Assessing the Effectiveness of a Heating Plant Operation Fed from a Horizontal Geothermal Heat Exchanger with Qualitative Regulation

Radomir Kaczmarek, Aleksander A. Stachel*

Department of Heat Engineering, West Pomeranian University of Technology,
Piastów 17, 70-310 Szczecin, Poland

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Abstract

This paper presents preliminary results of calculations of different cases of a geothermal horizontal heat exchanger, where the vertical extraction channel is manufactured as a tube-in-tube exchanger. Such a channel permits control of the mass flow rate of water flowing through its circular (inner) part or annular (external) part, where the latter part also forms the thermal insulation of the exchanger. Results of calculations enable us to control the extent of both outflowing flow rates of water, which will permit us to attain the required temperature of the fluid at an outlet from the exchanger. Due to the fact that the fluid is, at the same time, the energy carrier supplying the heat receivers, the postulated design is equivalent to the equality of rates of acquired geothermal heat and heat demand in receivers of a district heating network for some external temperatures.

Keywords: geothermal energy, geothermal heating plant, horizontal closed-loop geothermal heat exchanger

Introduction

The temperature found in the Earth's core is estimated to be 3,500-6,600°C because of the so-called residual energy coming from the period of the Earth's formation as well as spontaneous heat sources. Such processes consist primarily of natural radioactive decay of radicals, heat of fusion of substances forming the external core of Earth as well as heat of dissipation of tidal energy in the liquid Earth's core, induced by gravitational interaction between the moon and the sun. The sum of all these energies is called geothermal energy [1-3].

Temperature difference between the hot core and the cool surface of Earth renders the flow of the rate of geothermal heat with average density of about 63 kW/km^2, which after reaching Earth's surface is radiated outwards to space in the form of long-wave radiation.

*e-mail: andrzej.stachel@zut.edu.pl

Geothermal heat flux is not uniform across the Earth. The regions featuring the values of heat fluxes diverge from the mean value, and as a consequence with values differing from mean values of rock temperatures are known as geothermal anomalies.

Vertical changes of temperature of the Earth's crust are called geothermal gradient. A typical value of the geothermal gradient is about 30 K/km. It can be assumed that down to a depth of 10 km below the Earth's surface temperature T in the crust varies linearly with the depth in line with the relation (Fig. 1):

$$T_{sk} = T_{s0} + AH \ \ [°C]$$

...where:
H – depth [km],
A – geothermal gradient [K/km],
T_{s0} – mean temperature of soil at the Earth's surface [°C],
T_{sk} – temperature of rocks (and bed fluids) at depth H [°C].

The geothermal energy accumulated in the Earth's crust can be utilized in various ways, for example for supplying the heating plant as well as power plant or a heat and power plant [1-3]. One perspective method for acquiring geothermal energy is applying the so-called horizontal closed-loop geothermal heat exchanger (HCGHE), consisting of a set of underground horizontal and vertical pipelines, laid out at a significant depth. The liquid, serving as a heat carrier that is heated to adequate temperature (close to rock temperature) is pumped through them, transferring heat from the rock bed to the heat recipients (Fig. 2).

The extent of acquired geothermal energy is dependent on the depth of location of the geothermal heat exchanger, which is dependent, to a large extent, on the temperature of surrounding rocks as well as heat transfer surface and the flow rate of liquid. That topic has been thoroughly presented in [4-7].

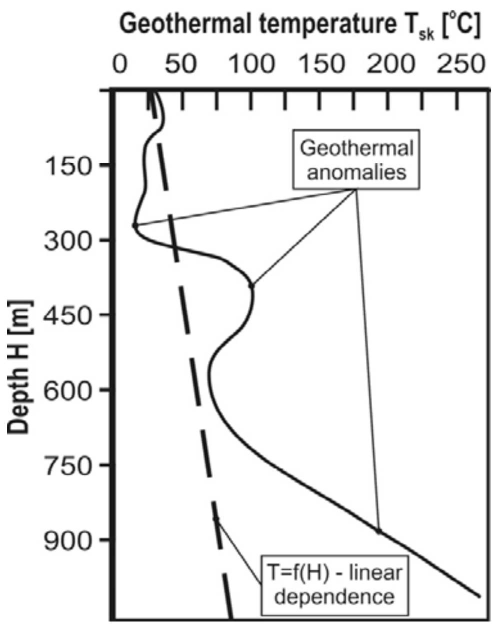

Fig. 1. Vertical change of temperature in the Earth's crust.

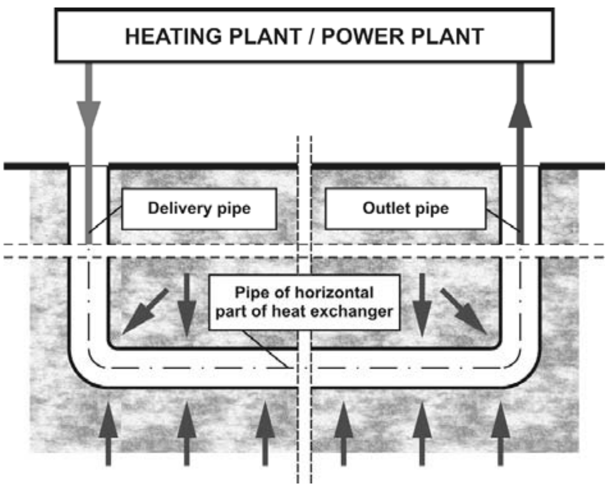

Fig. 2. Schematic of the underground closed-loop geothermal heat exchanger cooperating with the heating plant/power plant/heat and power plant.

The closed-loop geothermal heat exchangers feature significant location independence as well as a possibility for long-term operations at relatively small power of circulation pumps for liquid through the sealed exchanger's system. Their important feature is the possibility of elastic operation. Such heat exchangers enable acquisition of geothermal energy in all places where, due to geological reasons, the so-called open systems cannot be used, which utilize, for example, the geothermal water.

The major drawback of HCGHE is its high investment cost and the necessity of harnessing technological processes related to drilling and installing of sealed systems of pipelines at significant depths. Existing practical possibilities are applicable for carrying out drilling works with depths down to 5,000 m and a horizontal length up to 15,000 m.

It ought to be stressed that the idea of a deep horizontal geothermal heat exchanger is a possible solution that enables acquisition of geothermal energy under conditions characterized by relevant temperature of the rocky skeleton and serves as an alternative to so-called hot dry rock technology (HDR) [8]. An interesting research program related to the possibilities and economy of manufacturing of the horizontal closed-loop heat exchanger has been carried out by a group from the Technical University of Berlin [9, 10]. For some time now similar activities regarding that topic have been carried out at the Heat Technology Department of West Pomeranian University of Technology in Szczecin [11].

This paper assesses the effectiveness of the operation of a heating plant supplied from a horizontal closed-loop geothermal heat exchanger, where the active insulation is applied [12]. Such application will enable flexible qualitative control of supplied heat that results from central heating (c.o.) requirements and preparation of utility hot water (c.w.u).

In the analysis we utilized the modified analytical calculation model originally presented in [11].

System Description

The considered system consists of two parts, the first one where geothermal energy is acquired and which is in the form of an underground closed-loop geothermal heat exchanger, and the second one, where the energy is used (heat plant with a system of heat receivers).

A horizontal closed-loop geothermal heat exchanger consists of a set of underground pipelines through which the liquid is pumped. The liquid is the heat carrier for acquisition of geothermal energy from the rock mass, which can subsequently be distributed to relevant heat receivers. In the analyzed case the extraction part of the exchanger has been modified and consists of the outlet channel in the form of two coaxially aligned pipelines. Such an arrangement of system pipelines renders the annular channel through which a part of the fluid flow rate is going. The outer annulus additionally forms the active insulation. Inside the inner pipeline (circular channel) flows the remaining part of the fluid flow rate, which in our case is the primary heat carrier. The volumes of flow rates in annular and inner channels are closely related to each other and in total are equal to the amount of fluid pumped to HCGHE. By changing the proportion of fluid flow rates through the annular channel and a circular channel, it is possible to influence the temperatures of both fluids. Because of this, after mixing of both flow rates of fluids it is possible to attain the required temperature of the heat carrier that is adjusted to the required temperature of the network water supplying the heat receivers.

The heat plant consists of two counter-current heat exchangers operating to cover the needs of central heating and preparation of utility hot water as well as pipelines transporting the heat carrier, network water and utility hot water. A schematic of the heat plant together with supporting geothermal heat exchanger is presented in Fig. 3.

In relation to external air temperatures we can distinguish three phases of heat plant operation:

- phase one, related to the heating season and lowest external temperatures (-16-8.4°C); in this case the bypass “A-F” is closed and the entire flow rate is directed to the distribution node “B”, where the split of the flow rate onto the part directed to the heat exchanger supplying the c.o. installation and exchanger supplying the c.w.u. installation is taking place. Required temperatures and flow rates reaching these exchangers are adjusted by appropriate settings of bypasses “D-C” and “D-E”, and
- phase two, related to the heating season and higher external temperatures (8.4-12°C); in this phase a minimum temperature of extracted fluid from HCGHE is determined by the demand of c.w.u. installation. As a result, the energy surplus arises and is removed via the “A-F” bypass. Reduction of heat carrier temperature directed to the c.o. exchanger is realized by the “D-C” bypass. In that phase the “D-E” bypass is closed.
- phase three related to the period outside the heating period (external temperatures above 12°C); in this phase the part of the heat plant responsible for covering the demand for c.o. is closed. The required part of flow rate is directed to the c.w.u. exchanger. Remaining part of fluid is removed through the bypass “A-F.”

Geothermal Heat Exchanger – Assumptions for Calculation Model

Analysis assumes the following assumptions regarding the demand for preparation of water for domestic purposes as well as water for central heating [13, 14]:

- climate zone: I (minimum external temperature: T_{zmin} = -16 ºC),
- method of adjustment: qualitative regulation,
- external temperature at which heating starts: T_{zg} = 12°C,
- duration of heating season: τ_o = 4,368 hours (number of hours per annum: τ_c = 8,760 h),
- rates of heat capacities of network water and heat carrier are the same,
- temperature difference in heat exchangers: ΔT = 2 K,
- specific heat of heat carrier and network water: c_p = 4,18 kJ/(kgK),
- temperature of cold water for domestic purposes: T_{cwup} = 13°C,
- temperature of hot water for domestic purposes: T_{cwuz} = 60 °C,

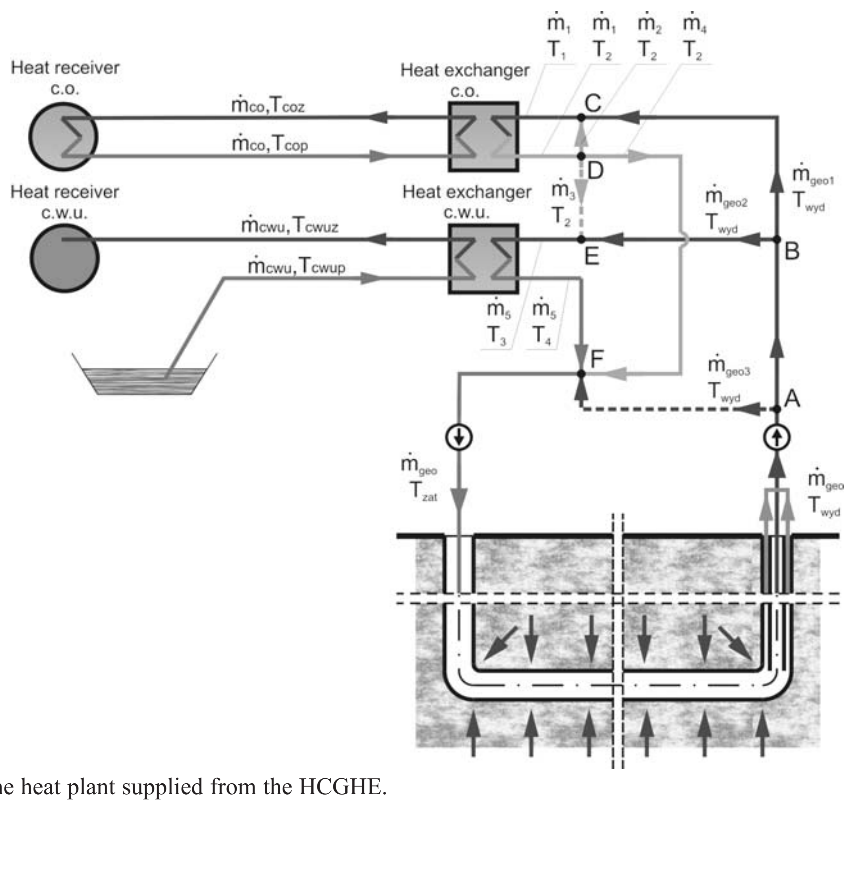

Fig. 3. Schematic of the heat plant supplied from the HCGHE.

- temperature of network return water: $T_{cop} = 40°C$ (constant),
- maximum temperature of network water at heating installation inlet (at $T_z = -16°C$): $T_{cozmax} = 95°C$,
- temperature of supplying network water varies linearly in function of external temperature:

$$T_{coz} = a + bT_z \quad (1)$$

- relation for reduced external temperature in function of reduced time [15]:

$$\frac{T_{zg} - T_z}{T_{zg} - T_{z\min}} = \left[1 - \sqrt[3]{\frac{\tau}{\tau_o}} + \left(\frac{\tau}{\tau_o}\right)^2 \left(1 - \sqrt{\frac{\tau}{\tau_o}}\right)\right] \quad (2)$$

- flow rate of water for c.w.u. purposes – $\dot{m}_{cwu}$, has been adjusted in such a way that the heat power was at the level of 15% of peak power consumption:

$$\dot{Q}_{cwu} = 0.15\, \dot{Q}_{co\,max} \quad (3)$$

Following the assumptions made in section 3, the maximum temperature at outlet from HCGHE has to be equal to 97°C. In order to ensure the flow rate with such temperatures, the geothermal heat exchanger will be placed at a depth of 3,500 m. According to [6], at such depths the temperature of rocks in the western part of Poland reach 110°C. For calculations of temperature fields in the pumping part as well as the horizontal part of HCGHE, the calculation model presented in [11] has been used, whereas for the extraction part the model contained in [12] was applied.

Remaining assumptions regarding the geothermal heat exchanger (annular part):

- external diameter of the pipeline D_z = 219.1 mm, wall thickness: δ = 3.76 mm,
- external diameter of circular tube (inner): D_w = 141.3 mm, wall thickness: δ = 3.41 mm,
- due to varying proportions of the amount of fluid flowing in the annular channel and circular channel, and therefore varying velocities, in calculations average values of velocities and constant values of heat transfer coefficients have been assumed.
- mean velocity of water flow rate in the circular channel: w_1 = 1.7 m/s,
- mean velocity of water flow rate in the annular channel: w_2 = 1.2 m/s,
- overall heat transfer coefficient between the fluid in circular channel and the one in annular channel: $k_{1\text{-}2}$ = 20 W/(m²K),
- overall heat transfer coefficient between the fluid in annular channel and the rock: $k_{2\text{-}S}$ = 125 W/(m²K),
- length of the horizontal part of exchanger: L = 7,000 m,
- temperature at Earth's surface: T_{s0} = 10°C,
- total mass flow rate flowing through the exchanger (total flow rate of fluid in annular channel and circular channel): $\dot{m}_{geo}$ = 46 kg/s.

Calculation Procedure

Assumptions presented in section 3 together with additional equations enable determination of values of coefficients a and b in formula (1) determining the relation between temperature of the network water supplying the c.o. receivers and external temperature.

Additional equations on the basis of [16]:

$$\begin{cases} \dot{Q}_{co} = \dot{Q}_{co\max} \dfrac{20 - T_z}{20 - T_{z\min}} \\ \dot{Q}_{co} = \dot{m}_{co} c_p \left(T_{coz} - T_{cop}\right) = \dot{m}_{co} c_p \left(a + bT_z - T_{cop}\right) \end{cases} \quad (4)$$

Following the solution of a set of equations we get:

$$a = \frac{20}{36}\left(T_{coz\max} - T_{cop}\right) + T_{cop} \quad (5)$$

$$b = -\frac{1}{36}\left(T_{coz\max} - T_{cop}\right) \quad (6)$$

As a result, the distributions of network water temperature supplying the c.o. receivers in relation to external temperature is obtained. Additionally, on the diagram presented are all changes of the fluid temperature in the heating period as in Fig. 4.

With the light colour denoted are temperatures related to the heat carrier supplying energy to the c.o. exchanger (at inlet – T_1, at outlet – T_2) and c.w.u. exchanger (at inlet – T_3, at outlet – T_4). With the dark colour denoted are temperatures of heated fluids in c.o. heat exchanger (at inlet – T_{cop}, at outlet – T_{coz}) and c.w.u. heat exchanger (at inlet – T_{cwup}, at outlet – T_{cwuz}). Additionally, Fig. 4 presents the temperatures of heat carrier at inlet to HCGHE (T_{zat}) and at outlet from HCGHE (T_{wyd}).

Additional equations enabling determination of flow rates have been obtained using the energy and mass balance equations in nodes, where the flow rates of liquid combine or split, that is:

- mass balance equation for node "A-B":

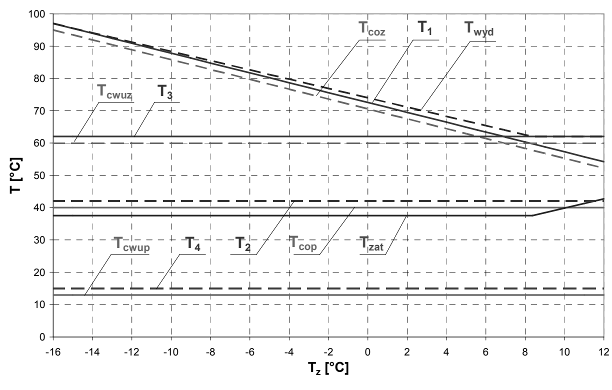

Fig. 4. Distributions of characteristic temperatures in the heat plant in relation to external air temperature.

Table 1. Tabulation of input data and results of calculations.

Parameter		Values in temperature range			Description
		-16 – 8.4 °C	8.4 – 12 °C	>12 °C	
$\dot{m}_{geo}$	kg/s	46.00	46.00	46.00	Mass flow rates in particular nodes of the system
$\dot{m}_{geo1}$	kg/s	43.24 - 38.41	38.41 - 26.42	0	
$\dot{m}_{geo2}$	kg/s	2.76 - 7.59	7.59	7.59	
$\dot{m}_{geo3}$	kg/s	0	0 - 11.99	38.41	
$\dot{m}_1$	kg/s	43.24	43.24	0	
$\dot{m}_2$	kg/s	0 - 4.83	4.83 - 16.82	0	
$\dot{m}_3$	kg/s	4.83 - 0	0	0	
$\dot{m}_4$	kg/s	38.41	38.41 - 26.42	0	
$\dot{m}_5$	kg/s	7.59	7.59	7.59	
$\dot{m}_{co}$	kg/s	43.24	43.24	0	
$\dot{m}_{cwu}$	kg/s	7.59	7.59	7.59	
T_1	°C	97.00 - 59.77	59.77 - 54.22	–	Temperatures in particular nodes of the system
T_2	°C	42.00	42.00	–	
T_3	°C	62.00	62.00	62.00	
T_4	°C	15.00	15.00	15.00	
T_{wyd}	°C	97.00 - 62.00	62.00	62.00	
T_{zat}	°C	37.54	37.54 - 42.76	54.24	
T_{coz}	°C	95.00 - 57.77	57.77 - 52.22	–	Temperatures of feeding, supply, and return water for c.o. and c.w.u
T_{cop}	°C	40.00	40.00	–	
T_{cwuz}	°C	13.00	13.00	13.00	
T_{cwup}	°C	60.00	60.00	60.00	
$\dot{Q}_{co}$	kW	9,940.9 - 3211.5	3,211.5 - 2,209.1	0	Heat power
$\dot{Q}_{cwu}$	kW	1,491.1	1,491.1	1,491.1	

$$\dot{m}_{geo} = \dot{m}_{geo1} + \dot{m}_{geo2} + \dot{m}_{geo3} \tag{7}$$

- mass and energy balance equations for node "C":

$$\dot{m}_{geo1} + \dot{m}_2 = \dot{m}_1 \tag{8}$$
$$\dot{m}_{geo1}T_{wyd} + \dot{m}_2T_2 = \dot{m}_1T_1 \tag{9}$$

- mass balance equation for node "D":

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 + \dot{m}_4 \tag{10}$$

- mass and energy balance equations for node "E":

$$\dot{m}_{geo2} + \dot{m}_3 = \dot{m}_5 \tag{11}$$
$$\dot{m}_{geo2}T_{wyd} + \dot{m}_3T_2 = \dot{m}_5T_3 \tag{12}$$

- mass and energy balance equations for node "F":

$$\dot{m}_{geo3} + \dot{m}_4 + \dot{m}_5 = \dot{m}_{geo} \tag{13}$$

$$\dot{m}_{geo3}T_{wyd} + \dot{m}_4T_2 + \dot{m}_5T_4 = \dot{m}_{geo}T_{zat} \tag{14}$$

Assuming qualitative control as well as utilizing equations (3), (7), (8), (11), (12), and (13) determined a constant value of the flow rate of heat carrier supplying the c.o. heat exchanger (equal to the flow rate of network water):

$$\dot{m}_1 = \dot{m}_{co} = 0.94\ \dot{m}_{geo} \tag{15}$$

The flow rate of fluid supplying the c.w.u. exchanger which, due to assumptions, is equal to the flow rate of hot utility water yields:

$$\dot{m}_5 = \dot{m}_{cwu} = 0.165\ \dot{m}_{geo} \tag{16}$$

Having determined values of flow rates supplying the c.o. and c.w.u. heat exchangers, as well as utilizing the mass and energy balance equations (7-14) determined were remaining flowrates together with corresponding temperatures and variation of these parameters for three ranges of temperatures, corresponding to three phases of operation of heating plant described in section 1.

All data and results of calculations are shown in Table 1, which presents changes of particular parameters in three temperature ranges corresponding to three phases of heat plant operation described in section 2.

Distributions of temperature fields have been made for three temperatures of pumped fluid to the HCGHE, which are characteristic for particular phases of heat plant operation.

In the diagram, additionally presented is a curve representing the rock temperature change (T_{sk}) with the depth of the well, which coincides with the length of the vertical part of the analyzed geothermal heat exchanger.

As is apparent from Fig. 5, the pumping temperature in analyzed cases practically does not influence the temperature of extracted fluid. Therefore, independently from the phase of operation of the heat plant it has been assumed that the fluid in the horizontal part of the exchanger is heated to 107.8°C.

Fig. 6 presents the range of temperature distributions of heat carrier in relation to the shares of flow rates in annular

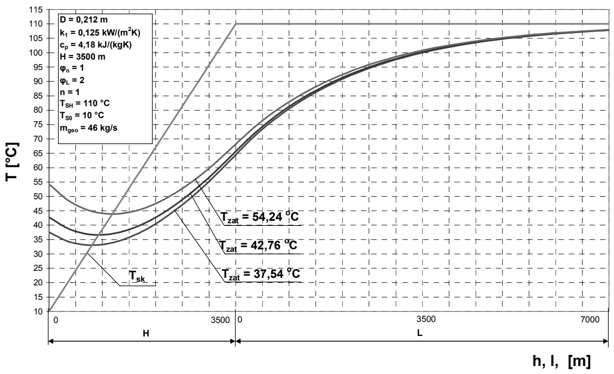

Fig. 5. Temperature field in the heat carrier flowing through the HCGHE.

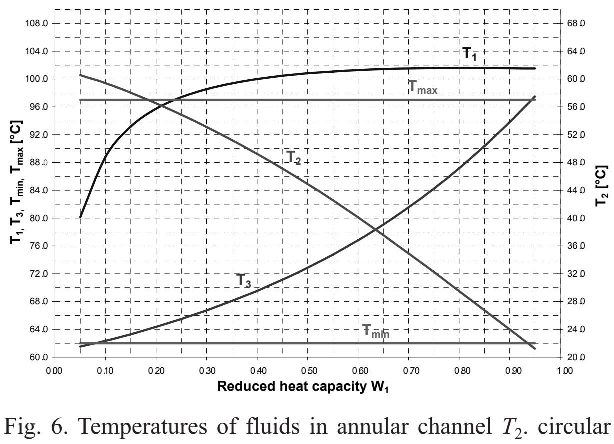

Fig. 6. Temperatures of fluids in annular channel T_2. circular channel T_1 and temperature of fluid after mixing T_3 at outflow from the extraction part of exchanger in relation to flow rates in these channels.

and circular channels. As stems from the figure, for adequately assumed values of flow rates the regulation of temperature in the range from 62 to 97°C is possible, i.e. the range which is indispensable for the analyzed system.

Results of Calculations for a Heat Plant

The amount of heat supplied to cover the demand for central heating in the whole heating season is calculated from the formula:

$$Q_{co} = \int_0^{\tau_0} \dot{m}_{co} c_p \left(T_{coz} - T_{cop}\right) d\tau \tag{17}$$

Using the relations (1), (2) and $\overline{\tau} = \tau/\tau_o$, the relation is finally obtained:

$$Q_{co} = \dot{m}_{co} c_p \tau_0 \int_0^1 \left\{ a + b\left[T_{zg} - \left(T_{zg} - T_{z\min}\right)\left[\left(\overline{\tau}\right)^{\frac{1}{3}} - \left(\overline{\tau}\right)^2 + \left(\overline{\tau}\right)^{\frac{5}{2}} \right]\right] - T_{cop} \right\} d\overline{\tau} \tag{18}$$

After substiting appropriate values, the heat required to cover the central heating heat demand is: Q_{co} = 19,701 MWh.

The amount of heat supplied in the whole year to cover the needs of preparation of utility hot water is calculated from the formula:

$$Q_{cwu} = \dot{m}_{cwu} c_p \left(T_{cwuz} - T_{cwup}\right) \tau_c \tag{19}$$

After substitution of relevant values the demand for heat for preparation of utility hot water is: Q_{cwu} = 13,062 MWh.

The total amount of heat supplied to recipients is:

$$Q_{cal} = Q_{co} + Q_{cwu} \tag{20}$$

After substitution of relevant values the total heat is: Q_{cal} = 32,763 MWh

All the results of calculations are presented in Fig. 7.

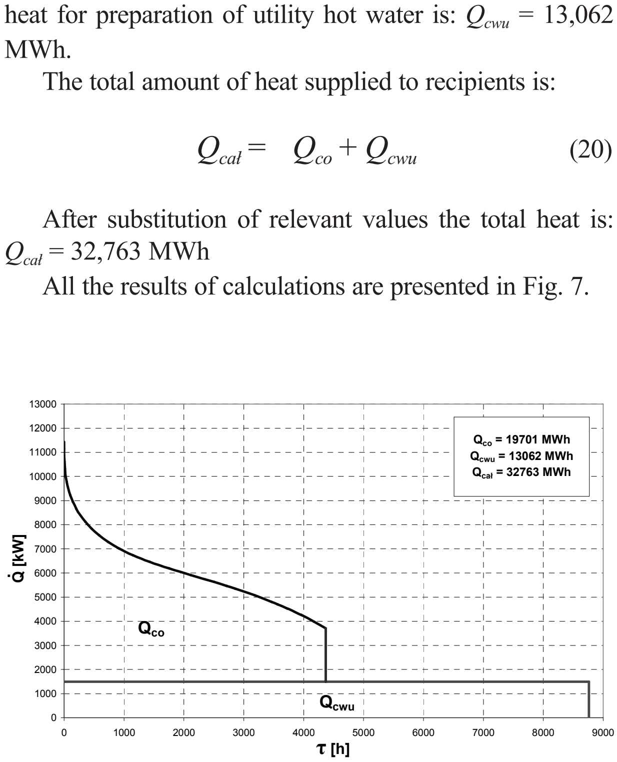

Fig. 7. Demand for heat demand and amount of heat supplied in c.o. (Q_{co}) and c.w.u. (Q_{cwu}) heat exchanger.

Conclusions

The following calculations were performed according to the procedure presented in the paper. The following values were obtained:

- $\dot{Q}_{co\,max}$ = 9,940.9 kW – maximum thermal power for c.o. requirements,
- $\dot{Q}_{cwu}$ = 1,491.1 kW – thermal power for preparation of utility hot water c.w.u.

Due to this, the heat plant covers the heat demand in the period of the year in the amount of:

- Q_{co} = 19,701 MWh in case of energy for central heating,
- Q_{cwu} = 13,062 MWh in case of energy for preparation of utility hot water,
- Q_{cal} = 32,763 MWh total amount of heat supplied to recipients.

Due to the fact that the analyzed system enables regulation of extracted rate of energy (in relation to air external temperature), the energy used is equal to the extracted one. However, referring the total capacity supplied to recipients to the maximum capacity that could be acquired if the maximum heat demand persisted for the whole year, the following is obtained:

$$\varphi = \frac{Q_{cal}}{Q_{\max}} = \frac{32{,}763}{100{,}144} = 0.327 \tag{21}$$

Nomenclature

HCGHE – Horizontal Closed-loop Geothermal Heat Exchanger,
c_p – specific heat, kJ/kgK,
$\dot{m}$ – mass flow rate, kg/s,
T – temperature, K, ºC,
T_{zg} – lowest temperature for heating start-up, K, ºC,
T_z – external temperature, K, ºC,
τ – time, hours,
Q – heat, MWh,
$\dot{Q}$ – rate of heat (heating power), kW,
w – velocity of fluid flow, m/s,
W – rate of heat capacity, W/K.

Subscripts

1,2,3, – relates subsequent nodes of installation,
co – relates central heating,
cwu – relates utility hot water,
geo – relates to water receiving heat in HCGHE,
p – relates to return water,
wyd – relates to extracted water,
z – relates to supply parameters,
zat – relates to pumped water.

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