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SPECIFYING THE NUMBER OF BOREHOLE HEAT EXCHANGERS BASED ON THERMAL RESPONSE TEST AND GEOENERGETIC ANALYSIS***

1. INTRODUCTION

Utilization of the rock mass for heating and cooling is increasingly being used. Energy of the rock mass can be exploited by heat pumps with borehole heat exchangers. This installation not only produces renewable heat, but also the rationally manages heat in the building. This process uses heat from the rock mass for heating during the heating season, and cold contained in the ground at the end of the heating season for air conditioning in rooms.

Having borehole heat exchangers, it is possible to use the rock mass cyclically. Streams of energy, rather than to atmosphere, are moved between the building and the rock mass. There is also a possibility to use this system in a passive way, i.e. without heat pumps. Electricity is used only by the circulation pumps.

The basic parameter of heat pump systems with borehole heat exchangers is heating power possible to use. This parameter has a significant effect on the depth and the number of borehole heat exchangers. The location is also an important element. It affects the volume of energy possible to exchange. The size of the system is affected by its construction [3].

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2. THERMAL RESPONSE TEST

To properly design the construction, number and localization of boreholes, a very good knowledge of thermal properties of rocks is necessary. One method allowing that is Thermal Response Test (TRT) (Fig. 1). Firstly, special equipment is installed at the outlet of a BHE. This equipment is powered electrically. The heat carrier (e.g. water, glycol) is warmed up with a heater (Fig. 2). Heat carrier circulates inside the borehole heat exchanger by operation of the pump. The test starts when the heater is set to a fixed heating power. Input and output temperatures of the heat carrier, momentary flow and atmospheric temperature during the heating are recorded. The values of all parameters are stored in computer memory. The condition for obtaining correct results is sufficient time of the test so as to achieve changes in temperature not only in the solidified grout but also in the surrounding rocks.The test time is variously accepted. By Austin et al. it should last 50 hours [1], Gehlin astates minimum of 60 h [2], while Złotkowski et al. administered 100 h [3]. Heating power occurring during the thermal response test is difficult to maintain at a desired level. Throughout the test the power fluctuates near the predetermined value.

Fig. 1. Thermal Response Testmobile equipment

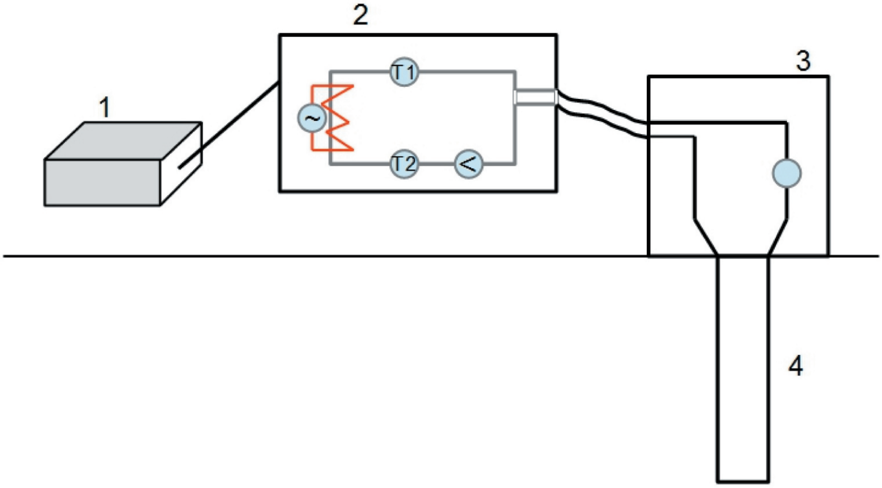

Fig. 2. Scheme of Thermal Response Test:
1– control module, 2 – pump module, 3 – valve module, 4 – U-pipe in the research borehole

3. ANALYSIS OF THE THERMAL RESPONSE TEST ON THE EXAMPLE OF THE BUILDING OF THE PRIMARY SCHOOL NO. 6 IN MYSZKÓW (SILESIA, POLAND)

This chapter will discuss results of the thermal response test, characteristics of the temperature of the system, characteristics of the heat pump, geological profiles, construction and quantity of projected borehole heat exchanger [5–8].

3.1. Results of the thermal response test

A thermal response test should be performed after drilling the first borehole heat exchanger. Based on this test, we can define the parameters of BHEs, such as their quantity, depth and location.

After the Thermal Response Test was obtained for a single u-pipe (DN 40) with a depth of 94 m, the effective thermal conductivity equalled $\lambda_{eff} = 4.39\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$. The average thermal efficiency of a BHE was estimated as $77.4\ \mathrm{W{\cdot}m^{-1}}$. Operation of the compressor heat pump was up to 2000 hours per year. The average initial temperature in the borehole was 10.2°C. Thermal resistance of the BHE is $R_b = 0.09\ \mathrm{m{\cdot}K{\cdot}W^{-1}}$ [8].

3.2. Temperature characteristics of the system

According to the project design, the system of borehole heat exchangers will be working only in the heating mode. Cooling load was not assumed. Throughout the calculated period (25 years), the temperature of the heat carrier on the inlet of the evaporator cannot be lower than 0°C.

Assuming the temperature drop of the heat carrier in the evaporator to be 4°C, the average temperature of the medium will be minus 2°C (temperature at the outlet of the evaporator to borehole heat exchanger is no less than minus 4°C). The planned energy performance of a building for the state after thermo-modernization has been presented in Table 1.

Table 1

The planned energy performance of the building [5]

Parameter	Unit	Value
Calculated heat power of the heating system	kW	104
Calculated heat power for the preparation of hot tap water	kW	20.4
Yearly demand for heat used for heating the building	GJ/yr	616
	MWh/yr	171.11
Calculated energy consumption for the preparation of hot tap water	GJ/yr	41.7
Minimum nominal heating power of heat pump	kW	144
Coefficient of performance (COP)	–	4.6
The temperature the heat carrier in the primary circuit	°C	10/5
Temperature the heat carrier in the secondary circuit	°C	50/40
The maximum input temperature on the secondary circuit	°C	60
The recommended minimum input temperature for the primary circuit	°C	–5

Based on data from Table 1 (annual heat demand for heating of the building, climatic data (from the measuring station in Katowice)) and the number of heating days in different months of the year, stated in the Regulation of the Minister of Infrastructure dated 17 March 2009 on the detailed scope and forms part of an energy audit and audit of repair, design cards audits, as well as the algorithm assessing the profitability of the project thermo-modernization, a monthly profile of the heat demand for heating of the building was estimated (Tab. 2).

The calculation (Tab. 2) assumes that the average air temperature in the building is 20°C. A monthly demand for heat to warm up utility water was calculated assuming the annual distribution of demand proportional to the amount of days per given month – excluding vacations, i.e. July and August.

Table 2

Monthly profile of the heat demand for heating the building

Month	The number of heating days in a month	Long-term average temperature of the air	The calculated internal temperature, °C	The number of degree days, day·K·month^{-1}	Distribution of heat demand for heating of the building
January	31	–2.8	20	706.8	0.185
February	28	–1.5	20	602.0	0.158
March	31	2.1	20	554.9	0.145
April	30	7.5	20	375.0	0.098
May	5	12.5	20	37.5	0.010
June	0	16.2	20	0.0	0.000
July	0	17.4	20	0.0	0.000
August	0	16.8	20	0.0	0.000
September	5	13.1	20	34.5	0.009
October	31	8.4	20	359.6	0.094
November	30	3.0	20	510.0	0.134
December	31	–0.5	20	635.5	0.167

Table 3

Monthly profile for heating the building and tap water

Month	Heating load			Hot tap water		
	MWh	GJ	%	MWh	GJ	%
January	31.66	113.98	18.50	1.18	4.248	10.20
February	27.04	97.34	15.80	1.07	3.852	9.25
March	24.81	89.32	14.50	1.18	4.248	10.20
April	16.77	60.37	9.80	1.15	4.14	9.94
May	1.71	6.16	1.00	1.18	4.248	10.20
June	0.00	0.00	0.00	1.15	4.14	9.94
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00
September	1.54	5.54	0.90	1.15	4.14	9.94
October	16.08	57.89	9.40	1.18	4.248	10.20
November	22.93	82.55	13.40	1.15	4.14	9.94
December	28.58	102.89	16.70	1.18	4.248	10.20
Total	**171.12**	**616.03**	**100.00**	**11.57**	**41.65**	**100.00**

Using data from the Table 3 and assuming specified in the project coefficient of performance for heat pumps (COP) equal to 4.6 a monthly profile of heat taken from the rock mass was estimated (Tab. 4).

Table 4

Monthly profile of heat taken from the rock mass

Month	Heating load and hot tapwater	Heating from the rock mass
	MWh	MWh
January	32.840	25.700
February	28.105	22.000
March	25.996	20.340
April	17.915	14.020
May	2.896	2.270
June	1.147	0.900
July	0.000	0.000
August	0.000	0.000
September	2.687	2.100
October	17.269	13.510
November	24.075	18.840
December	29.760	23.290
Total	**182.690**	**142.970**

Specified in Table 4, the profile of heat taken from the rock mass refers to basic load. It is a heating power, which is evenly loaded throughout the month and produces an amount of energy determined in Table 3. So it is a monthly average heating power defined as:

$$P_i = \frac{Q_i}{t_i} \tag{1}$$

where:

P_i – monthly average heating power, kW,

Q_i – heating load in selected month, kWh,

t_i – duration of one month, h.

Table 5 shows the heating power and time of peak load attributable to 24 hours. The nominal heating power of the pump assumed in the project documentation was taken as the maximum heating power.

Table 5

Maximum heating load (peak heating load) of the rock mass

Month	Maximum heating load of the rock mass	
	Heating power, kW	The duration of load, h/24 h
January	144.0	7.4
February	144.0	7.0
March	124.4	6.7
April	60.0	10.0
May	0.0	0.0
June	0.0	0.0
July	0.0	0.0
August	0.0	0.0
September	0.0	0.0
October	60.0	9.3
November	124.4	6.5
December	144.0	6.7

3.3. Characteristics of the heat pump

Tables 6 and 7 present the parameters specified by the manufacturer of the heat pump which will support the building (Viessmann BW302.B150).

Table 6

Points of heat pump's operation in 45°C at the feed of the heating circuit

Temperature at the circuit of the evaporator	°C	0	5	10	15
Heating power	kW	145.0	168.0	189.0	203.0
Cooling power	kW	108.6	131.2	152.0	165.6
Electrical power consumption	kW	38.4	38.8	39.0	39.4
Coefficient of performance (COP)	–	3.78	4.33	4.85	5.15

Table 7

Points of heat pump's operation in 55°C at the feed of the heating circuit

Temperature at the circuit of the evaporator	°C	0	5	10	15
Heating power	kW	139.0	156.0	178.0	194.0
Cooling power	kW	101.3	117.7	139.3	155.1
Electrical power consumption	kW	50.0	50.6	51.0	51.2
Coefficient of performance (COP)	–	2.78	3.08	3.49	3.79

3.4. Geological profile

Table 8 summarizes the lithological profile with the thermal parameters of each layer on the basis of literature data. Due to presence of aquifers in the profile of the test borehole and significantly watered area, especially in spring, the presented value thermal parameters relate to watered rocks. Despite the conditions, the effective thermal conductivity obtained from Thermal Response Test is almost 160% higher than the literature data. It may indicate a waterlogging of layers higher that assumed for calculations and significant velocity of water filtration, which may greatly shape energy processes given the convectional heat exchange.

Table 8

Lithological profile in Myszków

No.	Lithology	Top, m	Bottom, m	Thickness, m	Thermal conductivity coefficient, $W \cdot m^{-1} \cdot K^{-1}$	Volumetric specific heat, $MJ \cdot m^{-3} \cdot K^{-1}$
1	Sand, clay, gravels	0	12	12	2.3	2.3
2	Red caly	12	15	3	2.0	2.4
3	Clay	15	20	5	2.2	2.4
4	Sand	20	22	2	3.1	2.5
5	Clay	22	25	3	2.2	2.4
6	Dolomite	25	27	2	3.4	2.5
7	Red clay, clay stone	27	94	67	2.9	2.5
Weightedaverage					2.75	2.46

3.5. Construction of the borehole heat exchanger

A single u-pipe with a depth of 94 m was adopted. The diameter of the drilling tool was 121 mm. The distance between the axes of the heat exchanger tubes was 40–80 mm. The calculation assumed an average distance between the axes of pipes at 60 mm. The material used to fill was watered gravel (grain size 2.8 mm, $\lambda = 1.8\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$). The outer diameter of the tubes was 40 mm at a wall thickness of 3 mm. Exchanger tubes were made from polyethylene PE 100 with a thermal conductivity equal to $\lambda = 0.42\ \mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$.

3.6. Prospective quantity of borehole heat exchangers

The heating system is planned to consist of 32 boreholes (single U-pipe DN 40) with a depth of 94 m each (Fig. 3). The distance between the boreholes will be 8–9 m. The total length of the borehole heat exchangers will be 32 × 94 = 3008 m. The schematic configuration of borehole heat exchangers is shown in Figure 4.

Fig. 3. Scheme of a single U-pipe

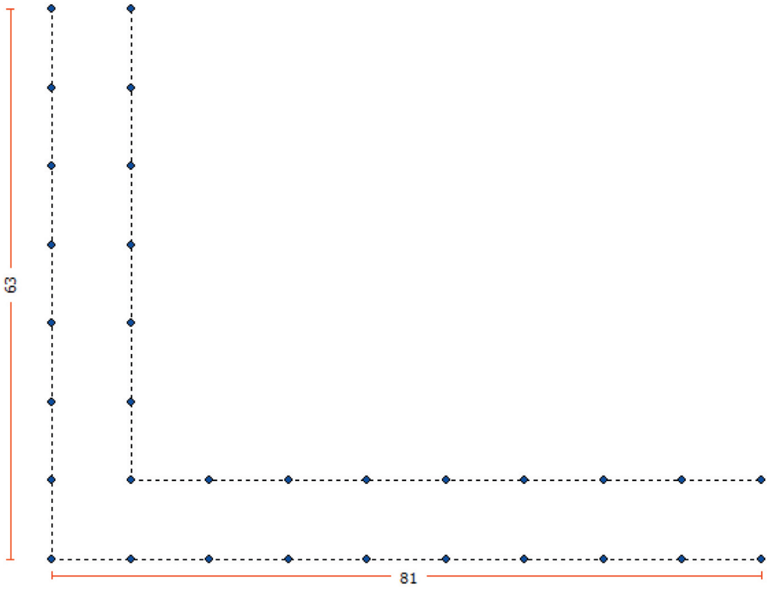

Fig. 4. Configuration of borehole heat exchangers

4. SYSTEM EXPLOITATION FORECAST

The exploitation of a system of borehole heat exchangers was forecast with the Earth Energy Designer (EED 3.21) computer software.

On the basis of simulation, changes in temperature of the fluid in borehole heat exchangers over 25 years of operation were calculated. Additionally, temperature of the fluid in borehole heat exchangers was estimated for individual months in the 25th year of operation. The results of these calculations are presented in Figures 5 and 6.

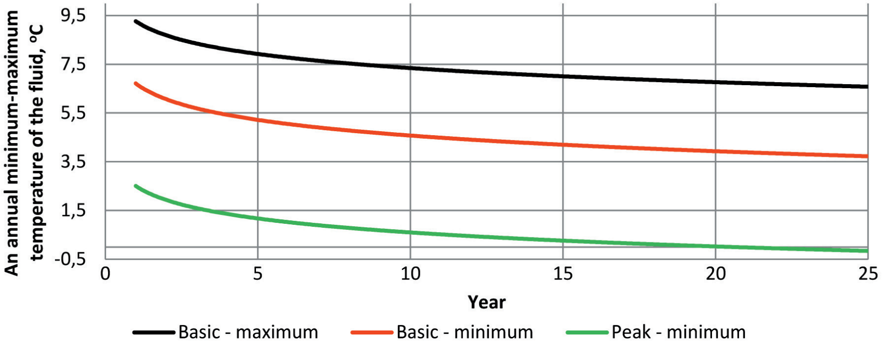

Fig. 5. Changes in temperature of the fluid in a system of borehole heat exchangers over 25 years of operation

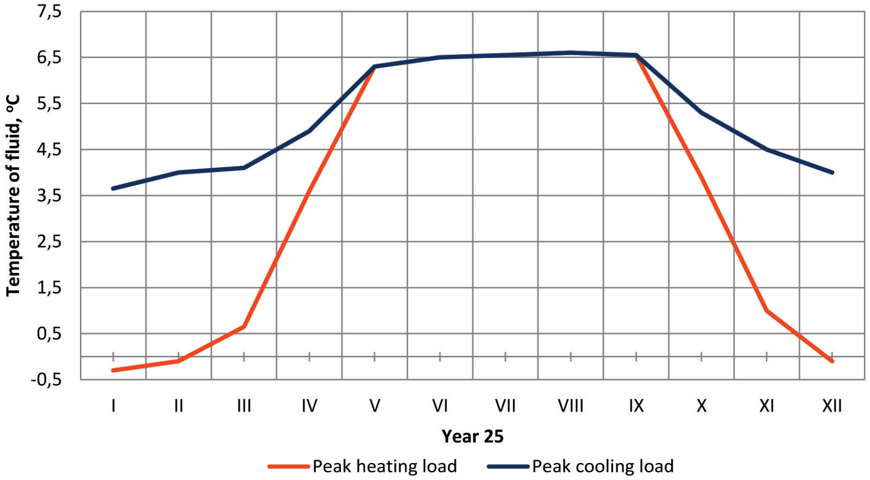

Fig. 6. Changes in temperature of the fluid in a system of borehole heat exchangers for individual months in the 25th year of operation

To determine the characteristics of the borehole thermal energy storage and the optimal variant of the project, a series of simulations to demonstrate the relationship between the number of borehole heat exchangers and their configuration and obtainable average temperature of the fluid in lower heat source was conducted. Table 9 and Figure 7 show the relation between the quantity of borehole heat exchangers and the average temperature of the fluid in the 25^{th} year of exploitation.

Table 9

Relation between the quantity of borehole heat exchangers and the average temperature of the fluid

Quantity of borehole heat exchangers	Average temperature of the fluid in 25 year, °C			
	basic heating load		peak heating load	
	min.	max.	min.	max.
24	1.98	5.84	–3.26	5.84
26	2.49	6.06	–2.34	6.06
28	2.91	6.22	–1.58	6.22
30	3.3	6.39	–0.89	6.39
32	3.64	6.54	–0.28	6.54
34	3.95	6.67	0.25	6.67
36	4.22	6.79	0.73	6.79
38	4.57	7.01	1.27	7.01
40	4.79	7.11	1.65	7.11

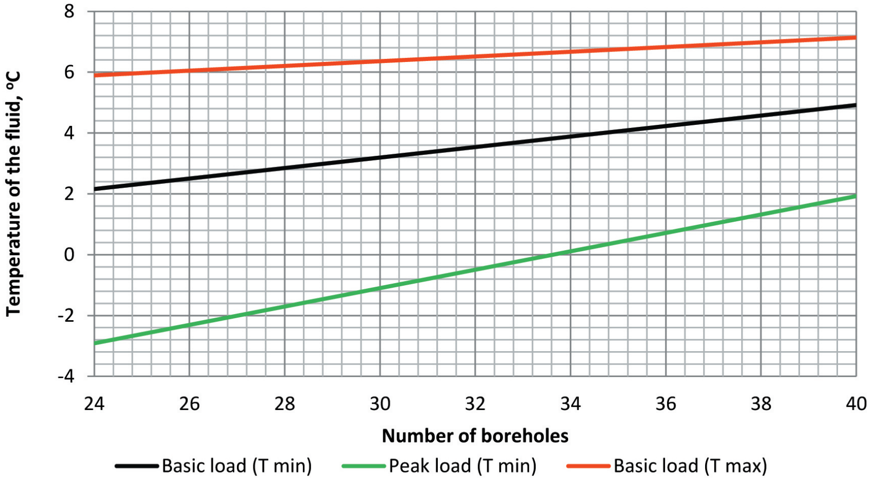

Fig. 7. Relation between the quantity of borehole heat exchangers and the average temperature of the fluid

Table 10 and Figure 8 show a relation between the distance between borehole heat exchangers and the average temperature of the fluid.

Table 10

Relation between distance between borehole heat exchangers and the average temperature of the fluid

Distance between borehole heat exchangers, m	Average temperature of the fluid in 25 year, °C			
	basic heating load		peak heating load	
	min.	max.	min.	max.
7	2.85	5.83	–1.06	5.83
8	3.27	6.21	–0.64	6.21
9	3.65	6.54	–0.27	6.54
10	3.91	6.79	–0.01	6.79
11	4.09	6.99	0.18	6.99
12	4.27	7.17	0.35	7.17
13	4.43	7.34	0.51	7.37
14	4.57	7.49	0.66	7.49
15	4.68	7.60	0.77	7.60
16	4.77	7.71	0.86	7.71
17	4.86	7.80	0.95	7.80
18	4.95	7.89	1.03	7.89
19	5.02	7.97	1.11	7.97
20	5.08	8.03	1.17	8.03

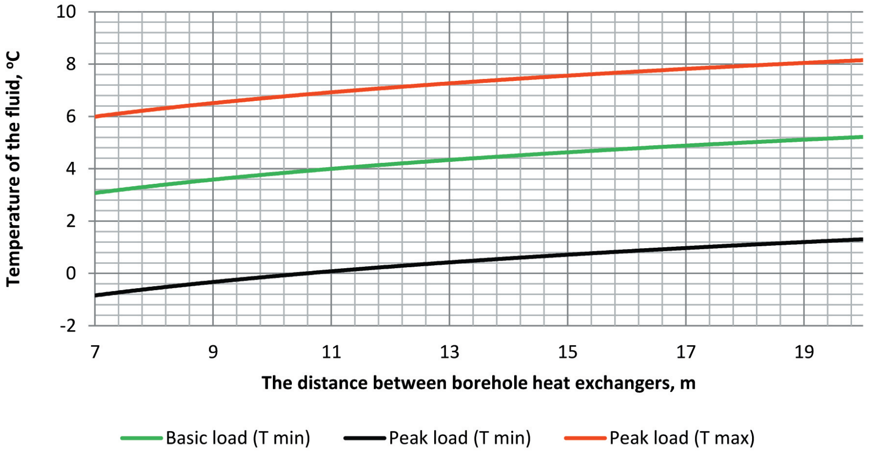

Fig. 8. Relation between distance between borehole heat exchangers and the average temperature of the fluid

By expansion of a what-if analysis a simulation was performed by using a variable quantity and distance between borehole heat exchangers. The results of these simulations are shown in Tables 11–14 and in Figures 9 and 10.

Table 11

Relation between quantity of borehole heat exchangers and the distance between borehole heat exchangers and the average temperature of the fluid

Quantity of borehole heat exchangers	Distance between borehole heat exchangers, m	Average temperature of the fluid in 25 year, °C			
		basic heating load		peak heating load	
		min.	max.	min.	max.
24	8	1.59	5.51	–3.65	5.51
	10	2.28	6.13	–2.95	6.13
	12	2.71	6.59	–2.52	6.59
	16	3.33	7.25	–1.91	7.25
	18	3.55	7.49	–1.68	7.49
	20	3.72	7.66	–1.52	7.66
26	8	2.08	5.7	–2.75	5.7
	10	2.78	6.34	–2.05	6.34
	12	3.19	6.77	–1.64	6.77
	16	3.77	7.39	–1.06	7.39
	18	3.97	7.6	–0.86	7.6
	20	4.13	7.77	–0.7	7.77

Table 11 cont.

Quantity of borehole heat exchangers	Distance between borehole heat exchangers, m	Average temperature of the fluid in 25 year, °C			
		basic heating load		peak heating load	
		min.	max.	min.	max.
32	8	3.27	6.21	–0.64	6.21
	10	3.91	6.79	–0.01	6.79
	12	4.27	7.17	0.35	7.17
	16	4.77	7.71	0.86	7.71
	18	4.95	7.89	1.03	7.89
	20	5.08	8.03	1.17	8.03

Table 12

Relation between quantity of borehole heat exchangers and the average temperature of the fluid in the 25th year (distance of borehole heat exchangers $L = 10$ m)

Quantity of borehole heat exchangers	Average temperature of the fluid in 25 year, °C (Distance of borehole heat exchangers at 10 m)			
	basic heating load		peak heating load	
	min.	max.	min.	max.
18	0.18	5.33	–6.79	5.33
20	1.01	5.64	–5.27	5.64
22	1.70	5.90	–4.01	5.90
24	2.28	6.13	–2.95	6.13
26	2.78	6.34	–2.05	6.34
28	3.20	6.50	–1.29	6.50
30	3.57	6.65	–0.62	6.65
32	3.90	6.79	–0.03	6.79
34	4.20	6.91	0.50	6.91
36	4.46	7.03	0.97	7.03

Table 13

Relation between quantity of borehole heat exchangers and the average temperature of the fluid in the 25th year (distance of borehole heat exchangers $L = 12$ m)

Quantity of borehole heat exchangers	Average temperature of the fluid in 25 year, °C (Distance of borehole heat exchangers at 12 m)			
	basic heating load		peak heating load	
	min.	max.	min.	max.
18	0.70	5.88	–6.28	5.88
20	1.49	6.16	–4.79	6.16
22	2.15	6.39	–3.56	6.39
24	2.71	6.59	–2.52	6.59
26	3.19	6.77	–1.64	6.77
28	3.59	6.91	–0.90	6.91
30	3.95	7.03	–0.24	7.03
32	4.26	7.17	0.34	7.17
34	4.54	7.28	0.85	7.28
36	4.79	7.38	1.30	7.38

Table 14

Relation between quantity of borehole heat exchangers and the average temperature of the fluid in the 25th year (distance of borehole heat exchangers $L = 16$ m)

Quantity of borehole heat exchangers	Average temperature of the fluid in 25 year, °C (Distance of borehole heat exchangers at 16 m)			
	basic heating load		peak heating load	
	min.	max.	min.	max.
18	1.44	6.67	–5.54	6.67
20	2.19	6.90	–4.09	6.90
22	2.81	7.09	–2.90	7.09
24	3.33	7.25	–1.91	7.25
26	3.77	7.39	–1.06	7.39
28	4.15	7.51	–0.34	7.51
30	4.48	7.61	0.29	7.61
32	4.77	7.71	0.84	7.71
34	5.02	7.79	1.33	7.79
36	5.27	7.87	1.76	7.87

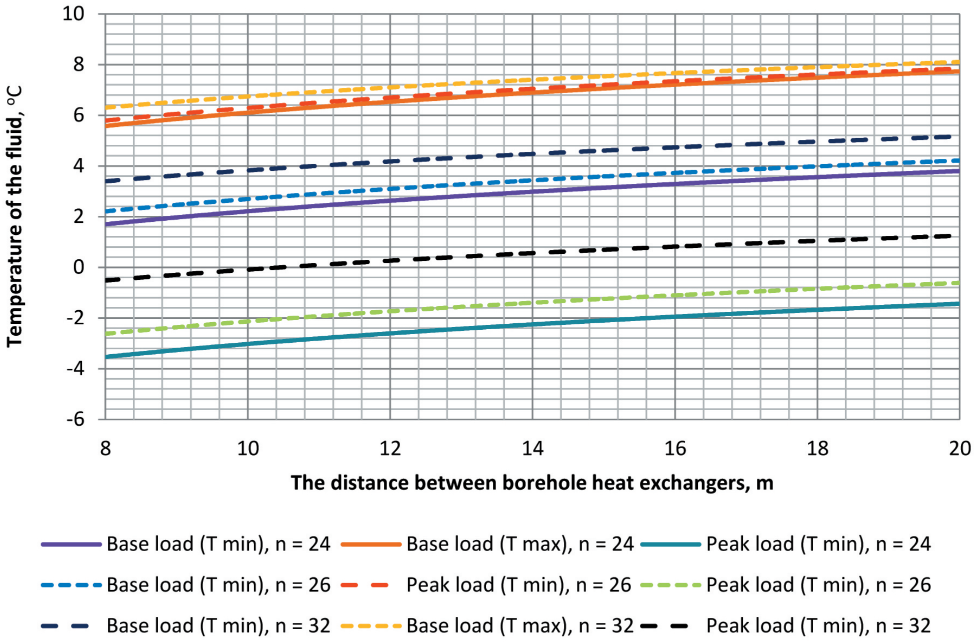

Fig. 9. Relation between quantity of borehole heat exchangers and the distance between borehole heat exchangers and the average temperature of the fluid (*n* – quantity of borehole heat exchangers)

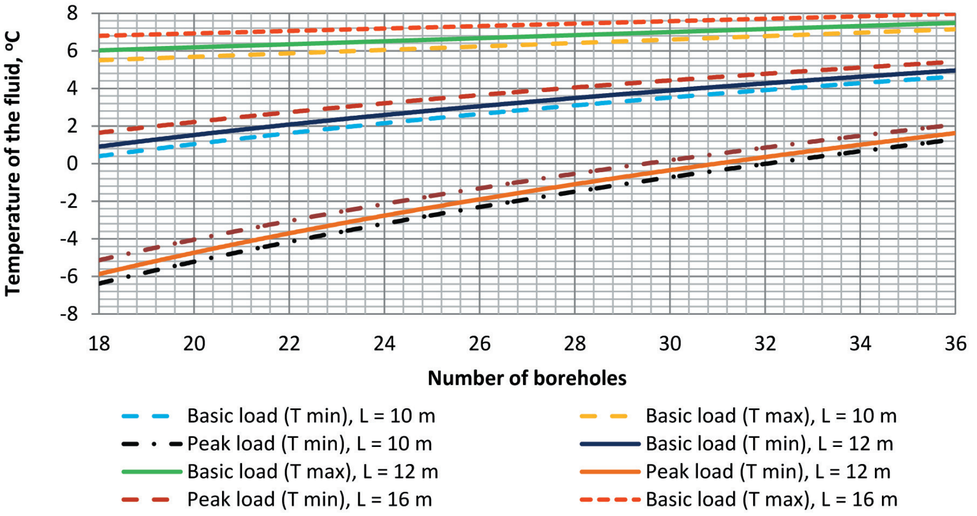

Fig. 10. Relation between quantity of borehole heat exchangers and the distance between borehole heat exchangers and the average temperature of the fluid (*L* – distance between borehole heat exchangers)

5. CONCLUSIONS

1. Effective thermal conductivity of the borehole heat exchanger achieved on the basis of Thermal Response Test is much higher than expected (resulting with profile lithological and thermal parameters of rocks described in the literature). A possible cause of this state is waterlogging of layers and a significant water filtration velocity, which ensures the work of the underground heat reservoir, being a natural source of regeneration for energy resources in the rock mass.
2. The number of BHEs assumed in the project (32 pcs, 94 m deep) is sufficient to meet project assumptions referring to minimum temperatures of the heat carrier (polypropylene glycol solution) at heat production of up to 658 GJ annually. Nonetheless, in the perspective of a long-term heat production from the rock mass, it will be difficult to achieve the heat pump efficiency coefficient assumed in the project at the level of 4.6. In the basic variant, the forecast COP value for the heat pump after 25 years of exploitation (at heat carrier's temperature of 50/40°C in the secondary circuit) amounts to 3.7 for basic load and 3.3 for peak load.
3. Increasing the efficiency of the system is possible with the use of additional regeneration heat resources in the rock mass (by adding into the formation of heat obtained in the process of air conditioning or other waste heat).
4. Numerical modelling enables the design of an exploitation forecast, which accounts for the groundwater flow and its influence on heat exchange. However, it calls for a hydrogeological opinion in reference to the velocity of filtration of groundwater.
5. Considering the hydrodynamic conditions, detailed numerical modelling demonstrate the necessity of a smaller minimum number of borehole heat exchangers.

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Additional materials

[5] Audyt energetyczny budynku dla przedsięwzięcia termomodernizacyjnego przewidzianego do realizacji w trybie ustawy z dnia 21 listopada 2008 r. o wspieraniu termomodernizacji i remontów, opracowany dla budynku Szkoły Podstawowej nr 6 w Myszkowie (Przedsiębiorstwo Usług Technicznych. Projektowych i Edukacyjnych Korterm Zbigniew Korek).

[6] Projekt robót geologicznych na wykonanie otworów wiertniczych w celu wykorzystania ciepła ziemi (plan sytuacyjno-wysokościowy) (oprac. Łukasz Gąsior).

[7] Projekt wykonawczy pt. „Przebudowa instalacji centralnego ogrzewania w ramach termomodernizacji budynku Szkoły Podstawowej nr 6 przy ul. Wapiennej 2 w Myszkowie” – instalacja c.o. (IDO S.C. D. Żabczyński, R. Kwiatek).

[8] Test reakcji termicznej przeprowadzony w dniach 20–26 IV 2016 na otworowym wymienniku ciepła wykonanym na działce o nr 2597/8 przy ul. Wapiennej w Myszkowie w woj. śląskim.