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Human-induced load on the environment when using geothermal heat pump wells

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Abstract. The research is aimed to study the process of change in temperature mode dynamics for the Earth subsurface layer when heat is extracted with geothermal heat pump systems, reveal and disclose specifics of effect on the ecology caused by technologies using geothermal resources and give practical recommendations regarding further development

of methods for designing heat pumps using low potential heat energy of soil based on the long-term forecast and efficacy assessment. Mathematical statistics and mathematical model methods were applied for assessment of economic and environmental effects. Methods based on principles of the theory of thermal conductivity, hydromechanics, theory of differential equations and mathematical analysis were applied for calculation of proposed systems and review of field observation findings. The authors had developed for research purposes an experimental geothermal heat pump system consisting of four structurally connected geothermal wells, each with installed U-shaped twin collectors of 200 m overall length, and a heat pump of 14 kW capacity with a heat energy battery for 300 L connected to the building heat-supply system. They also created a computer data archivation and visualisation system and devised a research procedure. The paper provides assessment of the effect caused by changes in the process operation mode of the heat pump system on the soil temperature near the geothermal well. As a result, the authors have found that the higher the intensity of heat energy extraction, the lower the soil temperature near the geothermal heat exchanger, in proportion to the load on the system. Moreover, it has been determined by experimental means that at critical loads on the geothermal heat exchanger the soil temperature is unable to keep up with regeneration and may reach negative values. The research also determined relation between in-service time and season of the system operation and temperature fluctuations of geothermal field. For example, it has been found by experimental means that the heat flow from the well is spread radially, from the well axis to its borders. Additionally, it has been proved that depending on the heat load value, the bed temperature is changed after the time of the first launch. For example, the geothermal field temperature has changed from the time of the first launch during 1-year operation by 0.5 °C in average. The research has proved that depending on the heat load value, under seasonal operation (heating only or cooling only) of the system, the soil temperature has decreased for five years by 2.5 °C and switched to quasi-steady state, meanwhile, stabilisation of the geothermal field in the state under 1-year operation (heating and cooling) occurred vet in the 2nd year of operation. In conclusion, the paper reasonably states that geothermal heat pump systems using vertical heat exchangers installed into the wells put no significant human-induced load on the environment. At the same time, still relevant are issues of scientific approach to development of the required configuration of the geothermal collector, methodology for its optimal placement and determination of efficacy depending on operation conditions.

Key words: human-induced load, geothermal well, heat pump.

Техногенне навантаження на довкілля при використанні теплонасосних геотермальних свердловин

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Анотація. Відомо, що геотермальні джерела енергії поділяються на петротермальні та гідротермальні. Геотермальні свердловини до 400 м використовуються в теплонасосних системах для забору теплової енергії з приповерхневих шарів Землі. У роботі виконано теоретичний аналіз впливу технологій використання геотермальних ресурсів на навколишнє середовище. Розроблено та сконструйовано експериментальну геотермальну теплонасосну систему. Проведені експериментальні дослідження із використанням геотермальних свердловин, та наведені практичні результати впливу відбору теплової енергії з приповерхневих шарів Землі на тепловий режим геотермального поля. Описані теплофізичні особливості притоку геотермальної енергії, яку генерують гірські породи до внутрішнього простору свердловин за відсутності процесу циркуляції в ній теплоносія на довгостроковому інтервалі часу. Виявлено та оцінено вплив зміни технологічного режиму роботи теплонасосної системи на температуру ґрунту навколо геотермальної свердловини та встановлено залежність тривалості та

сезонності експлуатації системи на температурні коливання геотермального поля. З'ясована залежність інтенсивності відбору теплової енергії геотермальними теплонасосними системами на регенераційні властивості геотермального поля. Доведено, що актуальним є питання наукового підходу до розробки необхідної конфігурації геотермального колектора, методології оптимального його розміщення й визначення ефективності в залежності від умов експлуатації. Обгрунтовано висновок, щодо екологічної безпечності використання геотермальних теплонасосних систем. З'ясовано, що актуальними залишаються дослідження температурного режиму навколо свердловинного простору при вилученні теплоти геотермальним теплонасосними системами з урахуванням літологічних особливостей робочого розрізу при збільшенні глибини свердловини. Отримані в ході дослідження дані мають важливе наукове і прикладне значення для подальшої розробки методики проектування теплонасосних геотермальних свердловин на основі довгострокового прогнозу й оцінки їх екологічної та економічної ефективності.

Ключові слова: техногенне навантаження, геотермальна свердловина, тепловий насос.

Introduction. One of the nowadays problems that are highly relevant for the world's society is need to determine the balance between satisfaction of current human demands and protection of interests of future generations. In Ukraine, as well as in many other countries of the world the impact of the power generation industry on the environment is associated with considerable emissions of pollutants from the companies of fuel and energy complex. One of the ways to ensure environmental security for the state may be the transfer to environmentally friendly technologies which is impossible without broad use of renewable energy sources. In climatic and geographical conditions of Ukraine, one of the promising areas of use of renewable energy, both for ecology and economy is application of heat pump geothermal systems (GTS) that use low-potential energy of subsurface layers of the Earth as a renewable energy source (Goshovskyi, Zurian, 2013).

To obtain primary energy, GTSs are equipped with heat exchangers installed in geothermal wells that all together set up an integrated system for extraction of low-potential renewable energy from soil.

Operational experience with geothermal wells shows that continuous extraction or discharge of heat energy causes considerable change in the soil heat balance. Change in the temperature background that is formed under long operation (GTSs) may result in significant change of the soil mass temperature (geothermal field) which is not immediately compensated by the background heat flows and has negative consequences for human-induced load on the environment (Saprykina, Yakovley, 2016).

Review of recent researches and publications. The practical issue of using heat pump systems in Ukraine and worldwide where low-potential energy of subsurface layers of the Earth is used as a primary energy source is studied in a lot of research works. (Boyle, 2014; Tidwell, Weir, 2016; Morozov, 2017; Limarenko, Taranenko, 2015). The works of Shubenko, Kuharec, 2014; Morrison and others, 2004; Hepbasli, Kalinci, 2009 have proved scientifically that a heat pump itself as a component part of the heat pump system is an environmentally clear appliance with the principal function of transferring low-temperature energy from a renewable source to the building heatsupply system with the consumption-grounded values of temperature and capacity. The studies by Gao and others, 2008; Li et al., 2009; Nikitin et al., 2015 assumed that human-induced load on the environment and environmental hazard may be induced by thermalphysic processes that occur in the geothermal heat exchanger - soil system. The work by Chao et al., 2016 shows mathematical analysis of the soil heat balance. Based on digital-analytical simulation of the system, the study by Kordas, Nikoforovich, 2014 has revealed the interconnection of energy exchange processes between soil and heat-carrying agent of the geothermal heat exchanger under stable conditions. Besides, analytical calculations based on the mathematical model aimed to devise methods for forecasting the temperature field under operation of the geothermal well in various processing conditions were made in the studies by Saprykina, Yakovley, 2017; Nakorchevsky, Basok, 2005; Filatov, Volodin, 2012. Krylov et al., 2015 have designed a laboratory bench and researched temperature changes near the well area using the experimental model. Review of the references showed lack of attention given to the experimental investigation of the environmental effect made by the geothermal well on the geothermal field under field operation of the GTS in terms of particular lithologic and geographical conditions. Research of the thermal field change dynamics is largely focused on mathematical calculations and experimental investigations with laboratory models which may not always give unbiased scientific information and requires for experimental confirmation in field conditions. In consideration of the above, it is required to find out the dynamics of changes in the temperature mode of the Earth subsurface layer under extraction of heat with geothermal heat pump systems under field operation of the heat pump unit, namely: describe specifics of energy in-flow from rocks to the inner space of the well without circulation of heatcarrying agent therein over the long time interval; find out the impact of change in process operation mode of the heat pump system on the soil temperature near the geothermal well and describe deviations of temperature fluctuations of the geothermal field in connection to duration and seasonality of the system operation; determine the impact made by intensive extraction of heat energy with geothermal heat pump systems on regeneration abilities of the geothermal field; give practical recommendations regarding further development of methods for designing heat pumps using low potential heat energy of soil based on the long-term forecast and assessment of environmental impact and efficacy.

Research data and methods. Mathematical statistics and mathematical model methods were applied for assessment of economic and environmental effects. Measurements were made by means of temperature sensors, pressure sensors and amount of heat-carrying agent flow with direct readings and DC sensors with electrical data transfer.

Digital data were processed with MAXYCON FLEXY controller and the software using FDB open configurator by RAUTAUTOMATIK. Methods based on principles of the theory of thermal conductivity, hydromechanics, theory of differential equations and mathematical analysis were applied for calculation of proposed systems and review of field observation findings.

Findings and review. Geothermal resources are considered to included, first of all, thermal fluid and warmth of heated dry rocks.

Geological regions of Ukraine differ in geothermal conditions. For example, the Ukrainian Shield, the Southern slope of Voronezh mountain group (the Northern side of Dnipro-Donetsk cavity), Volyn-Podillia basin have very low geothermal gradients. The Black Sea cavity, Plain Crimea, Transcarpathian inner bay have higher gradients and are promising in the view of using the Earth warmth.

The Ukrainian Shield in whole is featured with the lowest geothermal gradients compared to other territory of Ukraine. From the geothermal point, it is studied almost exclusively in the areas of ironore deposits of Kryvyi Rig and Bilozerka. Average value of the geothermal depth for Kryvyi Rig which represents the area of the lowest geothermal gradients is 116.3 m per grad. Generally, geothermal depth indicators within the Ukrainian Schield vary from 90 to 185 m per grad rising, mainly, in the areas of large tectonic breaks (Fig. 1).

The Earth heat energy is a power resource. Geothermal resources of Ukraine at developed depths are described with thermalphysic properties of the Earth, namely, temperature and density of heat flow.

The geothermal energy source has diversified impact on the environment. Since geothermal resources are a renewable energy source, environmental sustainability must be their principal advantage. So that, firstly, geothermal power stations do not require for large land space; secondly, discharge waters are pumped out back to the well which allows to maintain environmental security of the region and stable production process; thirdly, geothermal power stations release much smaller amount of toxic substances into the atmosphere, for example, a geothermal station releases 0.45 kg of CO2 emissions per 1 mW hour of produced power, while a thermoelectric power station that runs on natural gas releases 464 kg, 720 kg on fuel oil, and 819 kg on coal (Limarenko, Taranenko, 2015).

At the same time, geothermal power industry has its own disadvantages that can be summarised as follows: Firstly, action of mineralised geothermal waters and vapours; secondly, sinking of the earth surface located over the mined geothermal layer; thirdly, change of the underground water level, formation of sinkholes in soil, swamping; fourthly, gas emissions (methane, hydrogen, nitrogen, ammonia, hydrogen sulphide) and heat emissions into the atmosphere or surface waters; fifthly, contamination of underground waters and water-bearing layers, soil salting; sixthly, change of temperature fields of underground levels (Degtyarev, 2013).

Thus, in spite of allegedly simple and accessible use of geothermal energy, technical and environmental implementation of this method of power generation is a complex scientific technical issue.

Also, there has been particularly strong interest today in possible use of energy of subsurface layers of the Earth (at the depths up to 400 m) for heating systems both for residential buildings and industrial facilities using heat pumps (Limarenko, Taranenko, 2015).

Over 90% of the areas of Ukraine at the industrially accessible depths of 50 to 100 m below the Earth's surface level always maintain temperatures of 14 to 18 °C which can be classified as low-potential heat sources. This temperature range can not be utilised in the most production processes including the heating systems. In this connection, extraction of lowpotential energy with heat pumps that allow with relatively low cost to obtain the required heat-carrying agent temperatures seems to be the most promising (Saprykina, Yakovlev, 2017).

Heat pumps with vertical soil heat exchangers (VSHE) that are PE pipes placed in the wells at the



Fig. 1. Geothermal zoning of geostructures of Ukraine (made by the Ukrainian State Geological Research Institute, 2008)

depth of up to 400 m have been widely used. The space around them is filled in with special heat-conducting solution. The heat-carrying agent is heated in a VSHE and transfers its heat energy to an evaporator of a heat pump (HP), the vapour of which is condensed after compression in a compressor condenser. This process goes together with supply of extracted heat energy to consumers (Filatov, Volodin, 2012).

The principal advantage of a geothermal heat pump is its high performance which is achieved in result of a high energy conversion factor (ECF) for the heat pump (400% to 500%) which ensures that 4–5 kW of heat energy will be obtained for each 1 kW of consumed electrical power and thus allows for lower operational cost (Filatov, Volodin, 2012).

Introduction of heat pump technologies for heat production in Ukraine is one of the effective energy saving measures that allow to save fossil fuel and reduce pollution of the environment. Harmful emissions during heat pump operation are the ones generated where electrical power is produced. No harmful emission is produced right in the place of heat pump installation. Heat pumps with ECF equal to 3.0 compared with traditional boiler houses produce almost twice less emissions of nitrogen, sulphur, and carbon oxides than under operation on coal; more than 1.5 times less than under operation on fuel oil; and by 30% less than under operation on natural gas. (Goshovsky, S.V., Zuryan, A.V. 2017). Operational experience of existing GTSs shows that we have no enough information regarding: a) impact made by extraction of heat energy from subsurface layers of the Earth with the geothermal well on regeneration processes near the well area over the long time interval (5-7 years); b) relation between in-service time and season of the system operation and temperature fluctuations of geothermal field; c) connection of unstable operation of GTS with termination of heat exchange between the well and geothermal field; d) impact made by intensive extraction of heat energy with geothermal heat pump systems on regeneration abilities of the geothermal field.

The temperature field is a complicated object both for a natural (experimental) and mathematical study and is regulated by variable limit conditions that depend on climate of the region, operation mode of the object, season, change of thermalphysic properties of soil, etc.

For the purpose of investigation of the temperature field around the vertical well, the **Ukrainian State Geological Research Institute** developed and installed an experimental geothemal heat pump system to extract heat energy. Principal diagram of the geothermal experimental heat pump system is shown in Fig. 2. The land-located part of the experimental power system consists of a heat power battery and heat pump elements with automation system. The geothermal collector for collection of lowtemperature heat energy is made of plastic pipe of 32 mm in diameter and consists of four heat exchangers coupled in parallel. The pipe length in each heat exchanger is 200 m. Total length of the collector is 800 m. Aqueous propylene glycol solution 25% ($C_3H_sO_2$) was used as a heat-carrying agent.

For the purpose of study, the complex included measurement equipment and management information system.

Measuring devices that include temperature probes and heat-carrying agent flow-rate sensors are installed both in land-based and underground parts of the complex.

The temperature sensors (resistance thermal converters) TSP-204 were used for temperature measurements in the check points. Resistance thermal converters TSP-204 are included into the State Register of Measuring Devices of Ukraine under number U246-07. The working range of measured temperatures is -40 °C to +270 °C, thermal response indicator does not exceed 6-8 sec.

The temperature sensors in the land-based part of the power system are installed in supply and exhaust pipelines of all loops, on the heat battery and at input and output of heat-carrying agent flow-rate sensors. The sensor readings were taken automatically with a time interval of five seconds.

The water meter by SENSUS was used for measuring flow-rate of the heat-carrying agent. The rated flow is 10 m³per hour and withstands the working pressure of 16 bar.

Six heat-carrying agent flow-rate sensors are connected to the system: four at each line of heat-carrying agent supply to the probes (geothermal) and two at common lines for heat-carrying agent flow over lowtemperature and high-temperature loops of the landbased part of the system. The temperature sensors installed in the underground part of the geothermal power system allow for discrete measurements of soil temperature at depths of 0.02 to 50.0 m and heat-carrying agent temperature both in vertical and horizontal parts of the soil collector at the site between the geothermal well and entrance to the building (Goshovskyi, Zurian, 2015).

The MAXYCON FLEXY controller and special software using FDB open configurator by RAUT AUTOMATIK in the geothermal system allowed for data collection from the measuring devices to be further processed and recorded into the archive, interpreted and shown on the computer monitor by means of visualisation software in real time (Fig. 3). MAXYCON FLEXY controller allows to take readings from more than 36 data channels and operate the system remotely both offline and manually.

The research was carried out in three stages:

Description of thermalphysic specifics of geothermal energy in-flow generated by rocks to the inner space of the well without circulation of heat-carrying agent therein over the long time interval.

Investigation of the impact made by intensive extraction of heat energy with geothermal heat pump systems on regeneration abilities of the geothermal field.

Investigation of the impact of change in process operation mode of the heat pump system on the soil temperature near the geothermal well and determination of the extent of deviation of temperature fluctuations of the geothermal field in connection to duration of the system operation.

1. With the purpose of determination of regularities in seasonal temperature changes in the upper layers of the Earth and depth of annual temperature changes in soil, investigators applied the experimental research method which allowed for temperature measurements of intact soil during twelve months, from October 2018 to September 2019.



Fig. 2. Principal diagram of the geothermal experimental system



Fig. 3. Main measuring devices used for testing at the geothermal heat pump system: 1 – temperature sensors (resistance thermal converters) TSP-204; 2 – MAXYCON FLEXY controller; 3 – special software using FDB open configurator by RAUT AUTOMATIK

The temperature sensors installed in the well allowed to measure the soil temperature at standard depths during the experiment: 0.02; 0.30; 0.70; 1.2; 2.0; 5.0; 15.0; 35.0; 50.0 m. The sensor readings were taken automatically with a time interval of five seconds. Measurements of soil temperature were made at the geothermal landfill of the Ukrainian State Geological Research Institute. In order to maintain the experimental integrity, no heat extraction was effected from the geothermal field where the research was carried out both before and during the experiment.

Findings that allowed to make an analysis of relation between the soil temperature change and depth at various time intervals, from a day to a year, and to determine the relation of average monthly temperatures T and depth h for soil mass in the place where geothermal probes were installed (geothermal field), were obtained in the course of research.

It was found out by experiment that daily fluctuations of ambient air temperature caused by change of sunlight intensity had significant impact on the soil temperature at depth of up to 0.30 m. Starting from depth of 0.70 m and more, daily fluctuation of air temperature has no impact on change of the soil temperature. It is grounded scientifically that the soil temperature at depth of up to 2 m during the month tends to decrease continuously under general dynamics of decrease in the air temperature. Moreover, it is essential that change in the soil temperature at depth of up to 0.70 m depends on the air temperature, while the air temperature has no impact on the soil temperature at depth of over 5 m during the month. We can see the moment when the soil temperature at depth of 2 meters decreasing from 18 °C at the beginning of the month to 15 °C at the end of the month crosses the soil temperature isotherm at depth of 5 m (Fig. 4)



Fig. 4. Curve of soil temperature versus operation time of the geothermal system during October at depths of 50.00, 35.00, 15.00, 5, 0.5, 2 m

Month	Depth (h, M)										
	0.02	0.30	0.75	1.20	2.00	5.00	15.00	35.00	50.00		
October	8.0	13.0	15.0	16.5	17.0	16.8	13.2	12.8	12.0		
November	5.0	9.0	11.0	12.5	13.8	14.2	13.2	13.0	12.0		
December	4.5	8.0	9.0	10.5	11.8	13.0	13.2	13.0	12.0		
January	3.0	5.5	7.0	8.0	9.8	11.8	13.2	13.0	12.0		
February	2.0	3.5	5.5	6.5	8.0	10.0	13.0	12.8	12.0		
March	5.0	4.0	4.0	6.0	7.0	6.5	13.0	12.8	12.0		
April	14.0	11.5	9.5	8.0	7.0	7.4	13.0	12.8	12.0		
May	19.0	16.0	15.0	14.5	13.0	11.0	13.2	13.0	12.2		
June	21.0	18.0	17.0	16.0	13.8	11.0	13.2	13.0	12.2		
July	24.0	22.0	21.0	19.0	17.0	13.0	13.8	13.2	12.3		
August	23.0	23.0	22.0	20.0	18.0	16.0	13.9	13.3	12.4		
September	20.0	18.0	19.0	19.0	18.0	17.0	13.2	13.0	12.2		
T (°C)	12.37	12.63	12.92	13.04	12.85	12.31	13.26	12.98	12.11		
ΔT (°C)	22.0	19.5	18.0	14.0	11.0	10.5	0.9	0.5	0.4		

Table 1. Change in soil temperatures versus depth during the year without load on the geothermal filed*

*Note: T is the average soil temperature during the year; ΔT is the difference in extreme temperature values (the highest and the lowest temperatures) during the year

With experimental findings obtained during the year we can make conclusion as to existent tendency for the difference in extreme temperature values ΔT to decrease as the depth h increases (Table 1).

Besides the above stable tendency of 'compression' of temperature line bundle, the review of data given in Table 1 allowed to make conclusion as to independence of average annual temperature (T) from depth h for each measurement mass data. So, for the temperature change data in Table 1 we obtained, to the extent of acceptable to us increase in depth, the following values (T) (in °C): 12.37; 12.63; 12.92; 13.04; 12.85; 12.31; 13.26; 12.98; 12.11. Consequently, if we put h, to be the depth where no seasonal temperature fluctuations are found, then temperature $T(h_{i})$ can be determined as the arithmetic mean value for the average annual temperatures (T). In addition, considering that h_r value fulfils condition (T) (h_r) = 0, then we can see from the experimental findings given in Table 1 that h_r value fulfilling condition (T) (h_r) = 0 is within 15 m.

2. The impact made by intensive extraction of heat energy with geothermal heat pump systems on temperature fluctuations of the geothermal field has been investigated. The intensity of heat energy extraction from the geothermal field changed, according to the investigation procedure, with change in both number of wells with geothermal heat exchangers involved to extraction of the Earth's warmth and number of geothermal heat exchangers installed into the wells (Zurian, 2019). Technical capabilities of the experimental system allowed to carry out the experiment in the configurations of the geothermal heat exchanger as follows: 1) 4×2 : four wells, each with two U-shaped geothermal heat exchangers installed; 2) 4×1 : four wells, each with one U-shaped geothermal heat exchanger installed; 3) 2×1 : two wells, each with one U-shaped geothermal heat exchanger installed. Meanwhile, heat load on the system over the condenser loop was unchanged. Amount of flow-rate of the heat-carrying agent through the building heat supply system kept the same.

The investigation procedure and capabilities of the software developed by the Ukrainian State Geological Research Institute allowed to discrete time intervals required for research which enabled to obtain necessary findings and make conclusions regarding certain dependencies: 1- heat-carrying agent temperature at the output of the geothermal system condenser decreases with reduction in number of geothermal heat exchangers, however not significantly depends on their configuration; 2 temperature hysteresis for heat-carrying agent in the condenser loop decreases both in case of reduction in number of geothermal heat exchangers and when configuration of the heat exchanger is changed from U×2 to U×1; 4 – heating capacity of the geothermal system decreases when the number of geothermal heat exchangers is reduced and slightly lowers when configuration of the heat exchanger is changed from $U \times 2$ to $U \times 1$; 5 – heat-carrying agent temperature at the input and output of the geothermal system evaporator decreases with reduction in number of and depends on configuration of geothermal heat exchangers; 6 – heat-carrying agent temperature at the input and output of the geothermal system evaporator decreases when configuration of the heat exchanger is changed from U×2 to U×1; 5 – difference between the ambient medium and working body temperatures at the evaporator output is uniformly increasing both with reduction in number of geothermal heat exchangers and when configuration of the heat exchanger is changed from U×1 to U×2 (Table 2). the experiment. The temperature increasing dynamics for the heat-carrying agent in the heat supply system slowed down. The system was operated in such mode for short time period (Fig. 5).

At the time point of 6:33 pm, the output temperature of the low-temperature loop evaporator reached the extreme of 2 °C. This triggered the safety auto-

Deremeter	Operation mode of a geothermal heat exchanger									
Parameter	4x2	4x1	2x2	2x1	1x2	1x1				
t ₁ (°C)	45.00	43.85	43.5	43.00	42.98	37.90				
t ₂ (°C)	37.1	36.05	36.29	36.30	36.41	32.10				
$\Delta t_{k}(^{\circ}C)$	7.90	7.80	7.70	6.70	6.57	5.80				
V _k (м ³ ·h)	1.42	1.42	1.42	1.42	1.42	1.42				
W _k (kW)	12.46	12.30	12.10	10.57	10.36	9.15				
t ₃ (°C)	12.70	11.20	11.00	9.00	8.10	7.40				
t ₄ (°C)	9.90	8.40	8.10	5.90	5.00	3.00				
$\Delta t_{e}(^{\circ}C)$	2.80	2.80	2.90	3.10	3.10	4.40				
V _e (м ³ ·h)	3.00	2.85	2.87	2.36	2.40	1.62				
W _e (kW)	9.34	8.86	9.26	8.14	8.27	7.91				

Table 2. Summary of experimental and calculated data obtained during operation of the geothermal system under changed load*

*Note: t_1 is the temperature at the condenser output; t_2 is the temperature at the condenser input; Δt_k is the temperature hysteresis at the condenser; V_k is the heat-carrying agent flow rate over the condenser loop; W_k is the heating capacity of the geothermal system; t_3 is the temperature at the output of the geothermal collector (ambient); t_4 is the temperature of the working body at the evaporator output; Δt_e is the difference between the ambient medium and working body temperatures at the evaporator output; V_e is the heat-carrying agent flow rate over the evaporator loop; W_e is the cooling capacity of the geothermal system.

Accordingly, the experimental findings of temperature settings near the well area during heat energy extraction for operation of the collector heat pump prove that with increased intensity of heat energy extraction the soil temperature near the geothermal heat exchanger decreases in proportion to the increase in the system load.

In addition, in accordance with the tasks set, the GTS operation under extreme loads on the geothermal heat exchanger were studied.

As with previous experiments, the initial temperature of the heat-carrying agent in the heat supply system was 28 °C and that equal to 15 °C for propylene glycol in the soil heat exchanger loop under continuous circulation. At the beginning of the experiment, from 6:12 pm till 6:25 pm under 1×1 mode, the temperature changing dynamics both for high-temperature and low-temperature loops matched the processes that took place under the experiment conditions of 4×2 , 4×1 , 2×2 , 2×1 , 1×2 ; however, the experiment proved operation of the system under such mode conditions to be unstable. For example, propylene glycol temperature started to drop at the very beginning of mation signal. Further recurrent unstable operation of the geothermal system after 6:33 pm time point was associated with failure of 1×1 configuration soil heat exchanger in the geothermal system to restore the required evaporator input temperature under set options of 12 kW for heating capacity at the geothermal system output. Up to the moment the system switched to the emergency operation, the readings for temperature, flow rates of heat-carrying agents in low-temperature and high-temperature loops and calculated data for the system capacities under operation in 1x1 mode were: - temperature hysteresis at the input and output of the heating system at 6:30 pm time point was 5.8 °C; – difference between the ambient medium and working body temperatures at the evaporator output at 6:30 pm time point was 4.4 °C. In consideration of meter readings for heat-carrying agent flow rate of 1.419 m³ over the evaporator loop and 1.618 m³ over the condenser loop, we can conclude that the system is trying to maintain the required cooling and heating capacities but because of drop in evaporator input temperature which is the result of failure of the renewable energy source to maintain regeneration



Fig. 5. Curve of temperature versus system operation time when one geothermal heat exchanger installed into the well is connected to the geothermal system (1×1 mode): t_1 is the temperature at the condenser output; t_2 is the temperature at the condenser input; t_3 is the temperature at the output of the geothermal collector; t_4 is the temperature of the working body at the evaporator output

processes under routine operation, switches to the emergency operation. In other words, the soil heat exchanger of 1×1 configuration has capacity insufficient to ensure stable operation of the geothermal system even for short time.

Such operation of the geothermal system we believe to be the emergency mode. This is because further operation under such conditions without safety automation devices may result in ice formation on the heat exchanger and freezing of the well which makes regeneration of soil in the place of freezing impossible and the well may be exposed to thermal heating (freeze-over).

3. Relation between in-service time of the system operation and temperature fluctuations of the geothermal field was investigated by experiment. It was found out that with temperature setting of 40 $^{\circ}$ C

at the condenser input on the geothermal heat pump system which, with hysteresis of 8 °C, allows to supply heat-carrying agent to consumers at 48 °C, the soil temperature near the well area during short-term operation (to one point) may decrease from 3 °C to 12 °C (Fig. 6). At the same time, regeneration of the soil heat balance at the place of heat energy extraction may take 20 minutes to 1 hour.

Moreover, review of findings obtained in the short run (during one day) showed that at the depth of 50 m, temperature deviations in the place of heat energy extraction exceed 3 °C and tend to decrease in absolute values. Also, the ratio of charge duration till discharge of the soil battery was determined. The factors for fast discharge and slow charge of the thermal field were found out, as well determined that with given time interval of operation for the particular soil



Fig. 6. Curve for input and output temperatures on the condenser and evaporator of the heat pump geothermal system versus the load on the soil collector



Fig. 7. Curve of the geothermal field temperature change versus the year of operation plotted by experiment

battery the thermal field charge last five times longer than the discharge. At the same time it is relevant to carry out certain investigations to review how fast the temperate mode of the rock mass can be restored due to its thermalphysic properties and what changes in the temperature mode of the near the well area considering lithologic specifics of the working section may take place with the well depth increased.

We also determined that the soil temperature in the place of heat energy extraction regardless of the depth is to some extent influenced by intensity of sun insolation at the surface of the geothermal field. This influence has certain delay by time. This is connected with circulation of the heat-carrying agent in the geothermal heat exchanger over entire space of the geothermal well from top downward generating heat exchange between various soil layers adjacent to the well.

It has been proved by experiment that in the long run, namely during five years of the system operation, the soil temperature near the well area decreased by 2.5 °C (in average, by 0.5 °C each year). Measurements were taken during September at the beginning of heating season prior to the well operation at the depths of 15, 35, and 30 m with year-round thermal loading on the geothermal field. We have proved by experiment that the soil temperature in the sixth year of the system operation had stabilised and stopped at 10.5 °C. And at the beginning of the seventh year of operation it increased by 1.2 °C, i.e. Resulted in the effect of heat in-flow to the near the well area of the geothermal field (Fig. 7).

The findings obtained by experiment fully correlate with mathematical calculations made when

modelling the temperature field in conditions of multiple cyclic turn-ons and turn-offs of the heating system [2]. The numeric model is based on discrete presentation of the energy equation, extreme and initial conditions, with various densities of the heat flow and implemented by means of MathLab application software package. Main found factors present (Fig. 8) changes of the temperature field under conditions of cyclic heat supply to the well of 100 Wt per m²

With pre-set values for the thermal load, well and bed, the well cut-off temperature after seasonal operation in conditions of heat supply has increased by more than 20 °C. The bed temperature evened up under downtime of half a year, and temperature deviations at the moment of well cut-off from the background one were maintained within 2 °C. Cyclical alterations of heat supply modes and downtimes (i.e. when a heat pump is idle) cause heat accumulation effect that is compensated with background heat flows. Quazi-steady condition that constitutes cyclic mode without further temperature rise is assumed to occur in 2.5 years and in 3 years under downtime.

Conclusions.

Continuous heat energy extraction from or discharge into soil causes change in the heat balance of the geothermal field at locations of heat pump geothermal wells. The above changes depend on h=geological and hydrogeological specifics of the mined bed, background heat flows, climate conditions and operation parameters of the geothermal systems.

Long-term operation of heat pump geothermal wells has its specifics: – firstly, it has been found by experiment that under seasonal operation of the geothermal heat pump system during the first 5 years of



Fig. 8. Changes of the bed temperature obtained under modelling the temperature field [2]: a – temperature pattern of the geothermal field by depth; b – change in the bed temperature under unsteady heat supply starting from the first turn-on till quazi-steady operation

heat energy extraction, the soil mass temperature decreases in average by 0.5 °C each year of the system operation, and starting from the fifth year, operation of the geothermal heat pump system is stabilised and switched to the quazi-steady mode; – secondly, stabilisation of the geothermal field under year-round operation is achieved in the second year of operation; – thirdly, freezing of the geothermal well is possible, however, only under operation of the heat pump system in contingency and emergency.

It has been proved necessary to study the dynamics of changes in the temperature mode of the Earth subsurface layer under extraction of heat with geothermal heat pump systems under field operation of the heat pump unit in consideration of stratigraphical specifics of the working section with increased depth of the geothermal well.

Human-induced load of geothermal power industry on the environment and humans is insignificant, and use of geothermal heat pump systems for heat supply of residential and industrial facilities seems to be promising and environmentally friendly courses of renewable power industry.

The research findings have scientific and applied significance for future studies in the field of design and development of geothermal heat pump wells based on long-term forecast and assessment of their environmental and economic efficacy.

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