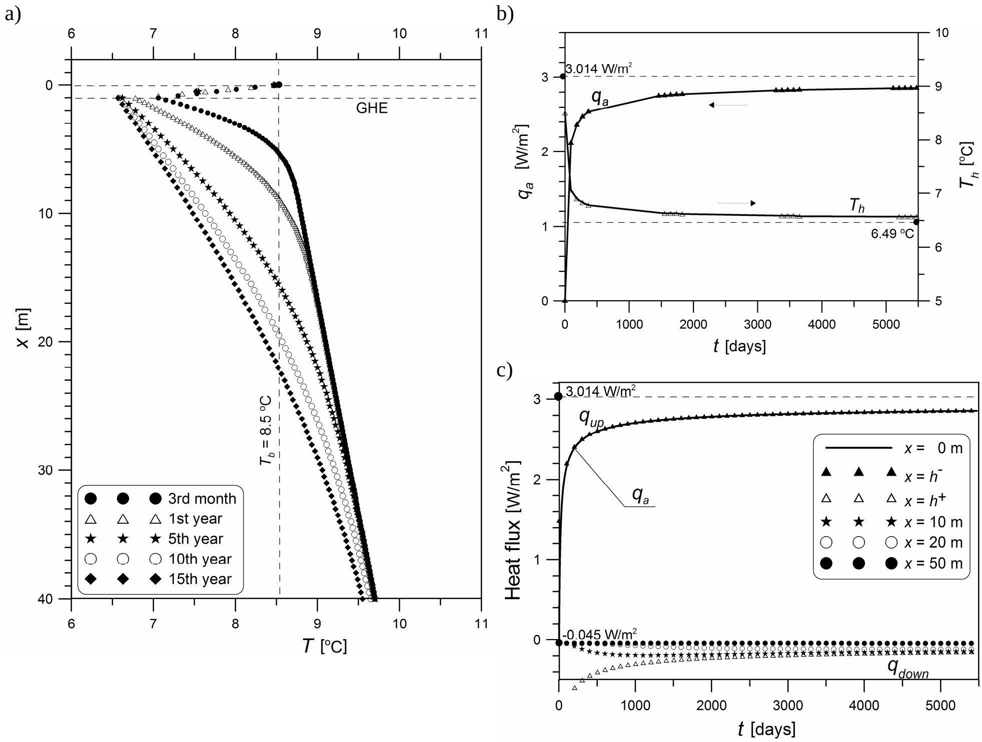

Fig. 4. The case of a constant ground surface temperature: a) ground temperature profiles, b) q_a and T_h vs time, c) heat fluxes in the ground at different depths vs time

On the basis of temperature profiles, temperature gradients can be determined. Among others, gradients of temperature for the top ($x = h^-$) and bottom ($x = h^+$) surfaces of the exchanger (Fig. 3) were determined, and they were used to find the values of the heat fluxes.

In Figure 4c heat fluxes transferred by different cross-sections of the ground with the heat exchanger are presented. Temperature gradients for the top surface of the exchanger, for its bottom surface and for several depths of the ground under the exchanger, and for the depth h_{inf} were determined. It can be seen from the figure that in the exchanger most of the heat is taken by the ground through the top surface of the exchanger, and that heat fluxes are highly variable with position and time in the initial period. Therefore, fluxes change even after 15 years despite the exchanger's constant operation and the fact that the ambient temperature was assumed to be steady.

The heat flux for the top surface of the exchanger q_{up} is almost identical with the flux q_a, which means that heat transfer above the exchanger is close to steady. The flux q_{up} is positive because gradient $(dT/dx)_{x=h-}$ is negative. The flux q_{up} increases with time. The limit is 3.014 W/m^2, which corresponds to the complete coverage of the heat flux collected from the ground in the exchanger by the heat flux q_a.

The remaining fluxes presented in Figure 4c are negative (pointing down) because temperature gradients under the heat exchanger are positive. The heat flux near the bottom surface of the exchanger q_{down} is much smaller (its absolute value) than q_{up} and decreases with time. The algebraic sum of both fluxes is constant and equal to $q_{up} + (-q_{down}) = 3.014$ W/m^2. For larger depths of the ground heat fluxes transferred upwardly become smaller. For sufficiently long times these fluxes decrease. The geothermal flux is the limit value for all the heat fluxes directed toward the top.

When there is no accumulation of heat, the temperature profile below the exchanger becomes a straight line at an angle $\beta = \text{atan}(G)$ to the vertical direction.

Convection, radiation and evaporation from the ground surface - no collection of heat from the ground

Calculations in this chapter were conducted by solving equation (1) with conditions (12) and (16). In order to determine the form of a boundary condition at the ground surface, the numerical values of the following quantities were assumed: wind velocity u = 2 m/s, relative humidity of air 60 %, average temperature of the ground surface 10 °C (saturated water vapour pressure at this temperature is p_{sat} = 1227 Pa), fraction of evaporation rate f = 0.3, albedo of the ground α = 0.1. The heat transfer coefficient calculated from formula (4) is h_0 = 13.3 W/(m^{2}K). After substitution of numerical values into (13), it was obtained that:

$$q_{\Sigma} = 6 + 87 \cdot \cos\left[\frac{2\pi}{365}(t - 175)\right] \tag{13a}$$

The ambient temperature T_a changes periodically according to the formula:

$$T_a = T_b + B \cdot \cos\left[\frac{2\pi}{365}(t - t_{max})\right] \tag{22}$$

where: T_b = 8.5 °C, B = 10.4 K and t_{max} = 198 days. Calculations refer to the natural conditions (no taking heat from the ground), so $q_{GHE} = 0$.

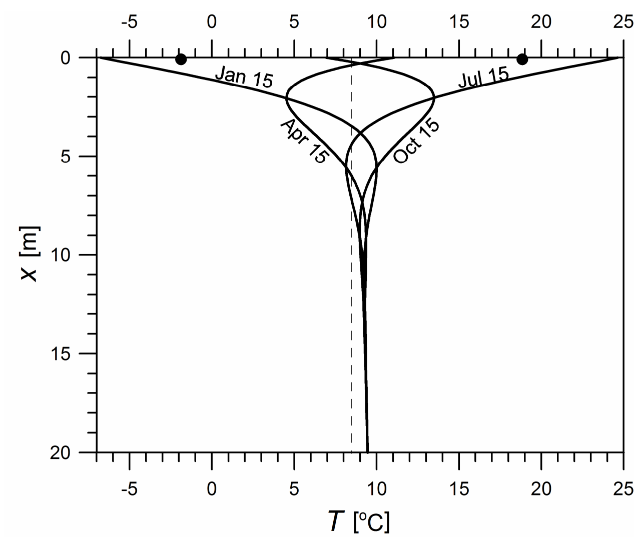

Fig. 5. Temperature profiles in the ground. No collection of heat from the ground

The presented results refer to a long term process. Therefore, temperature profiles practically do not change in time. Such profiles for four days in a year are presented in Figure 5. It can be seen from this figure that the common line characterizing the profile of the ground temperature at great depths is not vertical (temperatures do not stabilize with depth), which results from the fact that the geothermal flux is taken into account in the boundary condition. Moreover, ground temperatures at great depths are greater than the average ambient temperature (8.5 °C), which is consistent with data presented in [19].

Temperatures of the surface of the ground are between −7 and 25 °C, so their range is greater than the range of ambient temperature, which is between −1.9 and 18.9 °C for the assumed values of parameters T_b and B (extreme values of ambient temperatures are indicated with dots). Differences in the extreme temperatures of ground surface and environment result from taking into account the flux of solar radiation and the flux caused by humidity evaporation.

Convection, radiation and evaporation from the ground surface - periodic collection of heat from the ground

The third considered case refers to the collection of heat from the ground during the heating season. The following form of function defining the relationship between the flux of taken heat and ambient temperature was assumed:

$$q_{GHE} = \begin{cases} 10\ \mathrm{W/m^2} & \text{for} \quad 1\ ^\circ\mathrm{C} < T_a < 8.5\ ^\circ\mathrm{C} \\ 0\ \mathrm{W/m^2} & \text{for} \quad T_a \le 1\ ^\circ\mathrm{C} \quad \text{or} \quad T_a \ge 8.5\ ^\circ\mathrm{C} \end{cases} \tag{23}$$

It can be seen from formula (22) that condition (23), referring to taking heat from the ground, is fulfilled 94 days per year. Therefore, heat taken from 1 m^2 of the ground during a year is $10 \cdot 94 \cdot 24 \cdot 3600$ = 81.2 MJ/m^2. The pipes of an installed heat exchanger are located h = 2 m deep, and the assumed boundary conditions are the same as in the previous chapter (eqs. (12) and (16)).

Ground temperature profiles, steady over time for four days of a year, are presented in Figure 6a. Deviation of the temperature profiles from the vertical direction for large depths of the ground, and differences in winter-summer spans of the ground surface and ambient temperatures are analogous to the ones which are observed when heat is not collected from the ground.

Collection of heat from the ground causes its temperature to decrease. However, the reduction of the ground temperature leads to the increase of the amount of heat transferred from the environment, which partially compensates for further cooling of the ground. This can be seen in Figure 6b, in which it is presented how the average ground temperature changes over time. Cooling of the ground occurs more and more slowly, but it does not vanish completely, even after several decades.

In Figure 6c the relationship between the heat flux q_a and time during a calendar year (after many years of exchanger exploitation) is presented. The shape of this function confirms that the heat fluxes directed from the ground surface to the ground interior are greater than fluxes in the opposite direction. As a result of the integration of heat fluxes, it was obtained that the net heat transported from the ground surface to the ground interior is 78.8 MJ/m^2 (Fig. 6c). The geothermal heat flux (0.045 W/m^2) does not play a significant role in the heat balance, hence the thermal deficit of the ground is

78.8 – 81.2 = −2.4 MJ/m^2. This deficit can be easily recalculated for the annual reduction of the average ground temperature. It can be seen from the integrated form of relationship (17) that:

$$\Delta\overline{T} = \frac{1}{h_{inf} c_v} \int_0^t (q_a - q_{GHE}) dt = \frac{-2.4 \cdot 10^6}{50 \cdot 3 \cdot 10^6} = -0.016 \text{ K} \tag{24}$$

which is consistent with the value determined from the curve presented in Figure 6b.

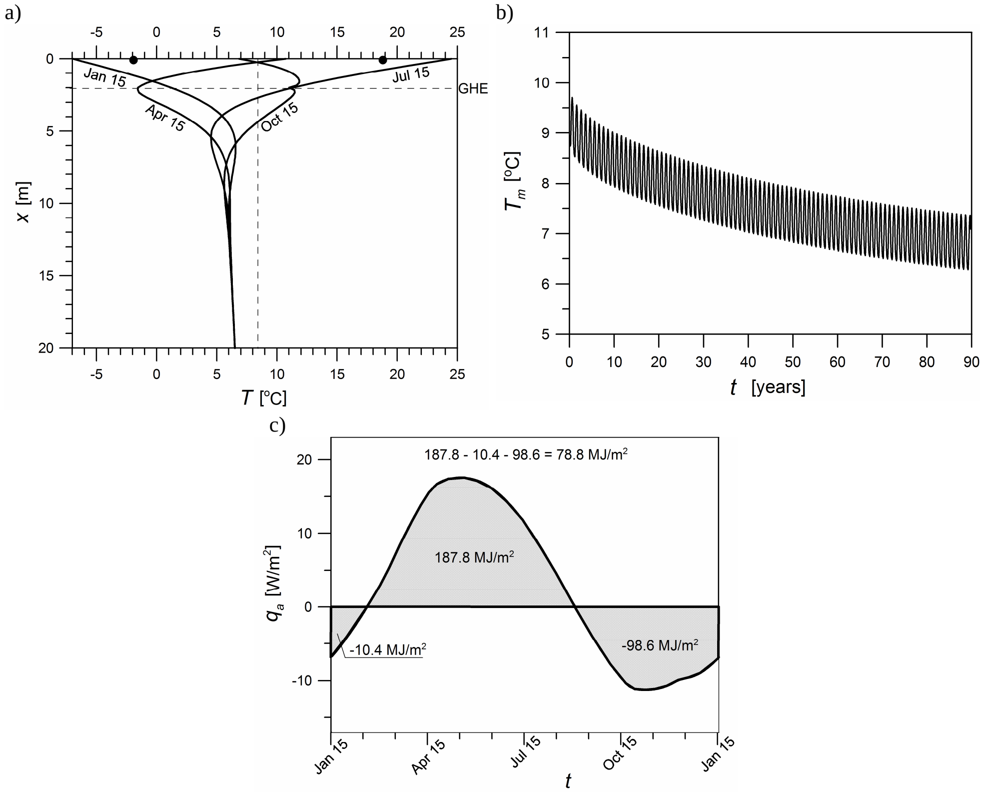

Fig. 6. Periodic collection of heat from the ground: a) temperature profiles in the ground, b) temporal variations of the average ground temperature, c) changes of heat flux between the environment and ground during a year

Conclusions

- When heat is collected from the ground and the ground surface temperature is constant, continuous lowering of temperature reaching greater and greater depths occurs under the place where the exchanger is located. When the flux of heat transferred to the exchanger from its bottom becomes equal to the geothermal flux, the heat transfer in the ground becomes a steady process. In this state the flux of heat taken in the exchanger is equal to the sum of the flux delivered to the ground interior from the ground surface and the geothermal flux.

- Modelling of ground heat exchangers requires that heat fluxes connected with radiation and moisture evaporation are taken into account in the boundary condition at the ground surface, except for the convective flux. Not taking these fluxes into account is equivalent to accepting that the undisturbed ground temperature and annular average ambient temperature are equal to each other.
- The net amount of heat transferred from the environment to the ground per year does not ensure complete compensation of the heat deficit; this deficit can be complemented by heat transfer from deeper layers of the ground.

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