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ANALYZING TEMPERATURE CHANGES IN THE GROUND MASSIF WITH A HORIZONTAL HEAT EXCHANGER IN THE COURSE OF THE HEATING SEASON

Summary

The article is devoted to temperature changes in the ground massif with the horizontal heat exchanger as an energy source for a heat pump. The article was aimed at analyzing temperature changes in the ground massif with the horizontal heat exchanger at the beginning, in the course of and at the end of the heating season. Another aim was to analyze temperature differences in the area of the horizontal exchanger and the reference lot. The heat flow utilized in the evaporator of heat pump was extracted from the ground exchanger (nominal output at the condenser was 10.5 kW). Temperatures of the ground massif with the horizontal heat exchanger were measured in its plane in depths of 0.75 m, 0.5 m and 0.25 m. The temperature inside the ground massif on the reference lot and ambient parameters were measured as well. It is obvious that the difference of energetic potentials inside the ground massif with the heat exchanger and on the reference lot is insignificant at the beginning of the heating season. During the heating season, the difference of ground massif energetic potentials increases; at the end it is constant. The difference of temperatures in horizontal planes was not significant at the beginning of the heating season; however, it gradually increased. Maximum differences were detected in the area of the heat exchanger. In higher strata, the difference between temperatures decreases. During a major part of the heating season, temperatures at pipes of the ground exchanger were negative. This fact affected amounts of heat extracted from the ground massif.

Key words: Heat pump; Horizontal ground heat exchanger; Ground source heat pump; Heat transfer; Energy potential; Heat season; Ground temperature; Temperature distribution.

INTRODUCTION

During heating season, the horizontal heat exchanger – as a source of energy – carries off the heat accumulated inside the ground massif in the summer. The ground massif temperature, together with the thermal characteristics of the massif, are dominant factors determining the availability of the entire energy system. The following thermal characteristics of the ground massif may be defined:

– conductivity λ [$W.m^{-1}.K^{-1}$], expressing the ability to share thermal energy among directly adjoining rock particles;

– specific thermal capacity c [$J.kg^{-1}.K^{-1}$], expressing the quantitative ability to absorb and release the heat energy;

– temperature conductivity a [$m.s^{-2}$], characterizing the speed of propagation of temperature changes in the ground massif during its heating and cooling.

The effect of ground massif conductivity and the material of exchanger piping on the function the horizontal exchanger should perform was studied by Song, Yao and No (2006). They developed the horizontal ground heat exchanger as a source for the heat pump. They simulated the effect of ground/piping conductivity on the thermal field and the exchanger's thermal capacity. The simulation results indicate that increasing ground conductivity increases heat transfer, while the ground temperature round the piping decreases to zero values. The heat field changes relatively faster together with conductivity changes near the piping. With increasing conductivity of the piping, both the heat transfer and the piping average temperature at the exterior surface increase as well.

Provided we know the characteristics of the ground massif, the temperature of the massif indicates its changing energy potential. In addition to the installed exchanger, the ground massif's thermal balance is affected by the daily and yearly variation of the ground massif temperature. In their paper, Mihalakakou et al. (1997) present a model for predicting daily and yearly variations of ground massif temperature. This model is based on the differential equation which describes convection, using the boundary condition of the formula for energy balance on the ground massif's surface. The equation of the energy balance includes the energy convection between the air and the ground massif, solar irradiation absorbed by the ground massif, latent heat flow due to surface evaporation and the long-wave radiation of the ground massif's surface.

A new approach to simulating the horizontal type of ground exchanger is presented by Piechowski (1997). His mathematic model and measurements are concentrated on the boundary between the ground and the piping. The model considers the heat and humidity transfer inside the ground massif; it enables prediction of the heat field and heat flows inside the massif (due to heat offtake by the horizontal ground exchanger) more precisely. As most models of heat fields and flows in the ground massif with a horizontal heat exchanger, this model stems from oversimplifying assumptions. The properties of the ground massif are considered uniform and constant. The same is valid for piping (specific flow). The exchanger is a small-diameter line tubular unit.

Regarding the system's energy efficiency it is important that the ground massif temperature should not decrease at the beginning of subsequent heating seasons; i.e. the energy accumulated in summer should always cover the deficiency of energy (due to its removal) at the end of the heating season.

This article links up to the results of testing published last year [Adamovský, Neuberger and Šeďová 2009]. It confirms and amends many results. The aim of this article is to analyze the differences of ground temperatures in the area of the horizontal heat exchanger and on the reference lot. Another aim is to analyze the temperature changes in the ground massif at the beginning, in the course and at the end of the heating season.

METHODS

1. Theoretical analysis

Inside the ground massif and at its boundary with the atmosphere, complex processes of heat transfer take place, comprising conduction, convection and radiation. Other thermal processes of heat transfer are represented by changes in state – evaporation, condensation, melting, freezing.

The equation for total specific heat flow in the ground massif may be written as (adapted according to Brandl, 2006; Rees et al., 2000)

$$q_{\tau,t} = q_{\tau,\lambda} + q_{\tau,\alpha,w} + q_{\tau,\alpha,v} + q_{\tau,r} + q_{\tau,lat} \left[\mathrm{W.m}^{2} \right] \qquad (1)$$

Where:

- $q_{\tau,t}$ – total specific heat flow in the ground massif [W.m^{-2}];
- $q_{\tau,\lambda}$ – specific heat flow transferred via conduction [W.m^{-2}];
- $q_{\tau,\alpha,w}$ – specific heat flow transferred via convection between water and ground [W.m^{-2}];
- $q_{\tau,\alpha,v}$ – specific heat flow transferred via convection between vapour and ground [W.m^{-2}];
- $q_{\tau\,r}$ – specific heat flow transferred via radiation [W.m^{-2}];
- $q_{\tau,l}$ – specific heat flow transferred during the change in the state of water [W.m^{-2}].

Specific heat flow $q_{\tau,\lambda}$ transferred via conduction inside a homogeneous isotropic material (in terms of the Fourier law) is given by the formula:

$$q_{\tau,\lambda} = -\lambda \frac{\partial T}{\partial x} \quad [\mathrm{W.m}^{-2}] \qquad (2)$$

Where:

λ – conductivity [W.m^{-1}.K^{-1}];

T – thermodynamic temperature [K];

$\frac{\partial T}{\partial x}$ – thermal gradient in the direction x of heat flow.

The difference of heat flow delivered to/dissipated from a control volume of material within a time period is equal to the accumulated heat flow:

$$-\frac{\partial q_{\tau,\lambda}}{\partial x} = \rho \frac{c_p \partial T}{\partial \tau} \quad [\text{W.m}^{-3}] \tag{3}$$

Where:

ρ – specific mass [kg.m^{-3}];

c_p – specific heat capacity [J.kg^{-1}.K^{-1}];

τ – time [s].

Inserting equation (2) into (3) we obtain:

$$-\frac{\partial}{\partial x}\left(-\lambda \frac{\partial T}{\partial x}\right) = \rho \cdot \frac{c_p \cdot \partial T}{\partial \tau} \quad [\text{W.m}^{-3}] \tag{4}$$

Provided λ and $\rho.c_p$ are constant, we can modify equation (4) into:

$$\lambda \frac{\partial^2 T}{\partial x^2} = \rho \cdot c_p \cdot \frac{\partial T}{\partial \tau} \quad [\text{W.m}^{-3}] \tag{5}$$

The equation for heat flow transferred via conduction in 3D space (*x, y, z*) may then be written as:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = \rho \cdot c_p \cdot \frac{\partial T}{\partial \tau} \quad [\text{W.m}^{-3}] \tag{6}$$

Let us introduce the heat conductivity coefficient:

$$a = \frac{\lambda}{\rho \cdot c} \quad [\text{m}^2.\text{s}^{-1}] \tag{7}$$

Then:

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = a \; div\, grad\, T = a\, \Delta T \quad [\text{K.s}^{-1}] \tag{8}$$

Provided there is a heat source of $q_{\tau,i}$ [W.m^{-3}] in the given control volume, the elementary heat conduction formula is:

$$\frac{\partial T}{\partial \tau} = a\,\Delta T + \frac{q_{\tau,i}}{\rho \cdot c} \quad [\mathrm{K.s^{-1}}] \tag{9}$$

Further forms of heat transfer in the ground massif may be described by the following formulae [Brandl 2006].

Convection transfer $q_{\tau,\lambda,w}$ between circulating water and the ground massif:

$$q_{\tau,\alpha,w} = c_w \cdot \rho_w \cdot \vec{w}_w \left(T - T'\right) \quad [\mathrm{W.m^{-2}}] \tag{10}$$

Where:

- c_w – specific heat capacity of circulating water [J.kg^{-1}.K^{-1}];
- ρ_w – water specific mass [kg.m^{-3}];
- $\vec{w}_w$ – water velocity vector [m.s^{-1}];
- T – water temperature [K];
- T' – ground massif reference temperature [K].

Convection transfer $q_{\tau,\alpha,v}$ between circulating vapour and the ground massif:

$$q_{\tau,\alpha,v} = c_v \cdot \rho_v \cdot \vec{w}_v \left(T - T'\right) \quad [\mathrm{W.m^{-2}}] \tag{11}$$

Where:

- c_v – specific heat capacity of circulating vapour [J.kg^{-1}.K^{-1}];
- ρ_v – vapour specific mass [kg.m^{-3}];
- $\vec{w}_v$ – vapour velocity vector [m.s^{-1}].

Transfer of water latent heat $q_{\tau,l}$:

$$q_{\tau,l} = l \cdot \rho_w \cdot \overline{w_v} \quad [\mathrm{W.m^{-2}}] \tag{12}$$

Where:

- l – water latent heat [J.kg^{-1}].

The intensity of heat transfer in the ground massif via radiation is minimal. Its ratio is less than 1% (Ress et al. 2000). A major heat ratio transferred via conduction inside the ground massif enables (especially in cases where the dimensions of the ground particles and pores are negligible if compared to the volume of the ground itself) to ignore other kinds of heat transfer. For instance, Firlag and Rucińska (2007) introduce the formula for calculating the ground massif heat resistance R_G:

$$R_G = \frac{I\left(X_{dz}\right) - I\left(X_{2H}\right)}{2\pi \cdot \lambda_{gr}} \quad [\mathrm{m.K.W^{-1}}] \tag{13}$$

Where:

λ_{gr} – coefficient of the ground massif heat conductivity [W.m^{-1}].K^{-1}];

$I(X_{dz})$– function for $X = d_z$;

$I(X_{2H})$– function for $X = 2H$;

d_z – piping diameter (horizontal ground exchanger) [m];

H – depth of the ground exchanger placement [m].

The values of functions I (X) are calculated according to formulae (14) and (15):

For $0 < X < 1$:

$$I(X) = \frac{1}{2}\left(-\ln X^2 - 0.57721566 + 0.99999193X^2 - 0.24991055X^4 + 0.05519968X^6 - 0.00976004X^8 + 0.00107857X^{10}\right) \quad [\text{-}] \tag{14}$$

For $1 \le X < \infty$:

$$I(X) = \left[\frac{1}{2X^2 \cdot e^{X^2}}\right] \cdot \left(\frac{A}{B}\right) \quad [\text{-}] \tag{15}$$

Coefficients A and B are described by following equations:

$$\begin{aligned} A &= X^8 + 8.5733287X^6 + 18.059017X^4 + 8.637609X^2 + 0.2677737 \\ B &= X^8 + 9.5733223X^6 + 25.6329561X^4 + 21.0996531X^2 + 3.9684969 \end{aligned} \quad [\text{-}] \tag{16}$$

2. Measuring methods

The site of our testing is situated in Southern Bohemia (Hlinice village, Tábor District) at altitude of 480 m asl. In this area, the calculated outdoor temperature is -15°C; the average temperature during the heating season is 3°C.

The horizontal heat exchanger in the ground massif was made of polyethylene pipes (D = 40 mm, pipe wall thickness = 2.5 mm, length = 400 m). The lot's ground plan was 27 x 25 m. Before the measurements were made, the ground exchanger had been operated for 4 years. The exchanger was working as the heat source for a heat pump evaporator; its nominal output at the condenser was 10.5 kW.

The temperature of the ground massif was measured by special NiCr-Ni sensors with a spike, intended for measuring ground temperature. The points of measuring are specified in fig. 1. The t_{13} sensor measured the ground massif temperature on the reference lot. The air temperature and relative humidity (t_e, φ_e) were measured beyond the reference lots by a combined sensor modified for meteorological measurements (2 metres above the ground surface). The measured parameters were detected once an hour in the course of one year.

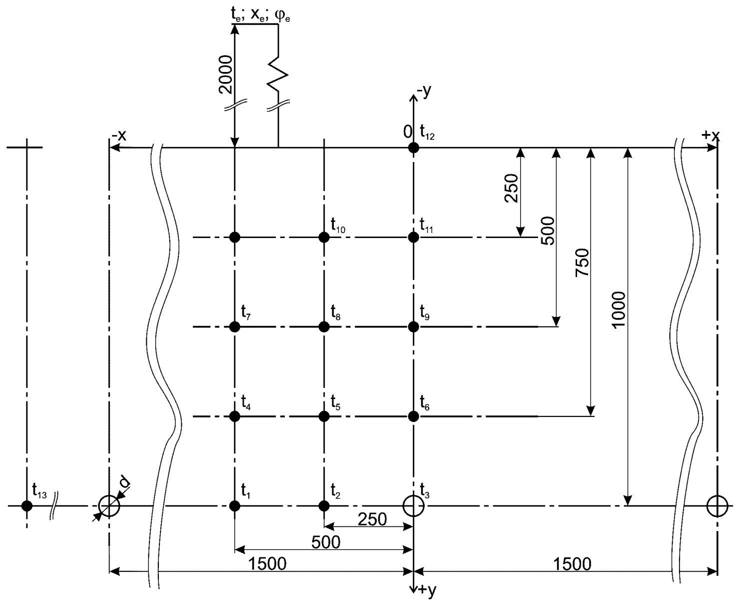

Figure 1. Scheme of measuring temperature in the profile of the horizontal exchanger

RESULTS AND DISCUSSION

The results of testing have proved that before the beginning of the heating season, the average temperature of the ground massif with a heat exchanger in the depth of 1.0 m (t_1, t_2, t_3 according to fig.1) was 0.2 K lower than on the reference lot. This result demonstrates the fact that even in the depth of the exchanger placement, the heat energy dissipated during the heating season was compensated due to the accumulated solar irradiation and the heat from precipitation. The behaviour of the temperatures in the ground massif with a heat exchanger (fig. 2) shows that the differences of the temperatures measured at particular depths are 0.1 – 0.2 K. They may be considered insignificant.

The temperatures in the ground massif (day 96 of heating season) are given in Fig. 3. The temperature difference near the heat exchanger and on the reference lot increased markedly to 3.3 K. The average temperature of the heat exchanger transferring medium at the inlet to/outlet from the heat pump evaporator was -3.4°C. The temperature behaviour in particular ground layers demonstrates the fact that the maximum difference at particular depths was 0.1°C; the temperatures in 0.75 and 1.0 m were identical. The temperature differences may be considered non-significant, too. In the middle of the heating season, the temperatures of the ground massif in the zone of the exchanger are negative.

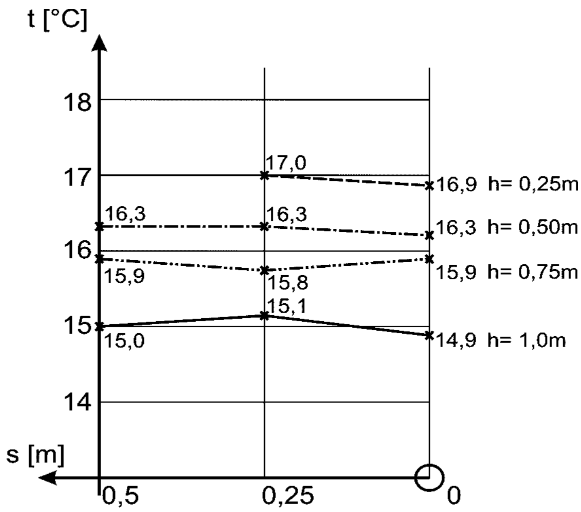

Figure 2. Behaviour of temperatures in the ground massif with a horizontal heat exchanger before the heating season (10/9/2008, 17:15) t_{12} = 22.2°C; t_{13} = 15.2°C; φ_e = 0.561; t_e = 19.7°C

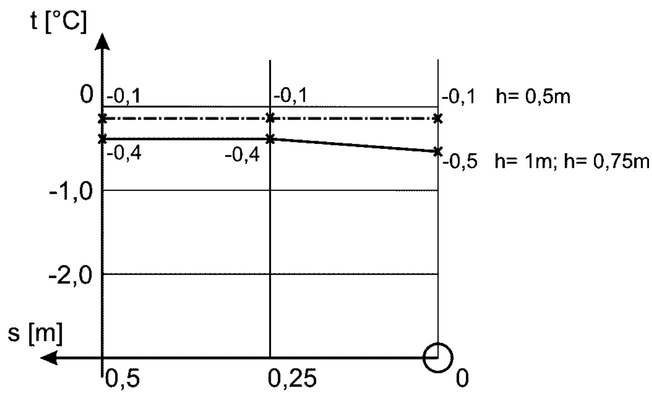

Figure 3. Temperature behaviour in the ground massif with a horizontal heat exchanger during the heating season (31/12/2008, 7:37) t_{12} = - 4.9°C; t_{13} = 2.8°C; φ_e = 0.988; t_e = - 12.05°C

The temperatures of the ground massif at the end of the heating season (Day 155 of the heating system operation) are shown in fig. 4. The temperature differences in the zone of the ground heat exchanger and on the reference lot achieved 2.6°C; they are thus less than in the middle of the heating season. The medium temperature of the heat transferring medium in the ground exchanger was – 3.5°C. The temperature behaviour in particular ground massif layers shows the fact that at the depth of the exchanger placement, the difference of the average temperatures (t_1, t_2, t_3) was 1.2°C; in 0.75 m (t_4, t_5, t_6) it was 0.4°C and at depths of 0.5 m and 0.25 m (t_7, t_8, t_9; t_{10}, t_{11},) it was 0.2°C. The temperature difference cannot be considered important. The temperatures of the ground massif in the exchanger zone are negative.

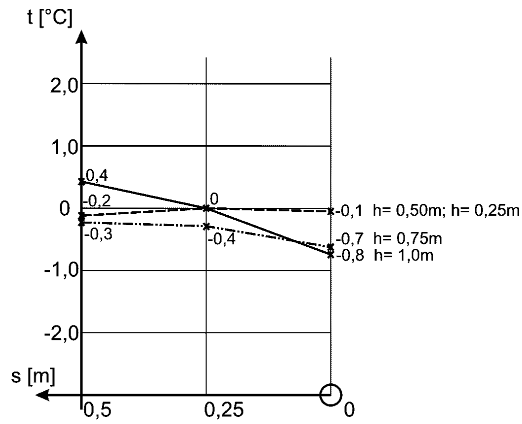

Figure 4. Temperature behaviour in the ground massif with a horizontal heat exchanger at the end of the heating season (28/2/2008, 14:50) t_{12} = 0.2°C; t_{13} = 1.8°C; φ_e = 0.968; t_e = 5.31°C;

CONCLUSION

The results of monitoring temperatures in particular layers in the plane perpendicular to the pipes of the ground exchanger have demonstrated that the temperature differences (t_1, t_2, t_3 and others) were in the range of 0.1–1.2°C within the entire heating season. With regards to the given spacing of the pipes in the ground exchanger and their depth of placement, the temperature differences may be considered unimportant. From the middle of the heating season, the temperatures in the ground massif were negative in the zone of the exchanger piping. According to expert literature (Dvořák, Klazar and Petrák, 1987), if the temperature of the ground massif decreases, water diffuses into the zone of the piping placement. At negative massif temperatures near pipes, diffused water changes its state. Considering the high value of the latent heat of water freezing (334 kJ.kg^{-1}), this change affects the heat flow distributed to the heat pump evaporator. A certain effect on the heat flow dissipated from the ground massif also results from the fact that the coefficient of ice heat conductivity (2.21 W.m^{-1}.K^{-1}) is almost four times higher than for water. The caloric capacity of ice (2.06 $kJ.kg^{-1}.K^{-1}$) is also half that of water.

The difference of the energy potentials inside the ground massif in the zone of the heat exchanger and on the reference lot (at the beginning of the heating season; expressed by temperature difference t_3 - t_{13}) was 0.3 K. At the end of the first half of the heating season, the temperature difference increased to 3.3 K. In the second half of the heating season, the difference did not increase. From the results of the first tests it implies that the energy potential of the ground massif regenerated during summer.

Within further routine tests of horizontal ground heat exchangers, we want to focus on specifying the caloric characteristics of the ground massif and the effect of its humidity on their values. We also want to create a mathematical model of heat flows and heat fields in the ground massif and to verify the possibility to increase the massif's energy potential via the heat pump's reverse operation in summer.

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