

Characteristics of a Geothermal Heat Exchanger in Order to Evaluate its Co-operation with the Heat Receivers

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Abstract

In the paper the authors present a computational model of a deep geothermal exchanger and the characteristics of a geothermal heat energy flux in a function of the depth of a geothermal heat exchanger and in a function of temperature of water injected into the heat exchanger as well as in a function of a volume flow of the water and insulation of the outside pipe of the exchanger. When taking into consideration appropriate characteristics of heat receivers, the characteristics for one-hole systems allow one to chose the most effective system of winning the geothermal heat energy for the designed system of heat removal and winning the geothermal energy.

Keywords: geothermal heat exchanger, one-hole heat exchanger, geothermal energy, geothermal heat flux, heat receivers

Introduction

Winning energy of the earth in order to use it in heat plants and power stations demands appropriate production systems. Their solutions depend on the kind of gained energy. In the case of the geothermal energy the following systems are used:

- two-hole systems with the injection well as well as production well,
- one-hole systems with the injection and production well.

One-hole deep heat exchangers may be used to win the geothermal heat energy. Employing the existing single holes, made during rock oil and gas explorations reduce the total capital cost. Poland is among the countries, which own more than thousand closed deep drill-holes [6,7] – Table 1. Drilling the new holes of the appropriate depth is also possible but it increases the capital cost of the installation.

Table 1. Selected deep drilling wells in Poland [6, 7]

| ? | Completion date | | | | Total | Depth of well |
|-------------------------|-----------------|-----------|-----------|-----------|--------------|-----------------|
| | 1952–1970 | 1971–1980 | 1981–1990 | 1991–2000 | | |
| 48 | 117 | 243 | 188 | 189 | 785 | 3,000 – 3,999 m |
| 9 | 8 | 31 | 50 | 43 | 141 | 4,000 – 4,999 m |
| 3 | 4 | 12 | 12 | 2 | 33 | 5,000 – 6,006 m |
| no documentary evidence | | | | | ~200 | |
| | | | | | TOTAL | ~1,159 |

A depth vertical geothermal probe (a heat exchanger) of a double-pipe type (Fig. 1) is located in a single hole of that kind. Water is injected through the ring-shaped channel and extracted

through the inner conductor [3,4,5]. At given temperature of a rock the depth of a geothermal heat exchanger is a substantial factor as it decides on the maximum temperature of the rock. The temperature should be optimal due to the efficiency of winning energy and co-operation with the heat receivers (low-parameter or high-parameter ones) as well as the capital costs. It is also important to insulate the outside pipe at the right depth. The depth depends on the temperature of water injected into a geothermal heat exchanger. In view of heat exchange and the value of gained geothermal energy, the insulation should be so long that the water flowing through the exchanger on its whole active length (the non-insulated one) will take the heat from the rock layer. Thus the authors, on the basis of their own computational models [3,4] for one-hole deep heat exchangers, worked out the appropriate characteristics. The characteristics determine the possibility of winning a geothermal heat flux in a function of the depth of a geothermal heat exchanger and in a function of temperature of water injected into the heat exchanger, a volume flow of the water as well as in a function of the temperature of a deposit and the insulation of a outside pipe of a heat exchanger.

When taking into consideration appropriate characteristics of heat receivers, the characteristics for one-hole systems allow one to chose the most effective system of winning the geothermal heat energy for the designed system of heat removal and winning the geothermal energy.

A computational model of a geothermal heat exchanger Field type with insulation of the outside pipe in its top part

The exchanger is located in impermeable rock massif, where temperature changes are linear. Overall heat transfer coefficient through the inside surface k is calculated from known classical formulae. The amount of heat exchanged between water flown through the outside part and the rock deposit is estimated by using a substitute overall heat transfer coefficient k_z , which value changes within time. Values of the substitute overall heat transfer coefficient may be estimated on the basis of the formulae presented in known publications [1].

Additionally, the exchanger is insulated in its top part (on the outside pipe) in the length that the temperature of water injected into the heat exchanger is the same as the temperature of the rock at the point S – Fig. 1 (the water in the whole non-insulated part of the exchanger takes heat from the rock layer).

The thermal field of fluid with appropriate designations is given in Fig. 1.

The calculations are made in relation to the axis $T^*, \Theta^* - X$. On the basis of balance equations for a fluid flowing in a ring-shaped channel and in the inside conductor when the equations of heat exchange are taken into account and introducing $\dot{W} = \dot{m}c_p$, $K = k\pi D_2 L$, $K_z = k_z \pi D_1 L$, $b = (K + K_z)/\dot{W}$, $a = K/\dot{W}$, $T_x = EX + F$, $\Theta_1 = T_1 - T_x$, $\Theta_2 = T_2 - T_x$ we obtain the following system of differential first-order equations:

$$\frac{d\Theta_1}{dX} = a\Theta_2 - b\Theta_1 - E, \quad (1)$$

$$\frac{d\Theta_2}{dX} = a\Theta_1 - a\Theta_2 - E. \quad (2)$$

The above equations' system has been solved by d'Alambert's method [2] and it can be written as follows [4]:

$$\Theta_1 = -C_2 \exp(\sqrt{\frac{2}{a}} X) + C_1 \exp(-\sqrt{\frac{2}{a}} X), \quad (3)$$

$$\Theta_2 = C_2 \frac{q_2}{p_2} \exp(\sqrt{\frac{2}{a}} X) - C_1 \frac{q_1}{p_1} \exp(-\sqrt{\frac{2}{a}} X) + \frac{E}{a}, \quad (4)$$

where: $\sqrt{\frac{2}{a}} = 0,5 \left(K_z / \dot{W} \right) \left[-1 \pm \sqrt{1 + 4(K/K_z)} \right]$, $(q_i/p_i) = -(\sqrt{\frac{2}{a}} + b)/a$ for $i = 1, 2$.

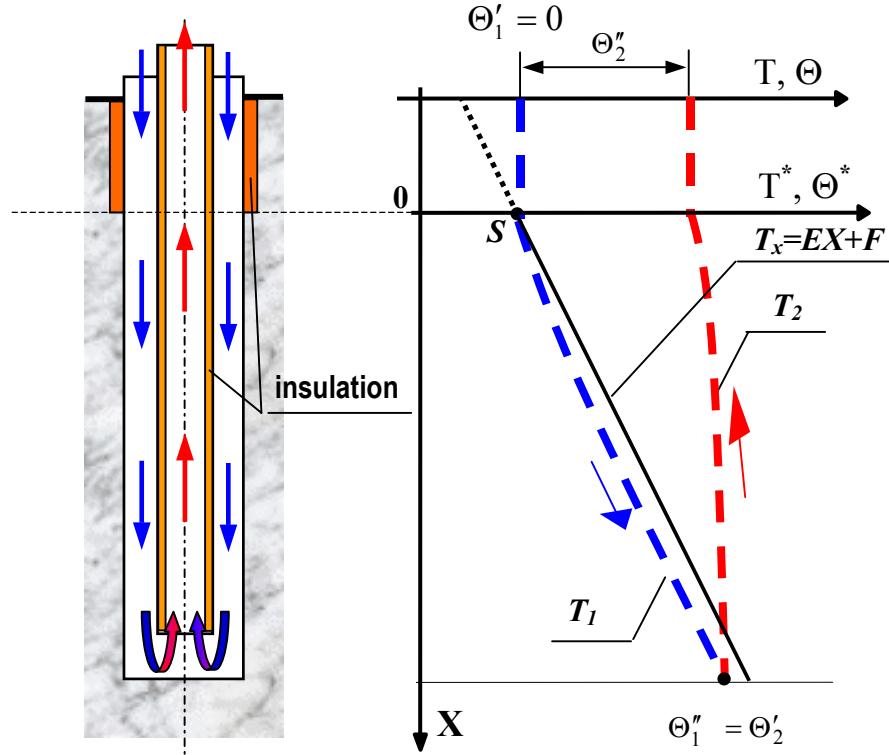


Fig. 1. The scheme of the geothermal heat probe (heat exchanger) with insulation

To obtain an explicit description of thermal field in the exchanger it is necessary to determine two integration constants occurred in relations (3) and (4), using the following boundary conditions:

$$\Theta_1(X=0) = \Theta'_1 = 0, \quad (5)$$

$$\Theta''_1(X=1) = \Theta'_2(X=1). \quad (6)$$

The integration constants are as follows:

$$C_1 = C_2 = C = \frac{\Theta'_2 - \frac{E}{a}}{\frac{q_2 \exp(v_2^2)}{p_2} - \frac{q_1 \exp(v_1^2)}{p_1}}, \quad (7)$$

Knowing the integration constants allows one to determine the thermal field of a heat exchanger. The temperature on the output of a heat exchanger is determined by the following relation:

$$\Theta''_2 = C \frac{q_2}{p_2} - C \frac{q_1}{p_1} + \frac{E}{a} = \frac{\left(\Theta'_2 + \frac{E}{a} \right) \left(\frac{q_2}{p_2} - \frac{q_1}{p_1} \right)}{\frac{q_2 \exp(v_2^2)}{p_2} - \frac{q_1 \exp(v_1^2)}{p_1}} + \frac{E}{a}. \quad (8)$$

A flow of heat collected by a Field heat exchanger is determined by the relation:

$$\dot{Q} = \dot{W} \Theta''_2. \quad (9)$$

Calculation results

The calculations (assuming constant work within 30 days) were done using the presented computational model for the following parameters (assuming that the top part of a geothermal heat exchanger is insulated at the given depth):

- temperature of a rock massif at the depth 4,000 m is 142°C,
- temperature on the earth surface is 10°C,
- the length of a heat exchanger L : 2,000 m; 3,000 m; 4,000 m,
- temperature of water injected into the exchanger $T_1 = T_{inj} = 20, 25, 30, 35$ i 40°C ,
- the length of the outside pipe insulation: $L_{ins} = \sim 303, \sim 455, \sim 606, \sim 758$ i ~ 909 m,
- a water flow in the exchanger $\dot{V} = 1 - 60 \text{ m}^3/\text{h}$,
- the inner diameter of the outside pipe $D_1 = 0.2445$ m,
- the outer diameter of the inside pipe $D_2 = 0.1143$ m,
- an overall heat transfer coefficient of the inside pipe $k = 0.91 \text{ W}/(\text{mK})$,
- the parameters of a rock: $\lambda = 3.46 \text{ W}/(\text{mK})$, $\rho = 3,200 \text{ kg}/\text{m}^3$, $a_s = 1.3 \cdot 10^{-6} \text{ m}^2/\text{s}$, $c_p = 837.1 \text{ J}/(\text{kgK})$.

Calculations for the case when the outside pipe of a heat exchanger is not insulated were done as well [5]. Results of the calculations in the appropriate heat-flow characteristics are presented in Figs. 2–5.

The characteristics show how the change of a volume value of a water flow in a geothermal heat exchanger (at the given temperature of injected water) influences the changes of the fluxes of gained geothermal heat with a real change of the temperature of the water on the output of the heat exchanger. The temperature depends on the characteristics of a deposit as well as on the length of a heat exchanger.

Conclusions

From the analysis of the graph (Fig. 2) the possibility of applying different types of governing is concluded. The possibility is the least when quality or quantity governing is applied as at a given temperature of injection of water in a heat distribution network there is only one point of co-operation. However, the co-operation is possible at the points situating on a curve of given temperature of injection. Considering the quality governing, the control range may be widened by injecting the changing amount of water in a heat distribution network. In case of quantity governing the same result may be obtained by using changing temperature of the water in a heat distribution network on the output of a geothermal heat exchanger. Therefore, while using geothermal exchangers co-operating with a heat distribution network, quantity-quality governing should be applied because then the point of co-operation a geothermal heat exchanger – a heat distribution network may move on a given surface. Thus Figs. 2 a and 2b show the area of the temperature rise in a heat exchanger when the mix governing is applied. In each case, the amount of total geothermal heat used in a heating season (central heating + warm consumption water) and out of the heating season (warm consumption water) is the parameter deciding on which type of the control should be chosen.

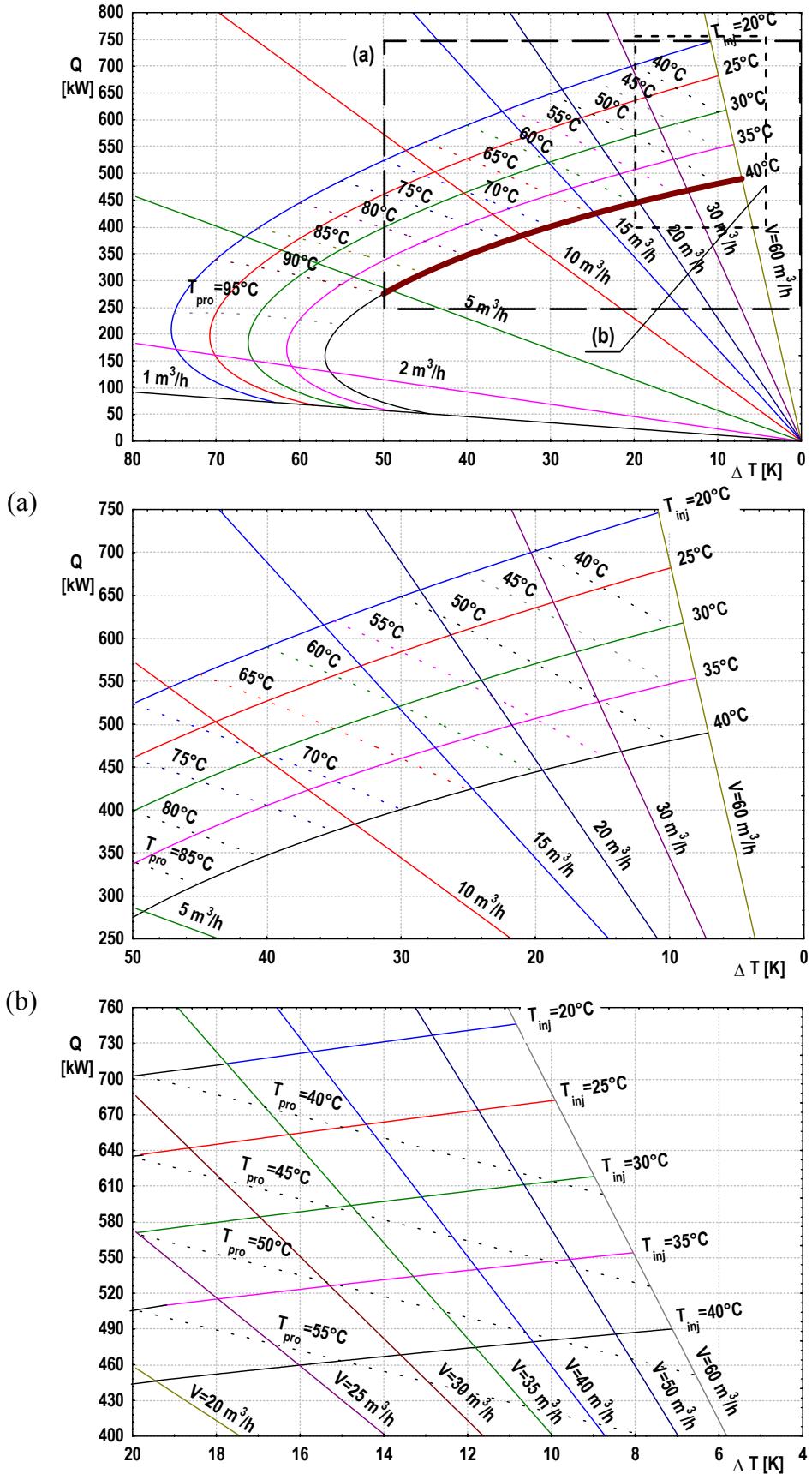


Fig. 2. The possibility of winning the energy from a geothermal heat exchanger of the length 4,000 m with separated areas of co-operation between a geothermal heat exchanger and a heat distribution network for the temperature rise: (a) $\Delta T = 0$ –50 K, (b) $\Delta T = 4$ –20 K

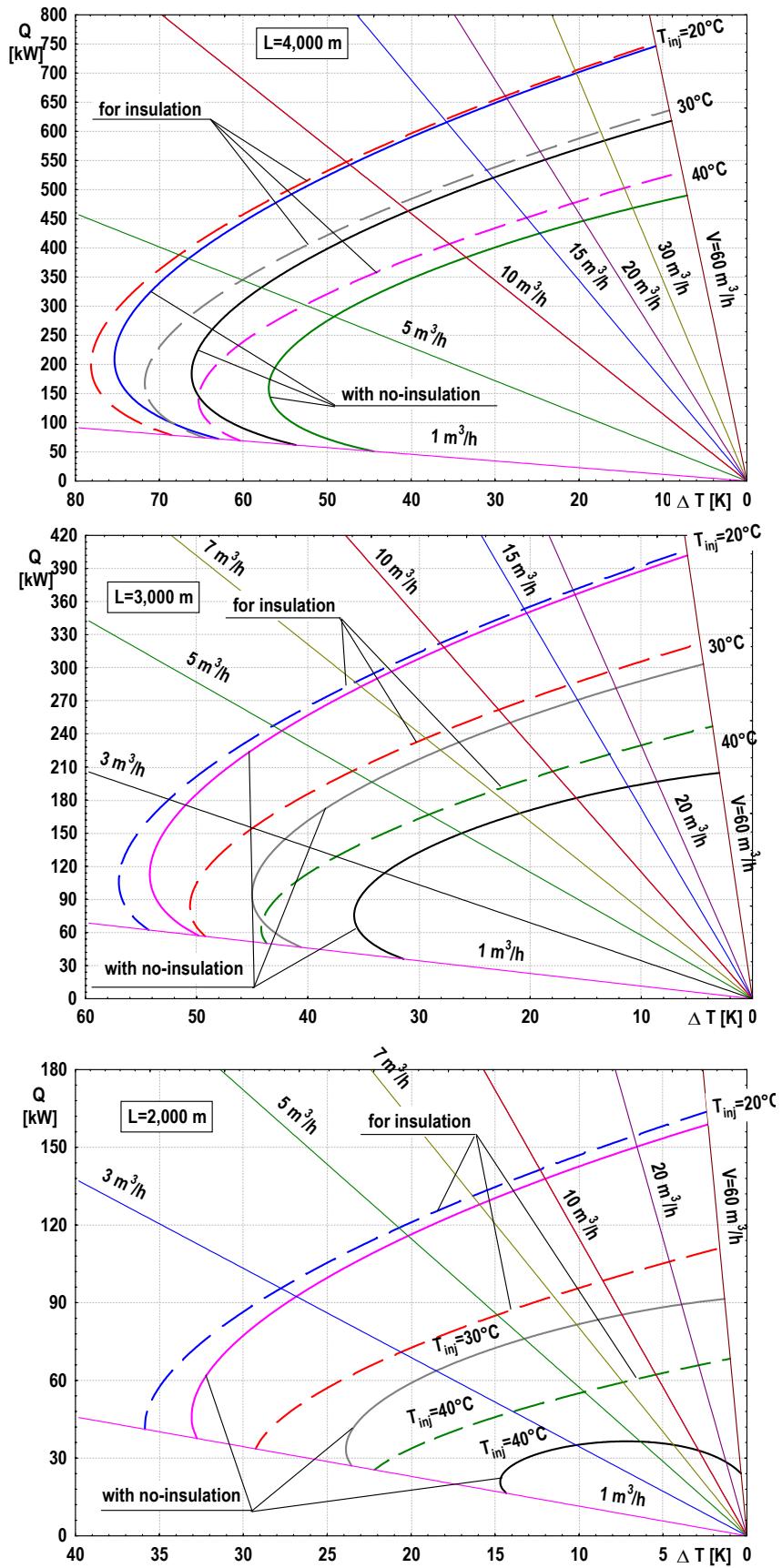


Fig. 3. The impact of insulation on flux of gained geothermal heat \dot{Q} for chosen lengths of a geothermal heat exchanger

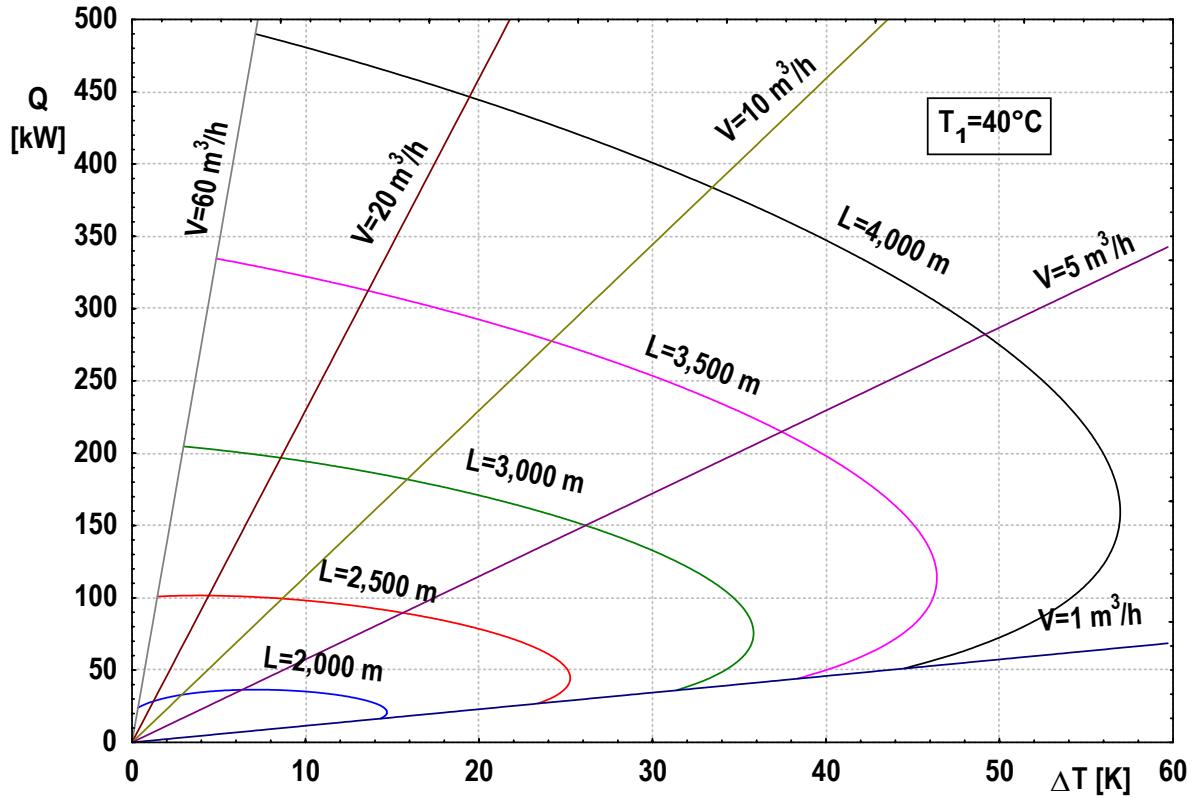


Fig. 4. The impact of a volume flow of a geothermal water \dot{V} , the length of a geothermal heat exchanger L and the difference of temperatures ΔT between extracted and injected water on a flux of gained geothermal heat \dot{Q} (variant without insulation)

The analysis of the graphs (Figs. 3 and 4) shows the following conclusions:

- it should be applied a proper type of a heat network regulation according to the parameters of a geothermal heat exchanger supplying a given group of heat receivers in the way to give the most efficient use of the winning geothermal energy.
- with the increase in a volume flow of water in a heat distribution network there is the increase in a flux of gained geothermal heat whereas the temperature rise on a geothermal heat exchanger decreases and reciprocally (Figs. 2–5),
- insulation in the top part of a geothermal heat exchanger at the depth, where the temperature of injected water is the same as the temperature of the ground, causes the increment in a flux of gained geothermal heat as well as the increase in a temperature rise of water in a heat distribution network (Fig. 4),

Nomenclature

a, b, C_1, C_2, C, p, q – constants,
 a_s – thermal diffusion of a rock, m^2/s ,
 c_p – specific heat at constant pressure, $\text{J}/(\text{kgK})$,
 D – diameter, m,
 E, F – constants, $^\circ\text{C}$,

| | |
|------------|---|
| k | – heat transfer coefficient, $\text{W}/(\text{m}^2\text{K})$, |
| L | – length of exchanger, m, |
| T | – temperature, $^\circ\text{C}$, |
| X | – reduced coordinate, |
| \dot{W} | – thermal capacity of heat flow, W/K , |
| ρ | – mass density, kg/m^3 , |
| v | – root of an algebraic equation, |
| λ | – thermal conductivity of a rock, $\text{W}/(\text{mK})$, |
| Θ | – difference of temperature, K, |
| ΔT | – difference of temperature ($T_2 - T_1 = T_{\text{pro}} - T_{\text{inj}}$), K, |

Subscripts

| | |
|--------------|--|
| $1,2$ | – the first fluid and the second fluid (in a ring-shaped channel and in the inside conductor of heat exchanger), |
| i | – i -function ($i = 1, 2$), |
| pro | – production well, |
| inj | – injection well, |
| ins | – insulation, |
| $'$ | – the temperature or difference of temperature at input, |
| $''$ | – the temperature or difference of temperature at output. |

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