The way of using geothermal resources for generating electric energy in wells at a late stage of operation

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Abstract. The mathematical model of volcanic treatment by means of conductive heat transfer from the well surrounding rocks has been suggested. We have shown that one of the ways of producing geothermal energy is to heat liquid in the double-tube monobore well. Water is pumped to the annulus between pump-compressor pipe (PCP) and casing pipe. Flowing down to the bottom hole, the liquid is heated up from a casing wall through convective and conductive thermal conductivity which adjoins surrounding rocks. The caloric goes to surrounding rocks from the earth crust interior. The heat flow is at an average equal to 50 MW/sq.m, it can differ depending on the region. The heated to the bottomhole water is lifted back to a surface through the PCP. To minimize heat wastes when lifting, PSP should be made of heat-insulating material. We suggest a multifaceted approach, combining the disposal of low-temperature geothermal energy which contained in the extracted product by means of thermopiles with utilization of the hydrokinetic energy, flood water through the system of formation-pressure maintenance by means of the hydroelectric turbine.

1. Introduction

In a number of the countries heat or electric power, produced by geothermal power stations (geotherms), compensate for an essential share of energy expenses. More often geotherms are widespread in regions with a large number of available hot springs due to natural specifics. Besides, geotherms are used where there is a deficiency of fossil fuels or delivery of energy resources is complicated by the area inaccessibility. Many countries around the world intensively develop geothermal energy. Particularly, in April, 2015 the World geothermal congress was held in Melbourne [1]. The number of the reports, accepted at the congress, went up two-and-a-half times from 1995 to 2015. The main reports considered the issues of geophysics, geochemistry and geology in research and management of geothermal resources. But there were no any reports on creating mathematical model of advancing geothermal system, although many projects were carried out in several continents for the last decade.

Electricity from geothermal sources is generated generally in those countries where there is a volcanic activity (26 countries). Besides, it is expected to set up geothermal power plants in many
other countries: Algeria, Argentina, Armenia, Greece, Hungary, India etc. As of 2014 [3] total power output of all geothermal power plants were 12731 MW (or 0.31% of world electric power production), and the produced electricity – 73694 GW*/p.h.

In this study we consider the way of using geothermal energy not only with a high, but with a low geothermal gradient as well.

2. Materials and methods

In the 90th years the total power of geothermal power stations of the world was estimated at 5 GW, by 2000 it rose beyond 6 GW. According to a number of assessments, we can draw a conclusion that now the development of geothermal energy exceeds 10 GW [1].

Figure 1 presents the leading countries on generation of electric power from geothermal sources.

For example, in Italy the share of the electric power developed from the geothermal sources is 0.8% in power and 1.9% in electricity, in Mexico 1.7% and 2.3% respectively, and in the USA only 0.3% and 0.5% respectively.

![Figure 1. Generated electricity from geothermal energy in the world throughout country’s as of 2015.](image)

Figure 2 illustrates the growth of generating electric energy in the world since 1950 to 2015 [3].
Figure 2. Total power (left) and generated electric power (right) from geothermal energy since 1950 to 2015.

Besides, around the world geothermal energy is used in various fields, such as: house heating, hydrotherapy (balneotherapy), greenhouses and pools heating etc [4, 5]. Figure 3 demonstrates percentage ratio of various alternatives of geothermal sources direct use. According to figure 3, more than 55% of cases use heat pumps.

Special focus should be directed on using geothermal energy for the purpose specified in China, in particular, for geothermal heat pumps, house heating, balneotherapy, as a leading country in the world on direct usage of geothermal energy [6].

Figure 3. Various alternatives of using geothermal sources directly.

Several studies [7-9] described long-term operations (hundreds of years) of geothermal sources, if the heat extraction rate is low than a defined value of $E_0$, that is heat flow from the earth crust interior. If the heat extraction speed is bigger than $E_0$, then it is impossible to level energy constantly. $E_0$ value is unknown in advance, but it can be estimated on the basis of exploration and production data. It has to be noted about the importance of selecting of injection rate [10-11]. If the heat extraction rate is more, than $E_0$, it can lead to cooling a shelf.

In China geothermal resources are used since 70th and 80th. In particular, in the districts of Urban and Syaotangshitan which are presented by limestones and dolomites, geothermal water production rate was 110 and 120 kg/s, that led to the drawdown by 1.5 m a year in [11].
In Iceland (Reykjavík) the development of geothermal sources started in 1990 with commissioning geothermal power plant with the total capacity of 100 MW. In 1998 the geothermal power plant with a power of 30 MW was opened in Nesjavellir. Nowadays its total capacity is 90 MW, it is planned to increase by 120 MW [10,11]. Geothermal water production rate is 440 kg/s. Reservoir pressure since the beginning of operation has been decreased by 70 kPa. The developed mathematical model predicts the pressure drop across 300 kPa by the year 2035. The work [12] considered the models predicting pressure build-up in the future, and studied how reversible processes in the layer can be within a long-term selection of geothermal energy.

Russia is the first country in the world where in 1967 the first-ever binary electric power plant using hot water heat (90 °C) to generate electric energy [12] was built.

Studies of the thermal mode of deep mineral resources of the earth (over 5 km) in the area of Russia have not conducted; the data are available only in monitoring wells [12]. The work [11] presents the first results on establishing the efficiency of single-well system of removing and transmitting deep thermal energy from subsoil to the surface without casing pipe depending on the speed of the heat transfer medium is up to 8.5% higher, than the single-well system of removing energy with casing pipe from the whole length of the well. In the article [12] the mathematical model of the nearsurface geothermal heat system (NGHS) with the conductive nature of heat exchange with surrounding rocks is considered. Nowadays, the share of petrothermal energy in fuel and energy balance is very small; it is explained by the extremely low costs for studying this field [12]. Consequently, the problem of developing the methods of using geothermal energy for power production becomes relevant.

3. Problem statement

Thus, based on the literature review, we can set the aim of our research. According to the analysis of the suggested mathematical models and carried out analytical research we can draw a conclusion about forecasting usage of the given method in a certain region. We have shown that the set up problem can be solved by the multifaceted approach, combining the disposal of low-temperature geothermal energy, contained in the extracted product, by thermopiles with utilization of the hydrokinetic energy, flooded into the water formation through the system of formation-pressure maintenance (FPM) by means of the hydroelectric turbine.

4. Theoretical part

In the research [12] the nearsurface geothermal heat system was considered. It is intended to accumulate heat from near surface layers no more than 200 m in depth. The scheme of the system is presented in the figure 4

The authors considered the case of low permeability rocks, where the main component of energy transfer is a conductive heat transfer. For problem statement the round channel in an unlimited continuous medium with constant temperature $T_n=\text{const}$ serves as the physical model. Heat exchange with the environment at a constant current of liquid in the round channel is governed by Newton's laws.

Solving simultaneous equations:

$$\frac{\partial t(z,\tau)}{\partial \tau} + u \frac{\partial t(z,\tau)}{\partial z} = \frac{S}{c_1 \rho_1} \alpha (t(z,\tau) - T(R, z, \tau))$$

$$\frac{\partial T(z, r, \tau)}{\partial \tau} = \frac{\lambda}{c_2 \rho_2} \left( \frac{\partial^2 T(z, r, \tau)}{\partial r^2} + \frac{1}{r} \frac{\partial T(z, r, \tau)}{\partial r} \right)$$

where $t(z,\tau) –$ heating medium temperature, $T(z, r, \tau) –$ rock temperature, $u –$ heating medium velocity, $\alpha –$ heat-transfer area per rock unit volume, $c_1$, $\rho_1$, $c_2$, $\rho_2 –$ thermal capacity and density of heating medium and rock respectively, $R_1 –$ channel radius, $\alpha –$ heat-transfer coefficient.
The relevant initial data for heating medium and rock are as follows:

\[ t(z, \tau = 0) = T_n \]  
\[ T(z, r, \tau = 0) = T_n \]  

That is, the authors supposed [19], that rock and heating medium at initial time are of the same temperature \( T_n \).

Boundary conditions are as follows:

\[ t(z = 0, \tau) = t_0 \]  

where \( t_0 \) – heating medium initial temperature the channel entrance.

At the boundary of the channel the functions \( t(z, r, \tau) \) and \( T(z, r, \tau) \) meet Newton’s boundary condition:

\[-\lambda_2 \frac{\partial T}{\partial r} \bigg|_{r=R} = \alpha \left( t - T \bigg|_{r=R} \right)\]  

The offered mathematical model [12] well describes the process of liquid heating when moving along the channel at the near surface layer, when the channel is not so deep, as the rock temperature vertically can be considered as constant. In case when the pipe is at great depth (over 1000m), we should take into account geothermal gradient, as in some areas the value of geothermal gradient can reach the value 6 – 7 °C per 100 m (or above) [12]. Thus, the equation (4) – the initial condition of temperature distribution of rocks will be as follows:

\[ T(z, r, \tau = 0) = T_n + Gz \]  

where \( T_0 \) – neutral layer temperature, \( G \) – geothermal gradient.

For the equation (2) is required one more boundary condition:

\[ T(z, r = R, \tau) = T_0 + Gz \]  

where \( R \) – radius of heat disturbance zone, that is when \( r > R \) the temperature of rocks will remain in the initial state.

The set of equations (1)-(2) with initial conditions (3) and (7), boundary conditions (5), (6), (8) was decided by the method of finite differences by explicit scheme [15-18].

The accepted thermophysical properties:

Rock thermal conductivity, \( \lambda_2 = 2.0 \ \text{Br/m*K} \); rock density, \( \rho_2 = 2500 \ \text{kg/m}^3 \); rock heat capacity, \( c_2 = 800 \ \text{J/kg*K} \); depth, \( H = 1500; \ 2000; \ 2500 \ \text{m} \); temperature gradient, \( G = 0.03 \ ^\circ \text{C}/\text{m} ; \ 0.04 \ ^\circ \text{C}/\text{m} ; \ 0.05^\circ \text{C}/\text{m} \); subsoil thermal influence radius, \( R = 10 \ \text{m} \); heating medium density, \( \rho = 1000 \ \text{kg/m}^3 \); heating medium heat capacity, \( c = 4190 \ \text{J/kg*K} \); initial temperature, \( T_0 = 15 \ ^\circ \text{C} \); heating medium capacity rate, \( Q = 3.6; \ 7.2; \ 10.8; \ 14.4 \ \text{m}^3/\text{p.h.} \).

Heat-exchange coefficient \( \alpha \) was defined by the method of similarity according to the mode of flow [19]. The outer radius of pump-compressor pipe and inner radius of casing pipe are the following: \( R_1 = 0.086 \ \text{m} \) and \( R_2 = 0.146 \ \text{m} \).
5. Practical relevance
As the method of solving the problem of improving well operation profitability under the conditions of low payback, we suggest an integrated solution of the problem not only via the usage (disposal) of the underground resources petrothermal (thermal) energy, but hydrokinetic energy of the reservoir waters, injected by the flood pattern.

It is known [14], that to lift formation fluid to the surface during well operation at the late stage of extraction, when formation pressure is lower than hydrostatic one, the downhole pumping equipment (DPE) is widely used (sucker-rod pumping unit SRPU and electrical submersible centrifugal pump ESCP) as it consumes significant volume of energy for power supply of its electric actuators.

Due to the fact, as a rule, that the profitability of well operation at the late stage of extraction is low, thus, oil-production enterprises widely use in practice methods which provide with the economy of electrical energy consumption for DPE.

Primarily, they include the use of frequency-controlled electric actuators, which allow to change the productivity of DPE depending on changes of operated formation productiveness. To save electrical energy consumption it is used the method of DPE periodic operation at the time of the day when the amount of electricity charges are the lowest.

In cases when gas factor of extracted product is quite high it practices the usage of associated gas for supplying electric and gas turbine-generators developed electric energy for DPE at the operation well actually.

However, this method of associated gas disposal at the late stage of operation is practically unacceptable, as in this case it is very low for its implementation.

As for the first two mentioned ways of electric power economy, we can state that the frequency-controlled electric actuator is rather expensive equipment, having the long term of payback. Thus, the use of DPE at that time of the days when the amount of electricity charges is the lowest, does not always warrant economically, because there is a high probability of production drawdown during the day when charges are higher [18].

For more reliable economy of the electric power irrespective of the day time, production drawdown and gas factor size, we suggest to equip the discharge line of the focal injection well with the device including in the structure ahydro-turbine electric generator, disposing kinetic energy of the formation water transported on water conduits from the surface to layers for maintaining formation pressure permanent by means of ground surface cluster pumping stations (cluster pumping station-CPS and modular cluster pumping station-MCPS).

At the same time the operational (reacting) wells are equipped at the mouth with the thermoelectric generators transforming thermal energy of formation fluid to electric.

Using similar devices will allow to lower electric power costs for power supply of the electric actuator of DPE and other consumers of the electric power on the well.

Let us consider the configuration of the equipment for the disposal of kinetic and thermal energy, which is contained in liquid, transported to the formation as well as selected from it, on the example of the five-spot well pattern, being the main composite element of the oil field majority development system (fig. 5) [13,19-22].

The five-spot well pattern includes four operating wells 1, located at the corners of equal-sided quadrangle and water injection (focal) well 2, located in its center.

The power supply and management of DPE (sucker-rod pumping unit (SRPU), electrical submersible pump unit (ESPU) in fig. 5 are not shown), is carried out by means of control cabinet for DPE 3. The power is supply moves to it via the power production line 4 (380 V). The water is pumped to the water injection well 2 in the water conduit 5 from the cluster pumping station (not presented in figure 5). The extracted through the producing wells 1 oil is taken by means of a gathering oil pipeline 6. The mouth of the water injection well 2 is equipped with the hydroelectric turbine 7 through which the liquid is forced on a water conduit 5 to the water injection well 2.

The mouth of operation wells 1 is equipped with the thermoelectric modules 8 containing heat transfer devices in its construction (not presented in figure 5), through which the formation fluid goes
from wells 1. It has the temperature higher than ground-level. On the other hand, the water flows from the FPM system brought in special land water conduits with smaller diameter 5a.

Figure 5. The completion scheme of five-spot well pattern with equipment for disposal of geothermal and hydrokinetic energy: 1- producing wells; 2- water injection well; 3- control cabinet for DPE; 4- power line ~380V; 5- water conduit; 6- gathering oil pipeline; 7- hydroelectric turbine; 8- thermoelectric modules; 9- power line ~220V; 10- power line =24V.

The electric energy up to 220 V, generated by the hydroelectric turbine flows in the power line 9, and comes to the production field network via the transformer (it is not presented in the figure 5). But the electric power, generated by the thermoelectric modules 8 up to 24 V of a direct current volt, is summarized from all transport power modules (TPMs) 8 and goes along the line 100 to power the telesystem - automatic control system of the technological processes (ACS TP) (it is not presented in the figure 5), which is used for automatic control of an operating mode of DPE and CPS of the FPM system.

The offered device for complex utilization of kinetic and thermal energy, generated in operation of the separate well pattern, works in the following way (fig. 5).

Power supply of DPE (not presented in the figure 5) located in producing wells 1 is carried out on the main power line 4 through the corresponding control cabinets 3. Water injection into bed is done through the focal well 2 moving along the entry line 5b to the next field cell (not presented in the figure 5). In the wellhead of the focal well 2 in the water conduit 5 the hydroelectric turbine 7 has been inbuilt. It is driven by kinetic energy moving along the 5th water conduit, then transforms it to the electric energy of voltage alternating current up to 220 V, which is taken away from it on the power line 9 for further consumption.

At the power lines 6 of every operating well 1 the thermoelectric power supply 8 are assembled. They modify the difference in temperature between reservoir fluid extracted from the well 1 and the
water pumped to the focal well 2 or by the temperature of the inground power line of the heat exchanger (not presented in the figure 5).

The electric power generated by each thermoelectric converter 8 in the form of a Volts direct current up to 24 V is summarized by the power generator line 10 and goes to the industrial control system telesystem - automatic control system of the technological processes (ACS TP) for further consumption.

6. Conclusion
According to the analysis of mathematical model and calculations we state that the fluid temperature depends mainly on the well depth, injection capacity, geothermal gradient. For comfort practical application of the given method of generating energy it is necessary to create nomographic chart, which allow to forecast the selection of wells with relevant conditions, such as well depth, shelf thermal and physical characteristics, well construction characteristics.

For practical usage of geothermal energy the theoretical basis of generating geothermal energy have not been studied enough. The existing mathematical models do not described the influence of geothermal gradient as a main factor on generated thermal energy. Carrying out calculated and graphical studies allow to conclude that the main influencing parameters are geothermal gradient, thermal fluid injection rate and bottom hole depth. The low temperature geothermal energy profitability can be improved through the combination of the geothermal energy with hydrokinetic water power disposal, pumped by the FPM system.

The low temperature geothermal energy can be disposed by means of thermoelectric elements, set at the flowlines of operating wells near injection well. Hydrokinetic energy, pumped through it into the water, can be disposed by means of hydro electric turbine, set inside discharge line (water conduit).

7. Acknowledgments.
We express gratitude to LLC "Cosmo Group" for financial support when carrying out the research, and to colleagues who will become interested in our study and state their judgments.

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