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On Possibility of Long-Term Use of Deep Heat of The Earth for Power-Supplying Autonomous Consumers.

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ABSTRACT

The paper considers matters of power-supplying autonomous consumers based on using deep geothermal energy. The problem of reducing the temperature of deep rocks at long-term extraction of geothermal energy is discussed. The methodology is presented for calculation of a single-well system for collection of deep geothermal energy with consideration of reduction of the temperature potential of deep geothermal energy. Assessment is presented of variation of thermal power of the deep heat-based energy source with time.

Keywords: deep heat, earth, power-supplying.

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INTRODUCTION

Today, rational use of fuel and energy resources constitutes one of the global problems, which, when solved successfully, will apparently have a defining significance not only for further development of the world community, but also for conservation of its natural habitat. Depletion of reserves of traditional fossil fuels and environmental consequences of its burning have determined a considerable growth of interest in renewable energy sources (RES) in virtually all of the world's developed countries over the last few decades [1-2].

The benefits of the RES-based heat and electric power supply technologies, compared to their conventional analogs, are not only defined by considerable saving of energy costs in life support systems of buildings and structures, but also their environment-friendly nature, as well as the new opportunities in terms of attaining a higher level of self-containment of life support systems [3]. However, most of non-conventional energy sources (solar energy, wind energy, energy of tidal waves and smaller rivers, energy of biomass) are characterized by such shortcomings as considerable territorial non-uniformity of distribution, dependence on climatic and seasonal fluctuations. Besides, using the aforesaid RES requires procurement and installation of expensive equipment for generation of thermal or electric energy. This is the geothermal energy – the deep Earth's thermal energy – which has the highest technological and economic potential among non-conventional sources of energy. Geothermal power generation is considered environment-friendly, based on using a renewable and a virtually unlimited resource. Geothermal power generation does not require large areas to be allocated, unlike large solar power plants or wind farms; neither does it pollute the atmosphere, as distinct from traditional coal power generation. Geothermal power generating technologies are getting predominant in the energy balance of some countries, while the share of geothermal power in the world energy balance is growing steadily. Four types of geothermal energy sources may be identified [4]: deposits of dry geothermal steam, sources of wet steam (a mix of hot water and steam), deposits of geothermal water and hot dry rocks.

Deposits of geothermal dry and wet steam, as well as sources of geothermal water are referred to steam-hydrothermal resources. Geothermal resources of this type are well-known and have been widely used since the ancient time.

The key property of such sources lies in thermal manifestations in the form of self-emitting sources of steam or liquid located in natural reservoirs at a small depth (to 2000 m). The main advantage is that these resources are accessible and easy to explore. However, they also have considerable shortcomings: the local nature of sources, the need in cleaning the polluted steam-hydrothermal fluid before use, in some cases – the environment pollution (formation of salt lakes; different chemical compounds, including carbon dioxide CO_2 [5-7] coming up to the surface along with hot water or steam). About 70% of the world's energy potential of steam-hydrothermal sources is accounted for by deposits with a fluid temperature at least 130^0C [8]. A considerable part of such geothermal resources is explored and is being developed to some extent. Among all the suitable-to-use geothermal resources, the steam-hydrothermal resources account for slightly over 1% [9].
A field more promising from the energy generation standpoint is using thermal energy contained in the deep Earth hard rocks (petrothermal energy). Compared to steam-hydrothermal resources, such energy can be found anywhere on the planet, regardless from its geographic location. In the territory of Russia, the potential of petrothermal energy is one hundred times as high as that of hydrothermal energy (3,500 and 35 trillion tons of reference fuel, respectively).

The most common use of the Earth's thermal energy is application of thermal pumps based on low-potential heat of surface layers up to 200 m deep [10, 11]. However, these systems are only acceptable for supplying heat to individual consumers with a low thermal load. Besides, the thermal conditions of the Earth's surface layers is known to vary with time and be largely dependent on seasonal and climatic factors [12]. It is more promising to use thermal energy contained in deeper hard rocks. Heating of the Earth's deep rocks is mostly related to the following factors [13]:

- spontaneous decay of radioactive elements (those with a half-life shorter than the period of formation of the Earth decayed at the initial heating of the planetary matter, whereas the decay of long-living elements is still under way);
- gravitational differentiation of the Earth's matter and its stratification, with formation of a dense core and a less dense mantle;

- tectonic processes causing vertical and horizontal displacements of large blocks of the Earth's crust and its elastic deformations;
- physical and chemical processes going on deep inside the Earth.

The thermal energy contained in dry hot rocks makes 99% of the total amount of available geothermal resources.

Description of the deep near-wellbore rocks temperature decrease estimation method

The key characteristic describing the thermal condition of the interior is the geothermic gradient, i.e., variation of temperature of rocks with depth. In the practice of geological and hydrogeological studies, the geothermic gradient is generally determined for the interval of 100 m, and on average this parameter lies within the range of (2 ÷ 6)°C per 100 m of depth [14]. Availability of geothermic gradient is determined by existence of a deep thermal flux directed towards the Earth's surface. The highest geothermic gradients are observed in the areas of volcanic activity.

The totality of instant values of temperature of rocks in all the points of the space under consideration for each moment of time is referred to as geotemperature field. Stationary and non-stationary geotemperature fields can be distinguished [15]. Referred to as stationary is a temperature field, if the value of temperature in each of its points remains unchanged with time and is the function of the coordinates only. Non-stationary is a field, the temperature of which would vary in space and time. The temperature field of the Earth is traditionally assumed to be quasi-stationary [15]. Besides, the types of the temperature field of the interior may be classified as follows:

- perfect temperature field, which would emerge in homogeneous and isotropic rocks having no heat sources or sinks;
- normal temperature field, which reflects regional patterns of geological structure of the Earth's interior and physical-geographical peculiarities on its surface, which is confirmed by variation of geothermic parameters in different geological-geographic zones;
- disrupted temperature field, which is formed as a result of effects of local exogenic or endogenic factors (e.g., in the areas of volcanic activity, a considerable non-uniformity of the temperature field of the interior is generally observed).

Due to uniform geological structure of the interior, the world's most widespread is normal temperature field.

For extraction of geothermal heat, it is sufficient to have one or more boreholes used as a basis for creating a circulation geothermal system, which may be implemented by two main methods: "open" and "closed". The open method is a multi-well system made up of injection and extraction wells interconnected with a volume formed as a result of hydraulic fracturing of formation. The main advantage of this system is a developed surface of heat exchange of the heat transfer fluid (water) with interior rock and, hence, a potential for considerable thermal power of the "open" collection system. However, this method has a significant shortcoming: as a result of a contact with the Earth's rocks, the heat transfer fluid is contaminated and mineralized, which results in premature wear of thermal engineering equipment and pipelines, which, in its turn, reduces considerably the service life of the energy source, in general. Besides, this method requires availability of at least two wells.

The "closed" method is a single-well system for collection of deep geothermal energy made up of an outer casing string of pipes and an inner extraction pipe placed coaxially therein. In fact, the single-well system for collection and transportation of deep geothermal heat to the surface is rather extended; the system is therefore a cylinder-shaped structure made of casing pipes of various diameters – from the larger diameter at the well mouth to the smaller one at the bottom.

One can distinguish the following advantages of the single-well collection system, which make it the most promising option for extraction of deep geothermal energy: the necessity to have one well only, low hydraulic friction of the collection system, no contact of heat transfer fluid with the interior rocks and, hence, no contamination or mineralization of heat transfer fluid.

For creating petrothermal circulation system, both newly drilled and existing wells may be used. At many of oil and gas fields, it is suggested to have out-of-use wells engaged in extraction of thermal energy: in Italy [16], China [17], Britain [18], Iran [19], Qatar [20] and the USA [21]. For example, as of today, in Russia's territory, there are more than 24 thousand oil and gas wells classified as unallocated subsoil reserve fund [22]. Such wells suitable for restoration may be used for extraction of deep geothermal energy [23] both for power-supplying geographically adjacent consumers, and for coverage of own needs of oil and gas fields.

As the heat of the Earth's interior is being extracted out of loose or hard rocks, the natural temperature field of the interior is disrupted, which is manifested in reduction of the temperature potential of the mass of rocks in the near-wellbore area in time, which leads to a decrease in thermal power of the source. This process is typical for both multi-well and single-well collection systems.

Due to a small surface of heat exchange in the case of the single-well collection system (which is actually limited to the inner surface of the casing string), with the course of time, the temperature of the Earth's rocks near the borehole wall would fall, which, in its turn, causes a decrease of thermal power of the single-well collection system. At the initial moment of operation of the single-well collection system, the temperature at the interface with the casing pipe is equal to the natural established value T_0, which corresponds to the temperature of rocks T_2 at a distance from the well. Then, as the single-well collection system keeps operating continuously, the temperature of rocks at the wellbore would decrease, and temperature perturbation would spread over the near-wellbore mass of the interior.

According to preliminary data obtained experimentally, this process is not infinite, and after a certain time, the system would enter a stable operation mode, with a new established temperature at the wellbore T_1 ($T_1<T_2$) [24, 25, 26, 27].

The effect of decrease of temperature potential of the rocks of the near-wellbore area at extraction of the Earth's thermal energy is experimentally confirmed for shallow (to 200 m) wells of a small diameter. As of today, perennial observations of the temperature of deep rocks have only been carried out for one single-well heat exchanger placed in the well at the depth of 105 m [24]. For the aforesaid collection system, entering the steady operation mode of the thermal exchanger took about 5 years. Over the time, the temperature of the ground mass around the well heat exchanger decreased, on average, by 1-2°C. Over the next 10 years, the temperature of the interior varied by 0.5°C only.

The results of the above study [24] of a shallow heat exchanger enable to assess cooling at smaller depths, only (to 100 m), no data from larger depths being available today. At the same time, without preliminary assessment of the temperature potential in the near-wellbore mass of the interior, it appears impossible to determine correctly the amount of thermal energy that could be extracted from the well, which, in its turn, would make impossible establishing the key operational characteristics of the collection system (heat transfer fluid flow rate, temperature of heat transfer fluid at the output of the collection system, etc.). Therefore, an estimation of the range of temperature impact is necessary for design and creation of systems for extraction of thermal energy based on existing out-of-use wells, as the process of cooldown determines reduction of the system's thermal power, when used for a long time. It is possible to estimate the range of temperature impact of a single-well collection system according to two methods described in [14] and [28].

According to [14], spreading of the front of temperature perturbation in the course of time is expressed by equation (1).

$$\frac{a\tau}{r_c^2} = \frac{\left(\frac{r}{r_c}-1\right)^2\left(\frac{r}{r_c}-2\right)}{36} \tag{1}$$

where: a is temperature conductivity of deep rocks, m^2/sec; τ is the time of operation of the single-well collection system, sec; r_c is the radius of the wellbore, where the single-well collection system is placed, m; r is the range of temperature impact. The estimate of the range of temperature impact according to equation (1) is only based on geometry of the collection system and the temperature conductivity of the interior, and does not consider variation of the temperature of heat transfer fluid at long-term operation of the single-well collection system.

A more precise estimate of the range of spreading of temperature perturbation in the near-wellbore mass of deep rocks may be obtained based on the method described in [28]. The variation of temperature field in the near-wellbore mass of deep rocks in time τ at distance r from the wellbore is estimated according to (2).

$$T(r,\tau)=\frac{1}{\ln(m)}\left(T_1 ln\frac{R}{r}+T_2 ln\frac{r}{R_0}\right)+ \\ +\pi\sum_{n=1}^{\infty}\left\{\frac{J_0(\mu_n m)V_0\left(\frac{\mu_n r}{R}\right)}{J_0(\mu_n)+J_0(\mu_n m)}\times e^{(-\mu_n^2 Fo)}\times\left[T_0-\frac{T_2 J_0(\mu_n)-T_1 J_0(\mu_n m)}{J_0(\mu_n)-J_0(\mu_n m)}\right]\right. \tag{2}$$

where: R_0 is the wellbore radius, m; R is the distance from the wellbore, at which the temperature of deep rocks is equal to initial natural value, m; r is the distance between R_0 and R, at which the temperature of deep rocks is estimated; T_0 is initial value of the temperature of deep rocks, K; T_1 is the temperature of deep rocks at the wellbore, K; T_2 is initial natural value of temperature at the relevant depth, K; m is the ratio of R to R_0; μ are roots of characteristic equation determined according to [28]; J_0 is Bessel function of the first kind; $Fo=\frac{a\tau}{R_0^2}$ is Fourier number, where *a* is temperature conductivity of deep rocks, m^2/sec, τ is the time of functioning of the single-well collection system, sec.

Implementation of the method to single-well system for collection of deep geothermal energy

Knowing the variation of the range of temperature impact, we can assess the thermal power that may be provided by the single-well system for collection of deep geothermal energy. Two heat fluxes come to the heat transfer fluid in the annulus:

a) from hot rocks at an arbitrary depth:

$$q_1(z)=k_{\text{п}}\pi(T_{\text{г}}(z)-T_1(z)) \tag{3}$$

where: $k_{\text{п}}$ is the coefficient of heat transfer from the rocks into the annulus of the single-well collection system, W/m^2·K;

$T_{\text{г}}$ is the temperature of the rock at a distance from the well at depth Z, K;

T_1 is the temperature of heat transfer fluid in the annulus at depth Z, K;

b) from the heated heat transfer fluid flowing along the coaxial inner pipe:

$$q_2(z)=k_{\text{к}}\pi(T_2(z)-T_1(z)) \tag{4}$$

where: $k_{\text{к}}$ is the coefficient of heat transfer from the inner extraction pipe into the annulus of the single-well collection system, W/m^2·K;

T_1 is the temperature of heat transfer fluid in the annulus at depth Z, K;

T_2 is the temperature of heat transfer fluid in the coaxial extraction string of pipes at depth Z, K.

The designed diagram of the single-well collection system is presented in fig. 1.

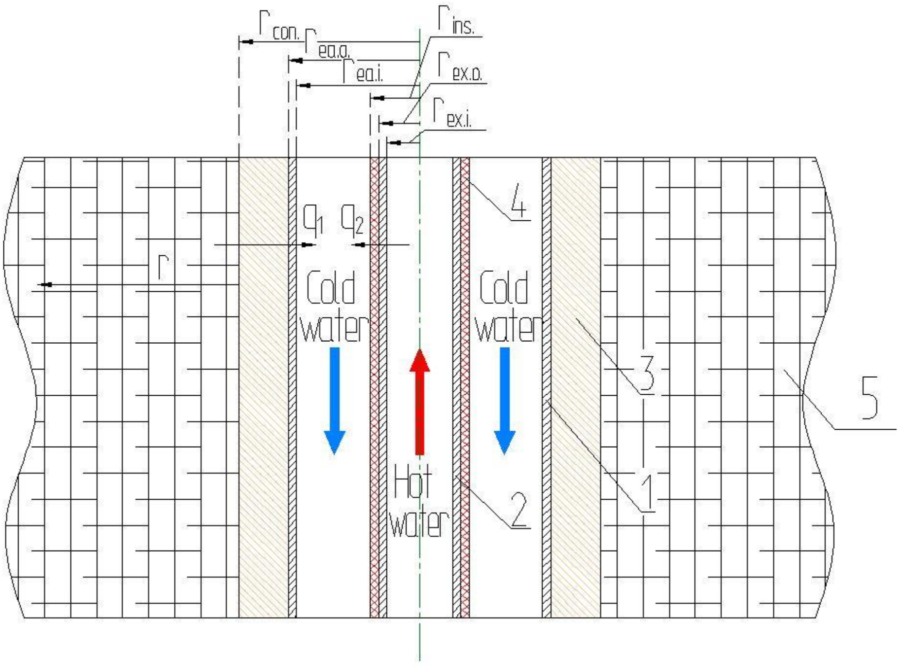

Fig. 1 – Diagram of designed model of single-well system for collection of deep geothermal energy: 1-outer (casing) string of pipes, 2-inner extraction string of pipes, 3-plugging concrete, 4-thermal insulation of inner extraction pipe, 5-deep rocks, q_1 and q_2 – thermal fluxes to heat transfer fluid in the annulus, $r_{ex.i.}$ and $r_{ex.o.}$ – inner and outer radii of extraction string of pipes, $r_{ins.}$ – outer diameter of thermal insulation, $r_{ea.i.}$ and $r_{ea.o.}$ – inner and outer radii of casing string of pipes, $r_{con.}$- radius of plugging concrete

For the diagram presented in fig. 1, the values of thermal fluxes per unit of length of the single-well collection system into the annulus at a specified depth will be determined from equations (5) and (6).

$$q_1(z) = \frac{\pi(T_r(z) - T_1(z))}{\frac{1}{2\lambda_r}\ln\left(\frac{r}{r_{con.}}\right) + \frac{1}{2\lambda_{con.}}\ln\left(\frac{r_{con.}}{r_{ea.o.}}\right) + \frac{1}{2\lambda_{ea}}\ln\left(\frac{r_{ea.o.}}{r_{ea.i.}}\right) + \frac{1}{\alpha_o 2r_{ea.i.}}} \tag{5}$$

where: λ_r is the thermal conductivity factor of near-wellbore rocks, W/m·K; r is the range of temperature impact of single-well collection system, m; $r_{con.}$ is the radius of outer surface of plugging rock, m; λ_{con} is thermal conductivity factor of plugging rock, W/m·K; $r_{ea.o.}$ is the radius of outer surface of the string of casing pipes, m; λ_{ea} is the factor of thermal conductivity of the casing string of pipes, W/m·K; $r_{ea.i.}$ is the radius of inner surface of the string of casing pipes, m; α_o is the heat transfer factor of the inner surface of casing string, W/m^{2}K.

$$q_2(z) = \frac{\pi(T_2(z) - T_1(z))}{\frac{1}{\alpha_1 2r_{ins.}} + \frac{1}{2\lambda_{ins}}\ln\left(\frac{r_{ins.}}{r_{ex.o.}}\right) + \frac{1}{2\lambda_{ex}}\ln\left(\frac{r_{ex.o}}{r_{ex.i.}}\right) + \frac{1}{\alpha_2 2r_{ex.i.}}} \tag{6}$$

where: α_1 is the heat transfer factor of the surface of thermal insulation of inner extraction string, W/m^2·K; $r_{ins.}$ is the radius of outer surface of thermal insulation of inner string of pipes, m; λ_{ins} is the factor of thermal conductivity of thermal insulation of inner string of pipes, W/m·K; $r_{ex.o.}$ is the radius of outer surface of inner string of pipes, m; where: λ_{ex} is the thermal conductivity factor of inner string of pipes, W/m·K; $r_{ex.i.}$ is the radius of inner surface of inner string of pipes, m; α_2 is the heat transfer factor of the inner surface of inner extraction string, W/m^2·K.

As source data for an example of estimation of thermal power according to the above methodology, the following geometrical and thermal-physical characteristics were assumed: well depth 3000 m, average diameter of casing string of pipes 0.136 m; thickness of wall of casing string of pipes 10.2 mm; the radius of outer surface of plugging annulus 0.150 m; conventional radius of inner string of tubing pipes 0.057 m; wall thickness of tubing pipes 10 mm; heat transfer fluid flow rate 475 m^3/day; the value of geothermic gradient is assumed to be the average for Russia's territory (3^{o}C/100 m); effective heat transfer factor of deep rocks 2.0 W/ m·K, and the average thermal capacity of rocks 800 J/kg*K, the average service life of a single-well collection system being at least 25 years.

Equations (2-6) are used for production of designed parametric studies on functioning of a single-well collection system for the above source data.

CONCLUSIONS

Based on equation (2), a variation of the range of temperature impact is determined based on the temperature difference on the wellbore wall and at a distance from the well, where the temperature of deep rocks corresponds to the natural value. The dependence of temperature impact of a single-well collection system on the difference of temperatures between the wellbore wall and the natural value of interior temperature is presented in fig. 2.

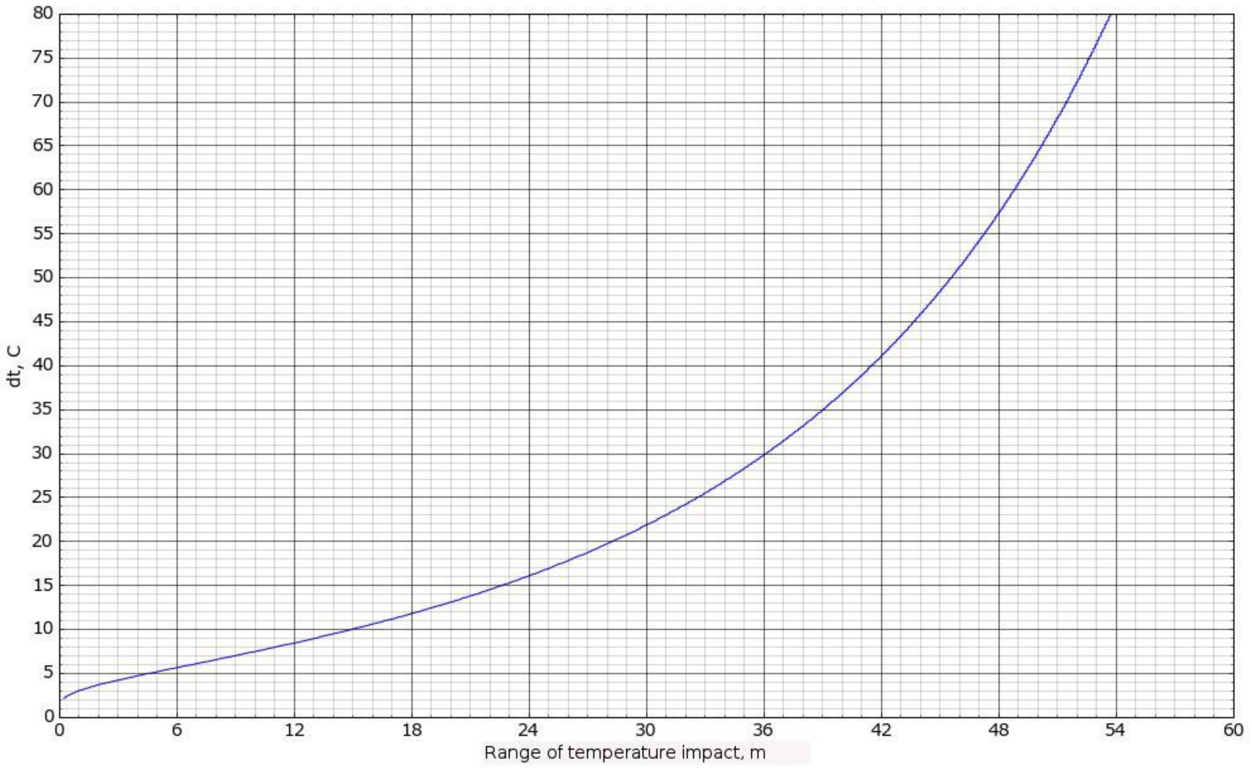

Fig. 2 – Variation of range of temperature impact based on the difference of temperatures on the wellbore wall and the natural interior temperature

By applying equations (3) – (6) to the designed model presented in fig. 1, it has been found that the potential thermal power of a single-well collection system at the beginning of the system's operation is about 350 kW. Due to the process of reduction of temperature potential of deep near-wellbore rocks, in the course of time, the thermal power would decrease to settle at the level of 253 kW, with the heat transfer fluid flow rate remaining unchanged. Therefore, design of thermal engineering equipment for a single-well collection system must be performed for the final settled thermal power, which will enable to raise the efficiency of equipment and to cut initial costs.

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