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An analysis of the boundary conditions model influence on the ground temperature profile determination

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In this work, the influence of boundary conditions model (environmental model) on the ground temperature profile is analyzed. A numerical model for transport phenomena in the area above the top ground surface and below in the ground is presented. The results of simulation – ground temperature profile and mean seasonal temperature which estimate the energy potential of the ground are presented. In addition, the results of implementation of five different environmental models for the area above the top ground surface are presented. It is found that none of the models is able to reproduce the temperature variation similar to the reference (most complex) model accuracy. On the other hand, it is found that with a slight error a similar result for low ground depth can be obtained using the simplest Model 1.

Keywords: heat transfer, ground heat transport, ground temperature profile, ground source heat pump.

1. Introduction

In recent times, a rapidly growing interest in the heat pump system with ground heat exchanger as a lower heat source has been noticed [1]. In most cases, this solution is economically justified in our climatic zone. The proper design of the ground source system, which partially collects heat in the summer and/or returns it in the winter (at least for regeneration) is a very complex task. It requires a specific knowledge of different areas such as: transport phenomena, engineering, geology and environmental protection.

The studies in [2] show that the ground has a large thermal potential. Ground temperature and ground thermophysical parameters are very important for assessment of the usefulness of the ground, and they directly influence the performance of the ground heat pump systems (GHPS) [3, 4]. The initial ground temperature profile is often one of the most important criteria for the economic justification of using this kind of system [1]. When selecting a system, one should pay attention not only to thermal potential, but also to coherence. The ground meets these requirements very well and it is a justified option in most cases, mainly due to a possibility of obtaining one of the highest coefficients of performance for the Linde cycle ($\mathrm{COP_L}$) and the seasonal performance factor (SPF) that is higher than in other lower heat sources.

When designing this kind of installations, a practical tool that does not overestimate is a computer simulation of ground heat exchanger [5, 6]. Simulations of this type allow for a detailed system analysis and the precise selection of system element. Designing of a heat exchanger for the lower heat source, without unnecessary re-dimensioning, leads to a significant reduction of investment costs [7]; however, underestimation, may lead to the improper system operation, often to deep freezing and, in the worst case, to damaging of ground heat exchanger.

In order to estimate precisely the ground potential and to conduct computer analysis, it is necessary to have information about the ground geological structure as well as boundary conditions, in particular the conditions occurring at the ground top surface, i.e., atmospheric conditions [8]. Without knowledge of these parameters, computer simulation which includes the complex models of heat transport in the ground [9] is not able to provide correct information for selection of ground heat exchanger. As the publications show [10–12] ground temperature at low depth has a significant daily and seasonal dependence on ambient temperature, but there are no studies about models which are a combination of different weather elements, e. g., solar radiation, wind speed or air temperature. In the most cases, (daily) average air temperature is the only known environmental parameter.

The present work aims to develop a computer model of heat transport in the ground, taking into account all key phenomena occurring in the ground and on its top surface. The analysis of such phenomena based on the temperature distribution at the different depth allows to decide which model components are the most important for this type of studies and which have to be accounted for. Determination of a temperature profile [3] and mean seasonal temperature of the ground allows also to estimate the ground thermal potential based on calculating theoretical $\mathrm{COP_L}$ values.

2. Mathematical model

In order to determine the temperature distribution in the stratified ground, it is necessary to have a mathematical model of the transport phenomena occurring inside the continuous medium and on all its surfaces [13]. Furthermore, for small depths, a key for the heat transport is the heat exchange with the environment. The scheme of the main elements of the energy balance taken into consideration in the presented model has been shown in Fig. 1. Symbol q_{con1} represents heat flux exchanged by natural convection, q_{con2} is the heat flux exchanged by forced convection, q_{sol} is the heat flux exchanged by solar direct and indirect radiation, q_{ter} represents the Earth's radiation, q_{pre} is the heat flux exchanged by precipitation, q_{eva} is related to the water evaporation from top ground surface, q_f represents heat flux related to the groundwater flow and q_{ph} heat flux related to phase change. The natural Earth's heat flux is represented by the symbol q_e. This study assumes that the ground consists of several lithological layers with L_i thicknesses and different thermophysical properties. A detailed information about the ground structure can be found in Table 2.

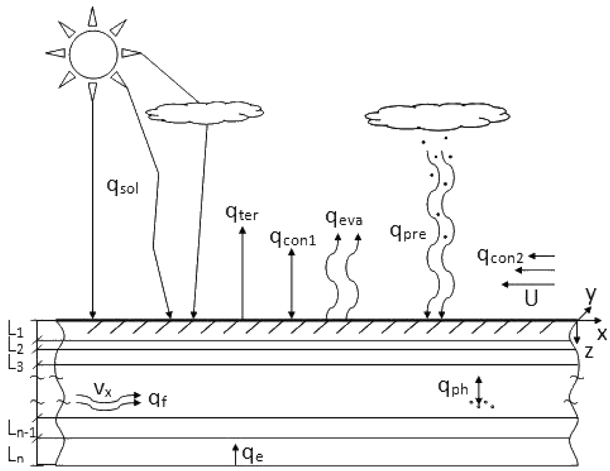

Fig. 1. Main elements of energy balance on the top surface and in the ground.

Assuming variations of ground properties with depth z only, non-stationary of the phenomena, ground water flow and phase changes, the equation for heat transport in the Cartesian coordinate system can be written as follows:

$$\rho_z c_{pz}\frac{\partial T}{\partial t} + \rho_w c_w\left(v_x\frac{\partial T}{\partial x} + v_y\frac{\partial T}{\partial y} + v_z\frac{\partial T}{\partial z}\right) = k_z\frac{\partial^2 T}{\partial x^2} + k_z\frac{\partial^2 T}{\partial y^2} + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + s, \tag{1}$$

where ρ_z, ρ_w are the ground and water density, respectively, kg/m^3, c_{pz}, c_w – specific heat of the ground and water, respectively, J/(kg·K), k_z – thermal conductivity of the ground, W/(m·K), t is the time, s, v_x are the Darcy velocity of groundwater flow in x direction, m/s, and v_y and v_z are respectively in y, z direction, and s represents a source term resulting from phase change (q_{ph} in Fig. 1).

2.1. Parameters of the ground

Thermophysical properties of the ground (ρ_z, c_{pz}, k_z) have an obvious significant influence on heat transfer in the ground and strongly depend on porosity, structure and the soil water content (saturation). In the case of wet soils, the thermal conductivity can be determined as follows [9]:

$$k_z = \left(k_{\text{sat}} - k_{\text{dry}}\right) K_e + k_{\text{dry}}, \tag{2}$$

where k_{sat} is the thermal conductivity for saturated ground, W/(m·K), k_{dry} is the thermal conductivity for dry ground, W/(m·K), and K_e is the Kersten number. The number K_e depends on the degree of saturation of soil moisture S_r. A detailed information about the determination of k_{sat}, k_{dry} and K_e for frozen and not frozen ground can be found in [9]. For saturated soils, density ρ_z can be determined from equation [9]:

$$\rho_z = \rho_{\text{dry}}(x_{\text{ice}} + x_w + 1), \tag{3}$$

where ρ_{dry} is the density of dry ground, kg/m^3, x_{ice} is the ratio of the mass of pore ice to the dry mass of the ground, kg$_{\text{ice}}$/kg$_{\text{dry}}$, x_w analogously as x_{ice}. Specific heat c_{pz} can be calculated as follows:

$$c_{pz} = \frac{\rho_{\text{dry}}}{\rho_z}(x_{\text{ice}}c_{\text{ice}} + x_w c_w + 1 \cdot c_{\text{dry}}), \tag{4}$$

where c_{dry} is a specific heat of dry ground, J/(kg·K), and c_{ice} is a specific heat of ice, J/(kg·K). Water content in the ground could freeze when the temperature is lower than 0°C; in this case, temperature- dependent ice conductivity is introduced.

Groundwater flow is included in Eq. (1) in terms including velocity components v_x, v_y and v_z. In general, the flow of water (if any) in the ground is typically in one depth interval and the flow velocity is in the order of 10 to 300 m/year [1], but locally velocity can be much larger. In this study, it is assumed that underground water flow occurs in the horizontal direction at depths between 4 and 6 m.

2.2. Elements of the energy balance on top surface of the ground

The equation of the energy balance of the top ground surface ($z = 0$) depends on the model under consideration and it may be written, in general form, as follows:

$$T(x, y, 0, t) = f(t) \tag{5}$$

in the case of Model 1, and in the following form for other types of models:

$$\frac{\partial}{\partial z}\left(k_z \frac{\partial T(x, y, 0, t)}{\partial z}\right) = f[q(t)] = f[q_{\text{tot}}(t)]. \tag{6}$$

Heat source q_{tot} variable in time, is a difference between the heat source delivered (q_{in}) to the ground surface and transferred to the environment (q_{out}):

$$q_{\text{tot}} = q_{\text{in}} - q_{\text{out}}. \tag{7}$$

This study takes into account all key atmospheric phenomena presented in Fig. 1. In accordance with the heat exchange methods provided, the heat flux balance for the ground top surface can be written as

$$q_{\mathrm{tot}} = \max(q_{\mathrm{con1}}, q_{\mathrm{con2}}) + q_{\mathrm{sol}} + q_{\mathrm{ter}} + q_{\mathrm{pre}} + q_{\mathrm{eva}}. \tag{8}$$

The first two balance components in Eq. (8) are free (natural) and forced convection. In the case of a positive temperature gradient above the ground surface, conditions for the existence of free convection q_{con1} are met, and in the case of air movement (wind velocity $|U| > 0$) forced convection q_{con2} occurs. Despite the high complexity of convection phenomena, one can assume that, at the local scale, Earth is a flat horizontal plate. Then, heat transport through convection can be determined as

$$q_{\mathrm{con1}} = \alpha_{\mathrm{con1}} \cdot (T_{\mathrm{air}} - T) \qquad \text{and} \qquad q_{\mathrm{con2}} = \alpha_{\mathrm{con2}} \cdot (T_{\mathrm{air}} - T), \tag{9}$$

where α_{con1}, α_{con2} are the heat transfer coefficients, W/(m^2·K), in case of free and forced convection, respectively, and T_{air}, T are surrounding air temperature and local ground temperature, respectively. The coefficients, similarly to the ratio of natural convection to the forced one, depend on a number of factors, including air thermophysical parameters, local difference in air-ground surface temperatures and air speed. Due to the necessity of solving complex model equations, semi-empirical solutions using the following characteristic numbers (Nusselt, Reynolds, Prandtl and Rayleigh number) are the most frequently applied:

$$\mathrm{Nu} = \frac{\alpha L}{k}, \qquad \mathrm{Re} = \frac{UL}{\nu}, \qquad \mathrm{Pr} = \frac{c_p \nu}{k}, \qquad \mathrm{Ra} = \frac{g\beta\,(T - T_{\mathrm{air}})\,L^3}{\nu a}, \tag{10}$$

where U is a magnitude of temporary value of wind speed, m/s, L characteristic dimension defined as the length of the area under consideration, ν, β, α and a parameters are the kinematic viscosity, m^2/s, thermal expansion coefficient of air, 1/K, heat transfer coefficient, W/(m^2·K) and thermal diffusivity, m^2/s, respectively. For forced convection, the value of the Nusselt number has been determined based on the dependencies [13]:

$$\mathrm{Nu} = 0.664\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3} \quad \text{for laminar flow}, \tag{11}$$

$$\mathrm{Nu} = 0.037\mathrm{Re}^{4/5}\mathrm{Pr}^{1/3} \quad \text{for turbulent flow } \mathrm{Re} > 10^5. \tag{12}$$

In the case of natural convection, the following formulas have been used for the heat transfer above a heated horizontal plate, depending on the nature of fluid movement [13]:

$$\mathrm{Nu} = 0.54\mathrm{Ra}^{1/4} \qquad \text{for} \qquad 10^4 < \mathrm{Ra} < 10^7, \tag{13}$$

$$\mathrm{Nu} = 0.15\mathrm{Ra}^{1/3} \qquad \text{for} \qquad 10^7 > \mathrm{Ra}. \tag{14}$$

At each point, only one type of convection (the one that had a higher magnitude in the balance) was used in the calculations.

Another element of heat balance on the ground surface is solar radiation q_{sol} reaching the Earth's surface:

$$q_{\mathrm{sol}} = (1 - A) \cdot I_T = (1 - A) \cdot (I_b + I_r), \tag{15}$$

where I_T is total solar radiation, W/m^2, and A – local Earth's albedo. Solar radiation may reach the ground surface directly I_b, W/m^2, and indirectly I_r, W/m^2 (diffuse solar radiation in the atmosphere); furthermore, a part of the radiation is reflected from the surface. All those items are accounted in the dependency (15). In the present study, a constant albedo has been assumed to be $A = 0.2$ (for lawn).

The last balance component in Eq. (8) taken into consideration is the Earth's thermal radiation q_{ter}. This type of radiation is also called long-wave thermal radiation and it causes a continuous reduction of the ground temperature. The amount of energy radiated from the Earth's surface in a time unit depends on temperature and the type of an external layer. Emissivity of typical natural Earth's surfaces (lawn, rock, sand, and even water) is about 0.95–0.98. On that basis, it has been assumed, in this study, that the Earth's surface can be treated as the approximation of a perfect grey body with the emissivity of 0.97 (for lawn). The amount of a heat due to thermal radiation can be determined from the following formula:

$$q_{\text{ter}} = \varepsilon \cdot \sigma \cdot (T(x,y,z,t)^4 - T_{\text{sky}}^4), \tag{16}$$

where ε – emissivity (for lawn), T_{sky} – reference (background or sky) temperature, K, and $\sigma = 5.67 \cdot 10^{-8}$ W/(m$^2 \cdot$K^4) is the Stefan-Boltzmann constant. The reference temperature can be specified on the basis of several models available in the literature [14]. In this study, the following formula has been applied:

$$T_{\text{sky}} = 0.0552 \cdot T_{\text{air}}^{1.5}. \tag{17}$$

Snow covering the ground surface or rain may also affect both the albedo and emissivity; furthermore, precipitation may cause additional heat exchange through melting and evaporation, heat accumulation or giving it back, both to the environment and to the ground. Due to the lack of the accurate measurement data, these phenomena have not been taken into consideration in the current analyses (q_{pre} and q_{eva} were omitted). Based on the heat balance, for the top ground surface, five different models taking into consideration different environmental phenomena have been developed. The models considered in this paper are summarized in Table 1 and take into account only selected or all balance equation components.

Table 1. Mathematical models for the top surface.

Assumed conditions on the ground top surface ($z = 0$)		
Model 1	$T(x,y,z) = f(t)$	Temperature in time function is given, specified on the basis of actual air temperature.
Model 2	$\dfrac{dT(x,y,z)}{dz} = f[q_{\text{con}}(t)]$	Natural and forced convection is taken into account, specified on the basis of actual air velocity and temperature.
Model 3	$\dfrac{dT(x,y,z)}{dz} = f[q_{\text{sol}}(t) + q_{\text{ter}}(t)]$	Solar and thermal ground radiation is taken into account, specified on the basis of actual solar radiation.
Model 4	$\dfrac{dT(x,y,z)}{dz} = f[q_{\text{sol}}(t) + q_{\text{con}}(t)]$	Natural and forced convection as well as solar radiation are taken into account.
Model 5	$\dfrac{dT(x,y,z)}{dz} = f[q_{\text{con}}(t) + q_{\text{sol}}(t) + q_{\text{ter}}(t)]$	Natural and forced convection, solar radiation and thermal radiation are taken into account.

The natural Earth's heat flux q_e is set up as a bottom boundary condition. In Polish conditions, this value is typically in the range from 0.04 to 0.11 W/m^2 [15], excluding local geothermal anomalies. For the current research, all models take into consideration the natural Earth's heat flux equal to 0.07 W/m^2.

3. Numerical model

Temporary values of air temperature T_{air} (dry thermometer), wind velocity magnitude U and solar total radiation I_T have been introduced into the model and came from meteorological measurements for the location: City of Kraków (performed in 2014 with sampling for about 6 minutes). In order to get statistically periodic solution (with the time period of 365 days), the same weather information was repeated for each calculation cycle. Time of each simulation was 10 years. Computer simulations were conducted on the basis of potentially occurring soil structures, characterized by variations of thermo-physical properties (see Table 2). The ground type 2 was developed based on actual rock measurements taken at the AGH University of Science and Technology area. In the present calculation, in order to obtain results that are possible to be compared, only the weight-average mean values of thermal conductivity and heat capacity are used. The ground type 1 has the lowest thermal conductivity, while the ground type 3 has the highest thermal conductivity. The ground type 4 has the thermal properties of ground type 2 with additional 40% saturation of water, and only in the latter case the phase change subroutine was activated. The geometry of analysis contains the area with the dimensions of $30 \times 30 \times 100$ m, in the directions x, y and z, respectively, and has been discretized using $30 \times 30 \times 118$ elements. The applied mesh was irregular, finer close to the surface, where temperature variation was the highest. In order to solve mathematical model, a numerical algorithm has been developed in Fortran 90, based on the finite volume method. All spatial derivatives were discretized using the central scheme and time derivatives used a three- level scheme. The strongly implicit procedure (SIP) algorithm was chosen to solve the resulting set of linear algebraic equations. Spatial and temporary discretizations have been determined on the basis of testing calculations, which allowed to make the solution independent of numerical parameters (i.e., grid spacing and time step). The local mean annual temperature equal to $T_{\mathrm{ini}} = 9.66°\mathrm{C}$ was used as the initial condition in the model. Lateral model surfaces have the same temperature as the initial condition. The natural Earth's heat flux was set at the bottom surface. For the cases with underground water flow, three Darcy velocity values were taken into consideration: $v_x = 10$ m/year, 100 m/year and 1000 m/year (at depth interval between 4 and 6 m).

Table 2. Topology of the ground types.

Ground	No.	Ceiling [m]	Floor [m]	Thickness L_i [m]	Lithology	Thermal conductivity [W/(m·K)]	Heat Capacity [MJ/(m^3·K)]	No. of grid points
1	**Ground 1 – Mean values**					**0.895**	**2.291**	**118**
2	1	0	2.2	2.2	dark grey windrow with rubble	1.60	2.40	11
	2	2.2	2.6	0.4	aggradate mud (grey soil)	1.60	2.40	2
	3	2.6	4	1.4	fine and silty sand, with clay content	1.00	1.80	7
	4	4	6	2	fine sand	1.20	1.70	8
	5	6	15	9	all-ups and gravel	1.80	2.40	30
	6	15	30	15	grey clay	2.20	2.30	30
	7	30	100	70	grey shale	2.10	2.30	30
	Ground 2 – Mean values					**2.006**	**2.293**	**118**
3	**Ground 3 – Mean values**					**3.130**	**2.573**	**118**
4	**Ground 4 – Mean values**					**1.800**	**3.969**	**118**

4. Results

Numerical results have been compared with experimental measurements of the ground temperature carried out in the region of Poznań City [16]. For the local thermal properties and approximate air temperature (based on proposed approximate function [16]) temperature at the two different depths during a whole year has been calculated ($z = 0.5$ m and $z = 1.5$ m) and compared with the measurements for calendar years (2009 and 2000/2007). Taking into account the fact that the exact environmental conditions and detailed ground structure are not known (only the air temperature average function calculated for a period of 10 years), it can be seen that agreement between the measured temperature and the numerical prediction at two different locations is quite good. The largest difference occurs in the middle of summer when the average temperature is the highest. This can be caused by air temperature averaging procedure and a fitting that uses cosine function [16] (with standard error of about 3.5 K).

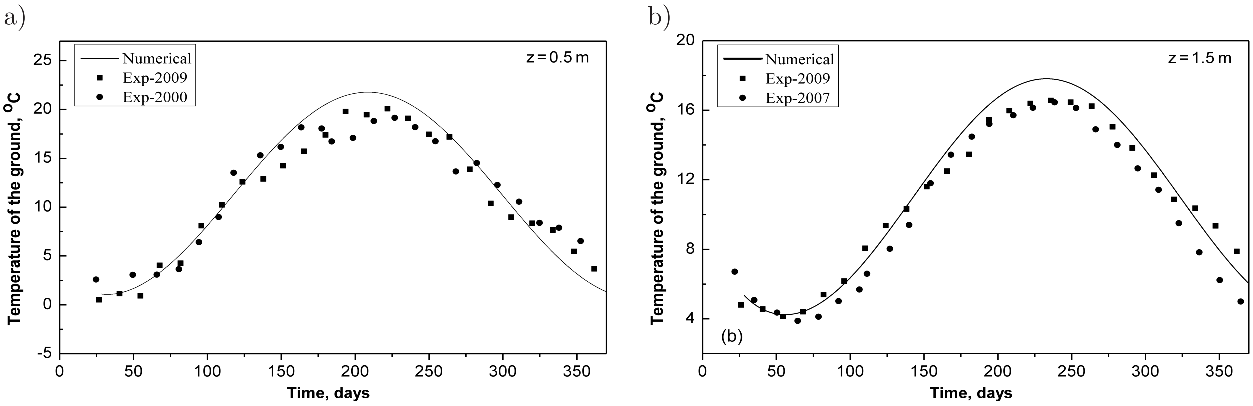

Fig. 2. Calculated temperature vs experimental measurement for region of Poznań City [16] and depth: a) $z = 0.5$ m and b) $z = 1.5$ m.

Figure 3 shows the temperature of the ground calculated by using different environmental models considered in this work. Figure 3a presents temperature at depth $z = 10$ m during the first seven

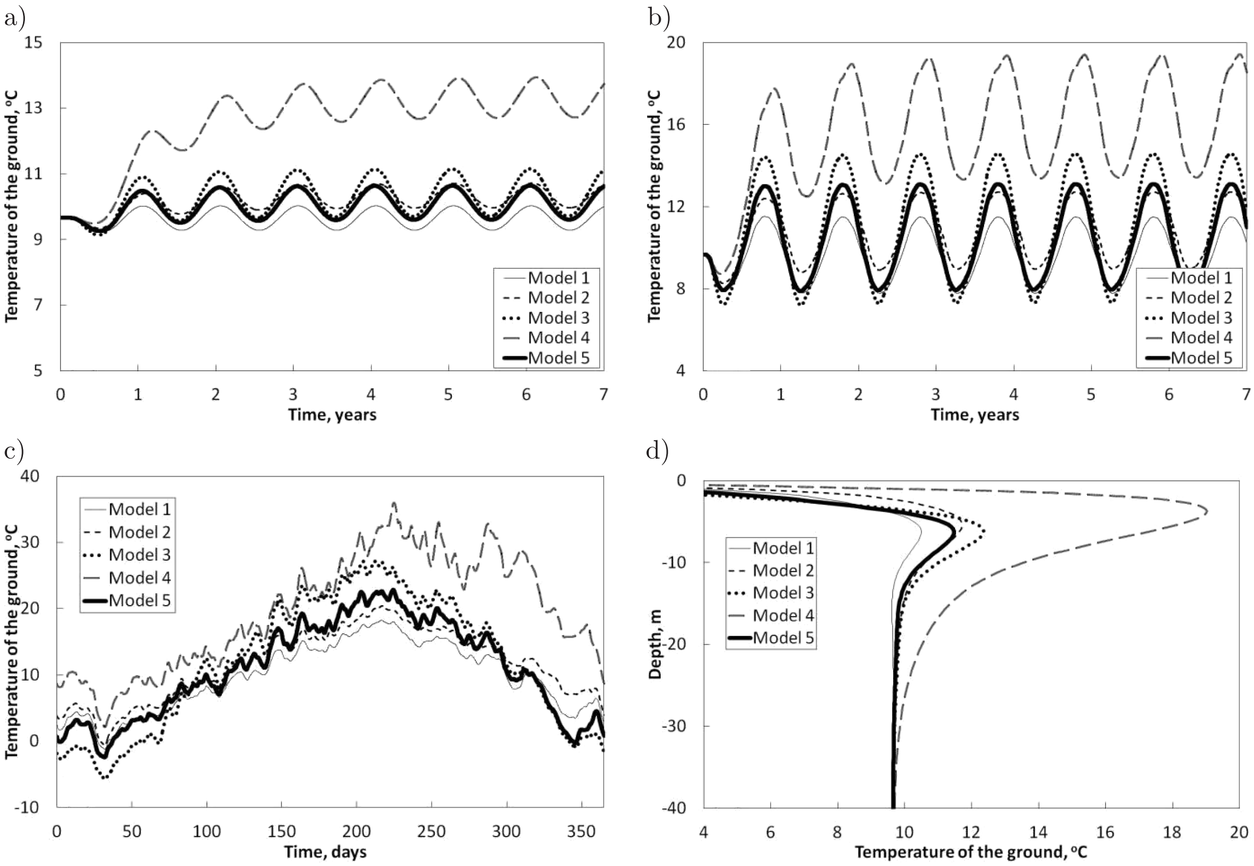

Fig. 3. Comparison of models for ground type 2 for $x = 15$ m, $y = 15$ m and at depth: a) $z = 10$ m, b) $z = 5$ m, and c) $z = 1$ m, and d) temperature profile at the end of simulation.

years of calculation. It can be seen that the most advanced model (Model 5), which is considered here as a reference model, could be roughly approximated by all presented models, except Model 4. Model 4 does not include the Earth's thermal radiation, and in consequence the predicted temperatures are significantly overestimated. Similar plot, but at depth z = 5 m, is shown in Fig. 3b, where the temperature range as well as the amplitude of temperature oscillations are much higher. Again, all models except Model 4 follow the reference Model 5. Amplitude for Model 3 is higher, and for Model 2 smaller than for the reference model. Model 1 follows minimum temperature, but underestimates the maximum temperature. In Fig. 3c, the temperature at depth z = 1 m and for one year (for clarity) has been presented. A strong weather condition dependence can be observed at this depth. The last plot, Fig. 3d, shows the ground temperature profile at the end of the simulation. The temperature profiles for different months and for ground type 2 without groundwater flow and ground type 2 with the underground flow (v_x = 100 m/year) are presented in Fig. 4. Stable values of the temperature time independent are reached at depth larger than z = 20 m. Additionally, it is observed that groundwater flow stabilizes temperature profile at flow interval (z = 4 – 6 m) as well as at lower depth. The temperature of the ground for different groundwater flow speeds is presented in Fig. 5. At the low speed (10 m/year) flow has almost no impact on the temperature, while at higher speed (100 m/year) the influence became significant and for the highest speed (1000 m/year) the temperature become almost constant (and equal to the temperature of the ground-water). Figure 6 shows the difference between four different ground types considered in this study. The amplitude of temperature fluctuations is the lowest for the ground type 1 and the highest for the ground type 3. The ground type 4 with large saturation has similar results as ground type 1, and typically water content in ground reduces thermal conductivity, but increases specific heat.

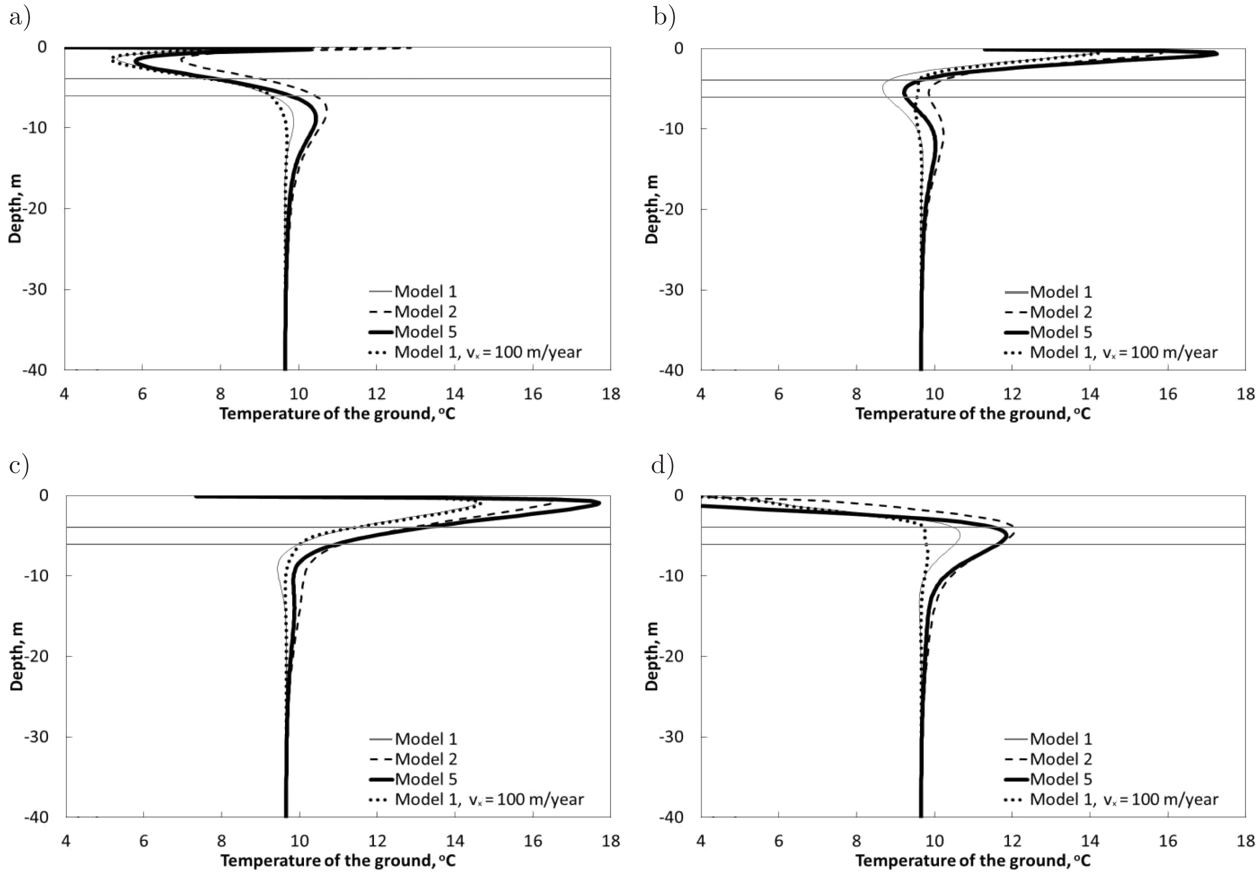

Fig. 4. Temperature of the ground type 2 for months: a) March, b) June, c) September and d) December.

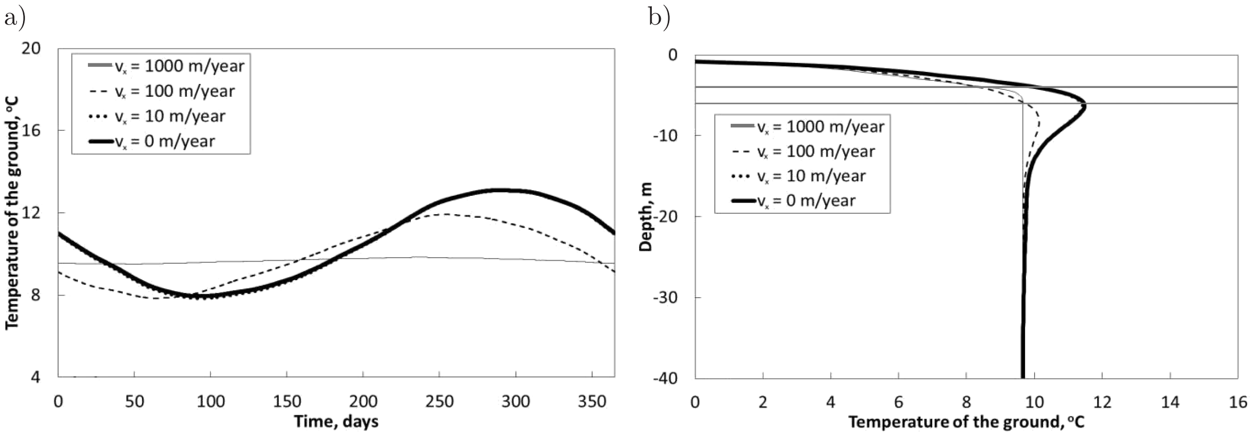

Fig. 5. Temperature of the ground type 2 for Model 5 for various groundwater flow speeds for x = 15 m, y = 15 m: a) at z = 5 m and b) profile of temperature at the end of simulation.

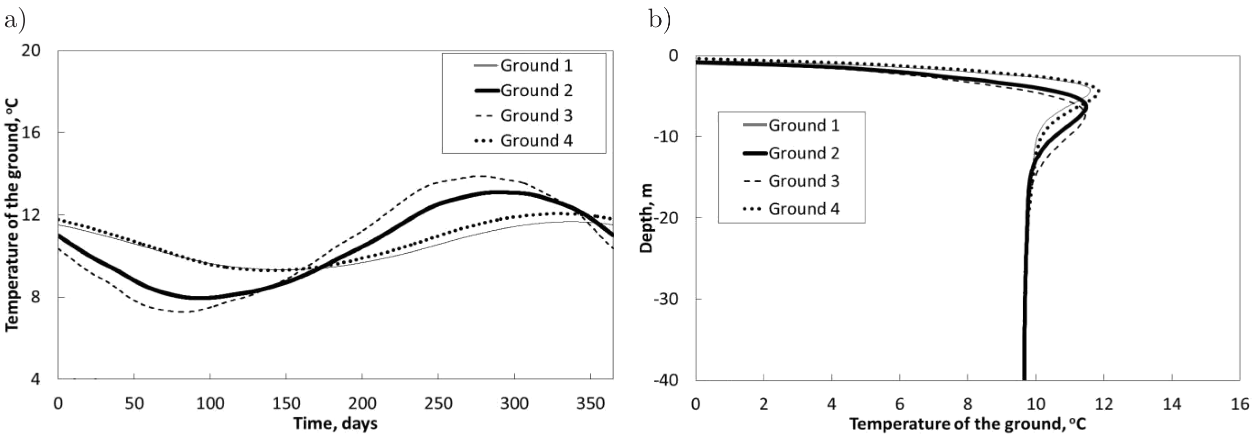

Fig. 6. Temperature of the ground calculated with Model 5 for different ground types for x = 15 m, y = 15 m: a) at z = 5 m and b) profile of temperature on the end of simulation.

On the basis of the calculation results, a mean ground temperature value was determined for the typical heating season in Poland (Table 3). Furthermore, for a heat pump (high-temperature

Table 3. Mean seasonal temperature of the ground at depth z = 5 m and Linde efficiency COP_L.

Mean values for the ground in a heating season (10th) (1 Sep. – 31 Mar.) at depth of 5 m		Model 1	Model 2	Model 3	Model 4	Model 5
		Conductivity	Conductivity + convection	Conductivity + (solar + Earth's) radiation	Conductivity + convection + solar radiation	Conductivity + convection + (solar + Earth's radiation)
Ground 1	T [°C]	10.07	11.35	11.81	17.20	11.03
	COP_L	6.37	6.65	6.75	8.21	6.58
Ground 2	T [°C]	10.19	11.48	11.91	17.61	11.13
	COP_L	6.39	6.68	6.78	8.34	6.60
Ground 3	T [°C]	10.06	11.37	11.69	17.37	11.02
	COP_L	6.36	6.65	6.73	8.26	6.57
Ground 4	T [°C]	10.07	11.40	12.28	16.91	11.33
	COP_L	6.37	6.66	6.87	8.12	6.64

source of 50°C), the efficiency of Linde's cycle, COP_L [17], was determined. It has been found that the ground type up to the depth of about 5 m, in contrast to the model type, does not significantly affect the achieved theoretical COP_L. Model 4 leads to significant overestimation of the ground resources. At the depth of 5 m, one can see similarity of the results for Model 5 and Model 2. As shown, for the purpose of selecting ground heat exchangers, the ground temperature can be determined based on Model 2 and Model 5 with similar approximation. In contrast to the analyses and results presented here, the authors' previous analyses in [18] show that Model 1 has the best fitting to the reference model but at the depth lower than about $z = 1$ m.

5. Conclusions

In this paper, various ground surface-environment heat exchange models have been studied. The reference Model 5 is considered to be the most complex, time consuming and in the best way non-linearly matching the real conditions. It has been found that none of the other models were able to reproduce the ground temperature variation with the similarity to the reference model. On the other hand, it has been found that with a slight error similar results can be obtained using the simplest Model 1. The best approximation has Model 2, for which mean seasonal temperature prediction differs only by 0.35°C in reference to Model 5 and 0.08°C for the COP_L result. This means that under the condition taken into account in this work, air temperature and wind speed are good representative factors for all environmental phenomena regardless of the type of ground (layer thickness, lithology or saturation). In any case, temperature at depth $z > 20$ m is model independent and equal, with good approximation, to mean annual air temperature. Based on the mean seasonal temperature calculated for all the models at depth $z = 5$ m and presented in Table 3, the coefficient of performance COP_L was calculated for a heat pump operating based on Linde's cycle. The achieved COP_L value is in the range from 6.57 to 6.68 both for Model 2 and Model 5. It is worth to notice that the COP_L values, acquired by means of the mentioned models, greatly overlap, regardless of the kind of ground type. The presented COP_L values should be treated as a theoretical upper limit values for two reasons: a) the coefficient of performance has been calculated using ideal Linde's cycle and not real one, and b) in the absence of the ground heat exchanger, the heat is not transferred from the ground into the heating system, and in real-life situations such a transfer will decrease local temperature (depending on ground type).

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