Mathematical Model for Using Soil Heat with Thermal Pumps
Matemātiskais modelis zemes virskārtas siltuma izmantošanai ar siltuma sūkņiem

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Abstract. Use of soil thermal energy in systems with thermal pumps is important during cold winters when the heat extracted from soil is insufficient, as well as when alternative thermal energy sources should be used for a shorter time. The amount of heat extracted from soil depends on several factors, e.g., cold carrier's technical parameters, the depth at which the cold carrier pipes are placed in soil as well as the distance between them, composition of soil, and average monthly air temperature during the building heating period. Thermal amount which is necessary for the building heating is influenced by geometrical parameters of a building, air temperature in rooms, as well as building technical parameters which are estimated by heat loss during the heating period. A computer program mathematical model of the thermal pumps' system is developed and analyzed in the paper. When planning the heating system, the mathematical model provides a possibility of calculating the distance between cold bearers (which is one of the main thermal pumps' construction parameters) with certain reserve. The developed mathematical model can be applied for any outdoor air temperature and soil thermophysical parameters which are considered when modifying the approximate coefficients. With the help of the computer system it is possible to analyze the already established thermal pump systems and to predict their efficiency – to determine the object's provision with thermal energy during the building heating season, to evaluate additional functions for the system, etc.
Key words: thermal pumps, soil**,** mathematical model, cold carriers.

Introduction

Because of the lack of traditional energy sources and increased environment pollution, energy saving is becoming more and more popular. To economically use traditional energy sources, as well as to acquire and utilize more extensively the alternative energy sources, application of modern technologies is increasing throughout the world. The most commonly used environment-friendly alternative energy sources are wind, sun, soil, and water. In Latvia, use of thermal pumps is expanding as they allow utilization of one of the alternative energy sources – solar heat accumulated in soil, water, air – with minimal electrical energy consumption.

The heat accumulated in soil upper or deeper layers can be used by installing boreholes in the soil (Blumberga, 2008). Under Latvia's climatic conditions, the soil upper level is rarely freezing deeper than 1.2–1.5 m.

Soil heat is usually used for building heating and water heating. The thermal pump heating system consists of three parts: surface collectors for extracting the heat from soil, a thermal pump for concentrating and shifting the external environment

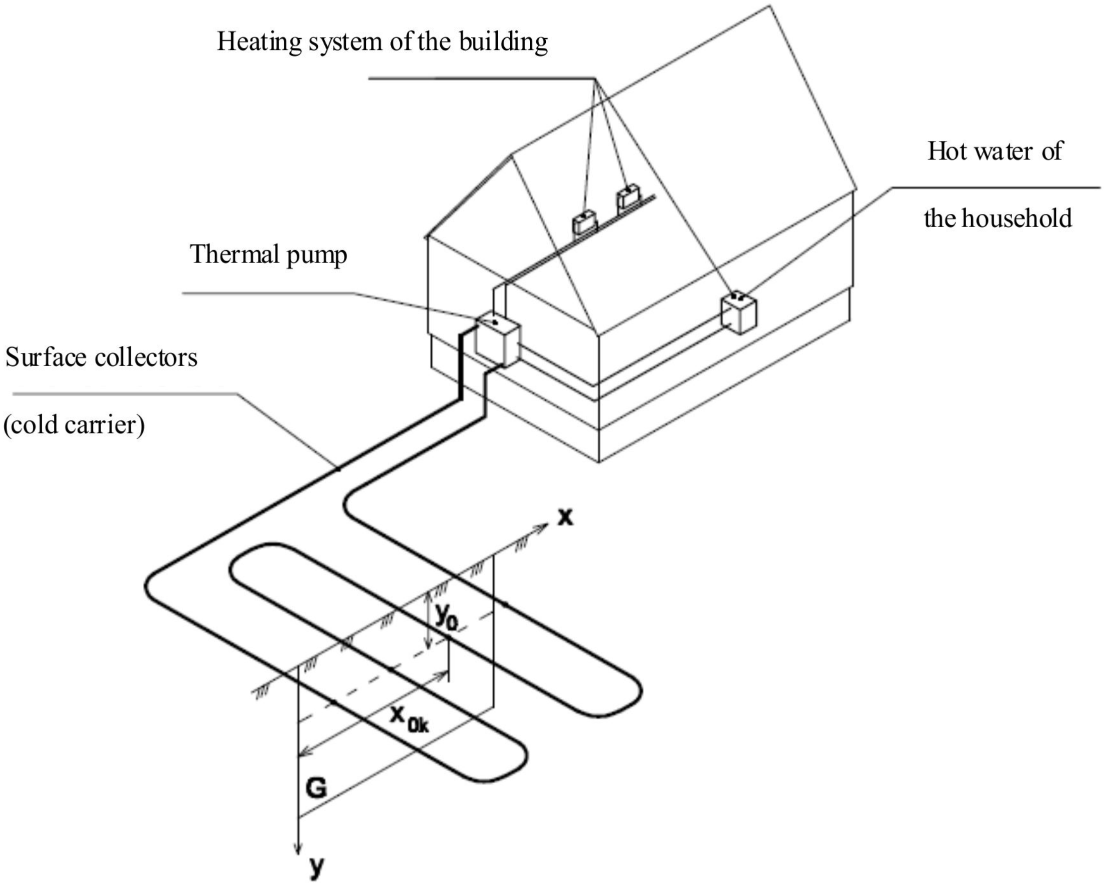

Fig. 1. The scheme of using soil surface heat for the building heating (Fakti par ..., 1997).

heat intended for heating of the building and water, and internal building heating systems (Fig. 1) (Fakti par ..., 1997).

For the building heating systems which use heat accumulated in the upper soil level, the cold carrier usually is made from polyethylene pipes.

The amount of heat extracted from soil and the power of heating system are influenced by the cold carriers' parameters (material of pipes, thickness, internal diameter), depth and distance between the pipes, soil texture (clayey, sandy, etc.), soil moisture, and soil freezing depth. When designing the building heating systems, it is very important to evaluate these parameters in order to provide minimal additional heating for the building heating system during the cold winter months. If there are mistakes in the process of engineering the heating system, system defects and even system work breaks during the heating season are possible. Mathematical modelling is widely used in the world (Blumberga, 2008; Hectors, van Reusel, Driesen, 2008; Cepite, Jakovičs, Halbedel, 2008; PrzyŁucki, 2008; Kuvaldin, Lepeshkin, 2008) for solving technical issues in various sciences.

The purpose of the research was to develop a mathematical model which would include the above-mentioned parameters, climatic conditions, different soil types, and building heating loss, which influences the heating system operation. By means of the developed mathematical model, the necessary distance between cold carriers can be determined.

Materials and Methods

A theorem in mathematics has been proven that for a correctly formulated mathematical physics problem (in our case it consists of equation (1), beginning condition (5), and boundary conditions (2-4)) there is only one solution – formulas (14–16). The problem solution scheme is well known and relatively large therefore, in this paper, it is not reflected fully but only to the extent that specialists in this field could develop a solution (14–16). For demonstration purposes the paper presents two cities, Dobele and Daugavpils, with different climatic conditions and two types of soil (sandy loam and loamy sand), polyethylene cold carrier

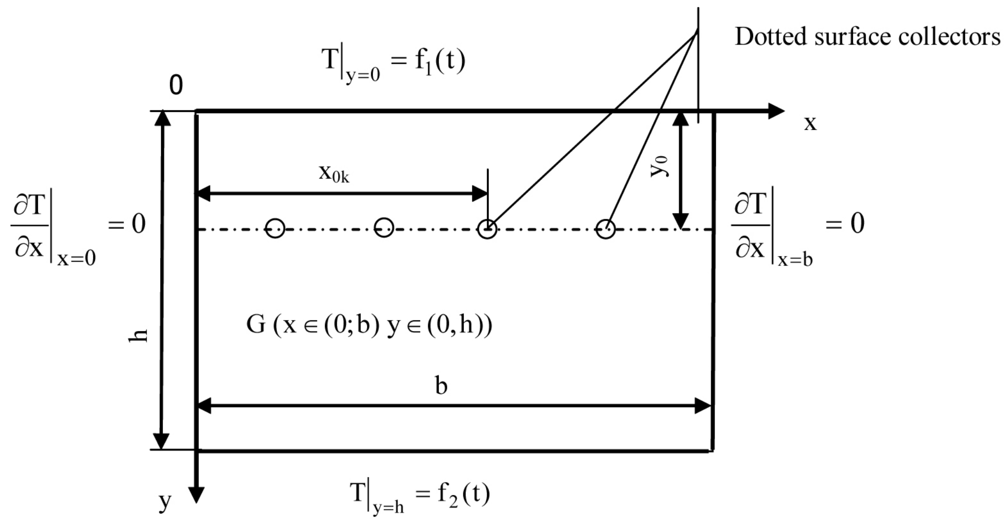

Fig. 2. The scheme of the mathematical problem for the building heating using thermal pumps.

pipes with internal diameter of 40 mm, built at the depth of 1.2 m, distance between the pipes – 1.5 m. Also other values are used.

It can be assumed that in a definite soil area G ($x \in (0;b)\ y \in (0,h)$) (Figs 1 and 2) there are installed cold carriers that serve as heat energy transformers for the building heating.

In order to calculate temperature division in soil, which in the plane xy (Figure 2) is presented as dotted cold carriers, a mathematical physics problem can be formulated. It consists of:

– non-stationary heat conduct equation:

$$\frac{\partial T}{\partial t} = a\Delta T + \frac{a}{\lambda} q(t) \sum_{k=1}^{N} \delta\,(x - x_{0k}; y - y_0)\,, \tag{1}$$

where

T	–	temperature, °C;
t	–	time, s;
λ	–	soil thermal conductivity coefficient, W m^{-1} K^{-1};
$a = \frac{\lambda}{c\rho}$	–	temperature conduct coefficient, m^2 s^{-1} (c – soil specific thermal capacity, J kg^{-1} K^{-1}; ρ – soil density, kg m^{-3});
$\Delta \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$	–	Laplace operator (x, y – coordinates);
q(t)	–	cold carriers' intensity (rate), W m^{-1};
$\delta(x\text{-}x_{0k}; y\text{-}y_0)$	–	cold carriers' delta function (describes dotted coordinates x_{0k} and y_0 of cold carriers), m^{-2};
N	–	number of cold carriers in soil;

– boundary conditions in the direction of x axis (heat does not move in the direction of x axis at area limits x=0 un x=b):

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0 \quad \text{and} \quad \left.\frac{\partial T}{\partial x}\right|_{x=b} = 0\,, \tag{2}$$

where

b – area latitude, m;

Table 1

Approximation coefficients of functions $f_1(t)$ and $f_2(t)$

Location	Coefficient a_i values for function $f_1(t)$			Coefficient b_i values for function $f_2(t)$		
	1	2	3	1	2	3
Dobele (sandy loam)	0.0014	-0.2666	7.1821	0.00009	-0.0465	10.410
Daugavpils (loamy sand)	0.0015	-0.2760	6.3384	0.00020	-0.0660	11.118

– boundary conditions in the direction of y axis:

$$T\big|_{y=0} = f_1(t), \tag{3}$$

which defines temperature change on soil upper level during the heating period:

$$T\big|_{y=h} = f_2(t), \tag{4}$$

which defines temperature changes in soil depth (h) during the heating period;

– beginning condition:

$$T\big|_{t=0} = F(0, y), \tag{5}$$

where function F(0,y) defines temperature division in the defined soil area G($x \in (0;b)$ $y \in (0,h)$) during time t=0 (Figure 2).

Functions $f_1(t)$ and $f_2(t)$ of the expressions (3 and 4) describe the average temperature change during the heating season, which close to the experimental measures (Справочник …, 1965) can be approximated by polynomials:

$$f_1(t) = a_1 t^2 + a_2 t + a_3, \tag{6}$$

$$f_2(t) = b_1 t^2 + b_2 t + b_3. \tag{7}$$

Coefficients a_i and b_i of the expressions (6 and 7) can be developed by the smallest quadrate method, which, for example, for the Dobele sandy loam soil and the Daugavpils loamy sand soil are presented in Table 1 (time periods were measured in days, the heating season started on October 15).

Figures 3 and 4 present the experimentally defined (Справочник …, 1965) average monthly temperature and its approximation functions $f_1(t)$ and $f_2(t)$.

In a sufficient depth, where annual temperature does not change, the geometrical gradient exists from 0.01 to 0.037 K m^{-1} (Pandalons, Iljins, 2001), which at a sufficient value (λ=1.5 W m^{-1} K^{-1}) of soil thermal conductivity produces heat flow of 0.015–0.055 W m^{-2}, which, in its turn, is very little and may not be taken into account regarding the building heating. As the function's $f_2(t)$ derivation according to y is proportional to the geometrical gradient, the function's $f_2(t)$ derivation according to y should be zero (0), which means that at the soil area where cold carriers are installed, heat from deeper soil layers is not supplied.

The mathematical physics problem (1–5) is solved using the popular method of variables separation. The scheme of the method is well known and described in mathematics textbooks. The scheme extension is relatively long and consists of lines of various integrals' calculations and long algebraic transformations, therefore all mathematical transformations are not presented. All necessary formulas are presented for a reader to calculate a solution.

Attention has to be drawn to the function F(t, x, y) (5). This formula has to be presented in a simple form, but maximum close to the actual soil temperature division. As there is no foundation to consider that at the start moment t=0 temperature division exists on x axis, it is presumed that function F does not depend on x. The function's F dependence on y can be developed differently. One of the

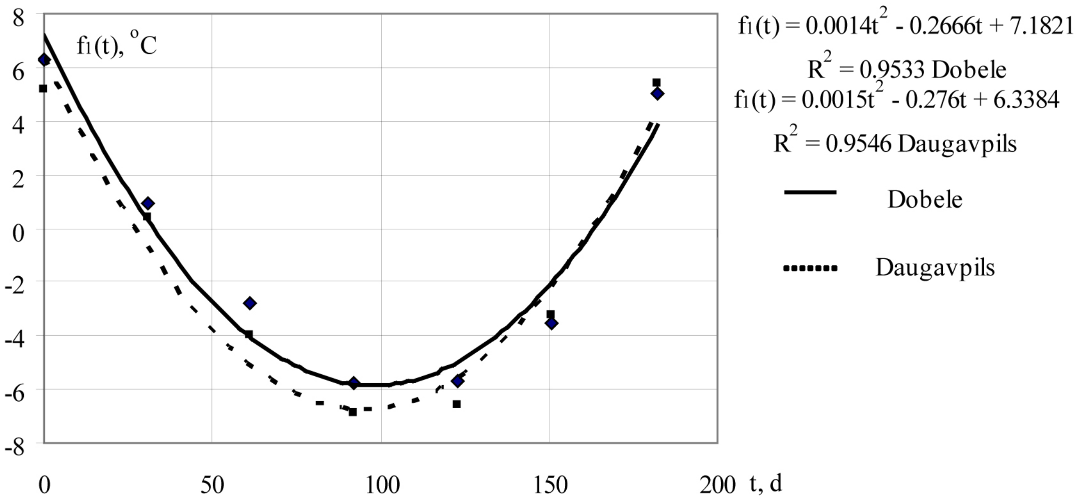

Fig. 3. Changes in the monthly average temperature $f_1(t)$ during the heating season (starting on October 15) in the soil upper level (y=0) in Dobele (sandy loam) and Daugavpils (loamy sand).

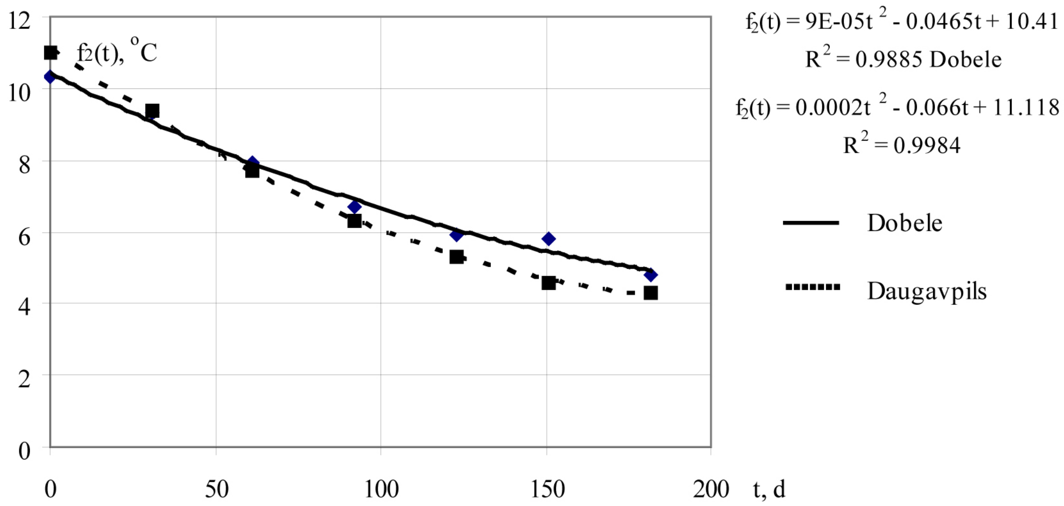

Fig. 4. Changes in the monthly average temperature in soil $f_2(t)$ during the heating season (starting on October 15), y=h=3.2 m, in Dobele (sandy loam) and Daugavpils (loamy sand).

possibilities described by the authors is to construct the function F as a linear combination of the functions $f_1(t)$ and $f_2(t)$. However, the obtained data varied significantly from the temperature division data on y coordinate found in the literature (Справочник …, 1965). Therefore the authors chose quadrate function's F dependence on y:

$$F(t;y) = f_1(t) + 2[f_2(t) - f_1(t)]\cdot\frac{y}{h} - [f_2(t) - f_1(t)]\cdot\frac{y^2}{h^2}, \qquad (8)$$

which corresponds to the literature (Справочник …, 1965) data. At the same time, function F has to satisfy certain limits which are discussed further in the text.

Compliance of the beginning condition (5), given by formula (8) at t=0 F(0, y), with experimental data is shown in Figure 5.

The basic idea of the variables separation method is to find the problem (1–5) solution as an infinite-line sum, where each line member is a multiplication of three functions; moreover, each of these three functions is only a function for a single argument function. Construction of a solution is possible only if problem limits (2–4) are homogeneous. The limit (2) is homogeneous, but limits (3, 4) are not homogeneous. Thus, the solution by substitution

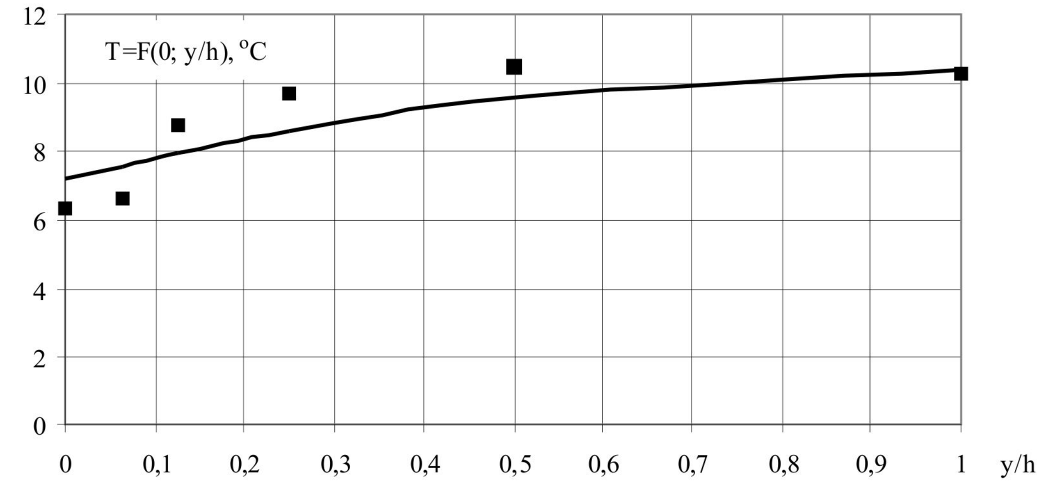

Fig. 5. Dependence of the function F(0, y/h) on the relative depth y/h at the beginning of the heating season, October 15, in Dobele.

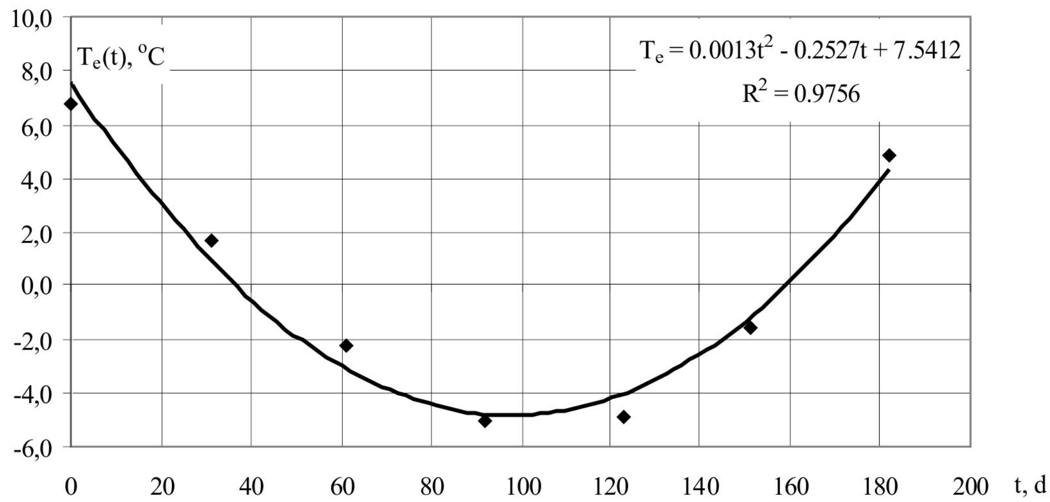

Fig. 6. Changes in the average monthly air temperature $T_e(t)$ in the heating season, starting on October 15, in Dobele.

$$T(t, x, y) = F(t, x, y) + U(t, x, y), \tag{9}$$

is divided into two parts. If the function F satisfies the limits, the function's U homogeneous limits remain. As it is seen, the authors' constructed function (8) does not contain coordinate x, and function's F(t, y) limits (2–4) are satisfied. Thus, function's U limits are homogeneous.

The second function which should be found is the necessary intensity q(t) of cold carriers' dependence on time. This can be developed presuming that cold carriers' intensity is proportional to the monthly average temperature difference in the inside and outside air. Using (Справочник …, 1965), data of an average monthly temperature change during the heating season in the Dobele area is developed (Fig. 6). This dependence can be quite precisely approximated by a polynomial:

$$T_e(t) = pt^2 + rt + q, \tag{10}$$

where coefficients p=0.0013 K d^{-2}, r=-0.2527 K d^{-1}, and q=7.5412 K are obtained by the smallest quadrate method (time (t) is calculated in days, starting on October 15).

Latvian building standards (Latvijas būvnormatīvs ..., 2001) present values of the coefficient h_A in dwelling houses, retirement homes, hospitals, and kindergartens. The normative heat loss coefficient H_{TR} for those buildings can be determined according to formula:

$$H_{TR} = h_A A, \tag{11}$$

where

- h_A – specific heat loss coefficient of a building's one-square meter floor area (h_A values for one-, two-, three-, four- and more storey buildings are, respectively, 1.05, 0.8, 0.7, and 0.6 W m^{-2} K^{-1}) (Latvijas būvnormatīvs ..., 2001);
- A – sum of floor area at all building stories, m^2.

Then the cold carriers' intensity q(t) can be found using formula:

$$q(t) = \frac{N(t)}{L} = \frac{H_{TR}}{L}(T_i - T_e(t)), \tag{12}$$

where

- $N(t)$ – total heating capacity used, depending on time, W;
- L – cold carriers' total length, m;
- T_i – internal temperature of a building, °C.

Considering formulas (10) and (11), the expression (12) can be rewritten in the following form:

$$q(t) = c_1 t^2 + c_2 t + c_3, \tag{13}$$

where

$$c_1 = \frac{h_A A}{L} p;$$

$$c_2 = \frac{h_A A}{L} r;$$

$$c_3 = \frac{h_A A}{L}(T_i - q).$$

For example, considering values T_i=20 °C, A=274 m^2, L=600 m, and h_A=0.8 W m^{-2} K^{-1}, the following coefficients are obtained: c_1=-0.0004749 W m^{-1} d^{-2}, c_2=0.09233 W m^{-1} d^{-1}, and c_3=4.5516 W m^{-1}.

Results

By solving problems (1-13) of mathematical physics by the method of separation of variables, a solution as an infinite line sum is obtained:

$$T(t,x,y) = T(t,y) + U(t,x,y), \tag{14}$$

where the expression's (14) first member does not contain coordinate x. The expression's (14) first member is calculated by summing the variable index j:

$$T(t,y) = F(t,y) + \sum_{j=1}^{\infty} \left(D_j (1 - \exp(-a\eta_j^2 t) + E_j t + F_j t^2 \right) \sin \eta_j y. \tag{15}$$

The function F(t,y) is presented by expression (8), but coefficients F_j, E_j, D_j can be solved using formulas:

$$F_j = \frac{\gamma_j}{\eta_j^2 a}, \quad E_j = \frac{1}{\eta_j^2 a}\left(\beta_j - \frac{2\gamma_j}{\eta_j^2 a}\right), \text{ and } \quad D_j = \frac{1}{\eta_j^2 a}\left(\alpha_j - \frac{1}{\eta_j^2 a}\left(\beta_j - \frac{2\gamma_j}{\eta_j^2 a}\right)\right),$$

where

$$\eta_j = \frac{\pi j}{h};$$

$$\alpha_j = \frac{b_2 - a_2}{h^2} e_j - \frac{2(b_2 - a_2)}{h} d_j - \frac{2a}{h^2}(b_3 - a_3)c_j, \quad \text{where} \quad c_j = \frac{2}{\pi} \cdot \frac{1 - \cos \pi j}{j}; \quad d_j = (-1)^{j+1} \cdot \frac{2}{\pi} \cdot \frac{h}{j};$$

$$e_j = -\frac{2}{\pi} \cdot \frac{h^2}{j} \left((-1)^j + \frac{2}{\pi^2} \cdot \frac{1 - \cos \pi j}{j^2} \right);$$

numerical values of coefficients $a_{1\text{-}3}$ and $b_{1\text{-}3}$ are presented in Table 1;

$$\beta_j = \frac{2(b_1 - a_1)}{h^2} e_j - \frac{4(b_1 - a_1)}{h} d_j - \left(2a_1 + \frac{2a}{h^2}(b_2 - a_2) \right) c_j;$$

$$\gamma_j = -\frac{2a}{h^2}(b_1 - a_1) c_j.$$

The function U in expression (14) is a double sum of variables i and j:

$$U(t, x, y) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \left(Q_{ij}(1 - \exp(-a\mu_{ij}^2 t)) + R_{ij} t + P_{ij} t^2 \right) \cos \zeta_i x \cdot \sin \eta_j y, \tag{16}$$

where

$$\zeta_i = \frac{\pi i}{b};$$

$$\mu_{ij}^2 = \zeta_i^2 + \eta_j^2 = \left(\frac{\pi i}{b} \right)^2 + \left(\frac{\pi j}{h} \right)^2;$$

$$P_{ij} = \frac{\alpha_{ij}}{a\mu_{ij}^2};$$

$$\alpha_{ij} = \frac{4ac_1 \sin \eta_j y_0}{\lambda hb} \sum_{k=1}^{N} \cos \zeta_i x_{0k};$$

$$R_{ij} = \frac{\beta_{ij} - 2P_{ij}}{a\mu_{ij}^2};$$

$$\beta_{ij} = \frac{4ac_2 \sin \eta_j y_0}{\lambda hb} \sum_{k=1}^{N} \cos \zeta_i x_{0k};$$

$$Q_{ij} = \frac{\gamma_{ij} - R_{ij}}{a\mu_{ij}^2};$$

$$\gamma_{ij} = \frac{4ac_3 \sin \eta_j y_0}{\lambda hb} \sum_{k=1}^{N} \cos \zeta_i x_{0k};$$

N – number of cold carriers in area G;
x_{0k}, y_0 – cold carriers' coordinates, m;
c_1, c_2, c_3 – are taken from expression (13).

Figure 7 shows temperature division in soil (h_A=0.8 W m^{-2} K^{-1}, A=274 m^2), which is calculated by using formulas (15) and (16). In Fig. 7A, temperature on the cold carriers' surface is identical (the lowest temperature is -4.1 °C), except on the cold carriers on either side of the graph, where the temperature is higher. Fig. 7B demonstrates that with the decrease of the distance between the cold carriers, decreases also the temperature on their surface (first group – -5.5 °C, second group – -4.6 °C, third group – -3.9 °C).

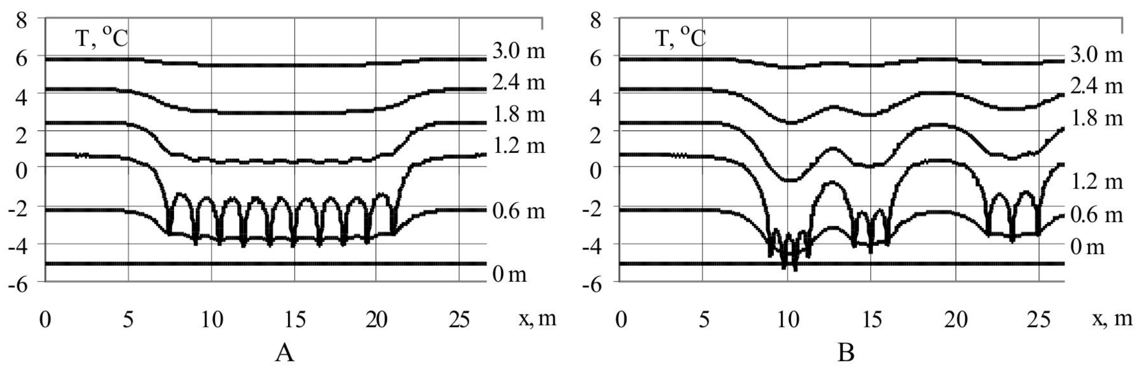

Fig. 7. Examples of temperature division at various soil depths y (h_A=0.8 W m^{-2} K^{-1}), depending on the placement of cold carriers:
A – cold carriers placed at an equal distance of 1.5 m; B – three groups of cold carriers placed at different distances (in the graph – from the left): 1st group – at the distance of 0.75 m (4 cold carriers); 2nd group – at the distance of 1 m (3 cold carriers); 3rd group – at the distance of 1.5 m (3 cold carriers).

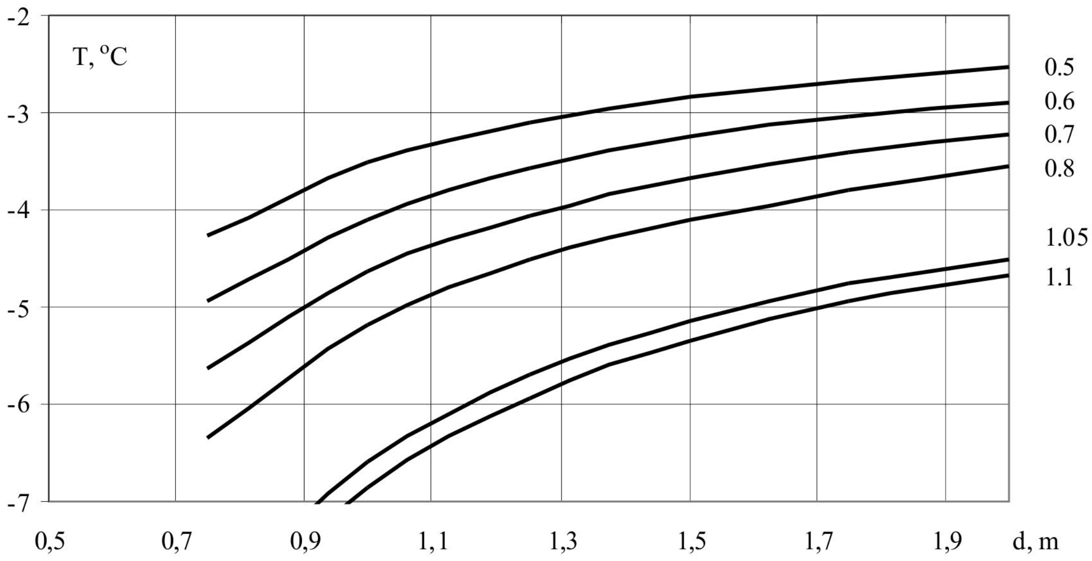

Fig. 8. The temperature on the cold carriers' surface, t=112 d (days), starting from the beginning of the heating season (October 15), depending on the distance between the cold carriers (d), for different building specific heat loss coefficients, h_A=0.5-1.1 W m^{-2} K^{-1}, at cold carrier's diameter of 40 mm and installation depth y_0=1.2 m.

Since constructively it is not allowed that the temperature on cold carrier's surface is lower than -5 °C (Viesmann ..., 2006), it is necessary to develop a computer program which would analyze temperature division in soil according to the following algorithm. Firstly, the collectors' working time has to be chosen when the temperature on the cold carrier elements is the lowest. It could be 110–115 days (i.e., on February 2–7) beginning from the system's start-up on October 15. At this time, using formulas (15) and (16), a graph is developed according to the parameters of the building, soil, and climate (Fig. 8). For example, if h_A=0.8 W m^{-2} K^{-1}, A=274 m^2, y_0=1.2, the cold carrier's diameter is 40 mm, and the lowest temperature on the cold carrier's surface is -4 °C, then distance between the cold carriers has to be 1.6 m. Whereas, if the distance between the cold carriers is 1.0 m, the lowest temperature on the cold carriers' surface will be approximately -5.2 °C, which means that pauses in the system's operation might occur. The graph shows temperature on the average cold carriers' surface depending on distance (d) between them at different values of the building's specific heat loss coefficient h_A. The building heat loss coefficient can be determined by the building's heat usage in the previous years or by the building project energy audit. The minimal distance between cold carriers, demonstrated in Figure 8, is determined for engineering the thermal pump, which will allow to keep the temperature at the necessary temperature limit, i.e., at -5 °C .

Conclusions

1. The mathematical model with an appropriate computer programme, using a surface collector for extracting the soil heat, ensures the following benefits:
- designing of the soil heat usage systems (to determine parameters of systems) for heating of dwelling houses and water. The program is able to evaluate collectors of different diameter, depth, and distance;
- evaluation and analysis of various soil heat usage projects with particular parameters of thermal pumps, collectors (material, size, installation depth, distance between collectors, and total length), soil (soil type, moisture, density, etc.), as well as climatic conditions (air temperature) of the geographical area. For example, specification of the winter air temperature, at which the system will be able to heat the building, as well as prediction of the number of days, during which alternative heating sources will be used at a low air temperature;
- analogical analysis of the constructed soil heat usage systems, as well as determination of whether additional building or water heating systems can or cannot be connected.

2. The mathematical model and computer program can be changed for designing the building's heating systems, using vertical collectors, as well as collectors installed in an open-water facility.

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Anotācija

Zemes virskārtā akumulētās siltuma enerģijas izmantošanas sistēmās ar siltuma sūkņiem ir svarīgi, lai aukstās ziemās, kad no zemes iegūtais siltuma daudzums ir nepietiekams, ēkas apsildīšanai pēc iespējas īsāku laiku būtu jāizmanto alternatīvi siltuma enerģijas avoti. No zemes virskārtas iegūstamais siltuma daudzums ir atkarīgs no vairākiem faktoriem, piemēram, aukstuma nesēja tehniskajiem parametriem, aukstuma nesēja cauruļu novietošanas dziļuma zemē un to savstarpējā attāluma, grunts veida un mitruma, kā arī no apsildāmās ēkas āra gaisa mēnešu vidējās temperatūras ēkas apsildes periodā. Savukārt ēkas apsildīšanai nepieciešamo siltuma daudzumu ietekmē apsildāmo telpu ģeometriskie parametri, telpās nodrošināmā gaisa temperatūra, kā arī ēkas tehniskie parametri, ko novērtē ar siltuma zudumiem apsildes periodā. Darbā izstrādāts un analizēts siltuma sūkņa sistēmas matemātiskais modelis ar datorprogrammu, kas sistēmas projektēšanas gaitā ievērtē iepriekšminētos faktorus. Matemātiskais modelis dod iespēju, projektējot apkures sistēmu, aprēķināt ar zināmu rezervi aukstuma nesēju savstarpējo attālumu, kas ir viens no galvenajiem siltuma sūkņa izbūves parametriem. Izveidotais matemātiskais modelis ir piemērojams jebkurām āra gaisa temperatūrām un jebkuriem grunts termofizikālajiem parametriem, kas tiek ievēroti, variējot attiecīgos aproksimācijas koeficientus. Ar datorprogrammas palīdzību iespējams analizēt arī jau ierīkotas siltuma sūkņu sistēmas un prognozēt to darbības efektivitāti – noteikt objekta nodrošinājumu ar siltuma enerģiju ēkas apsildes sezonā, novērtēt iespējas sistēmai uzticēt papildu funkcijas u.tml.