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Physical Simulation of Near-Wellbore Rocks Temperature Reduction Process in the Earth's Interior

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Abstract

The paper considers simulation of the near-wellbore rocks cooldown (potential reduction of temperature in the course of time). Two general extraction methods of deep geothermal energy interior are described. The problem of lowering the interior temperature at long-term thermal energy extraction of terrestrial rocks with the use of single well «tube in tube» heat exchanger is stated. Substantiation is presented for physical simulation of the deep heat energy of the Earth's interior extraction. Experimental research method of deep heat of the Earth extraction is presented. The error in the modelling process of Earth's deep thermal energy extraction is determined with the physical model in the scale 1:100.

Keywords: heat of the Earth's interior rocks, thermal energy, single-well system for deep geothermal energy extraction, renewable energy sources

INTRODUCTION

As it is known, in the Earth's interior, a natural (normal) temperature field is formed ubiquitously, which is characterized by the totality of instant values of rocks temperature in all points of the space under consideration for each moment of time and reflects regional regularities of the geological structure of the interior [1]. This temperature field is traditionally assumed to be quasi-stationary.

The key thermal characteristic of the Earth's interior is the geothermic gradient, which determines variation of rocks temperature with depth and which, on average, amounts to 2 to 8 °C/100 m on the most of the land surface.

Two main methods are known for extraction of deep geothermal energy: the single-well system, which constitutes a heat exchange device of the "tube-in-tube" type [2], and the multi-well system made up of two or more wells [3].

The multi-well system for extracting deep geothermal energy comprises a number of injection and extraction wells interconnected with a volume formed by hydraulic fracturing of formation [4-5]. Such system is generally characterized by a considerable thermal power owing to a developed surface of heat exchange, which is a deep reservoir making a volume of deep rocks with multiple interconnected fractures. However, owing to such drawbacks as high contamination and mineralization of the heat transfer fluid due to its contact with deep rocks as well as carryover of the heat transfer fluid off the reservoir (up to 20% of the reservoir volume per year), operation of such heat collection systems is difficult.

The single-well heat collection system is made up of two coaxial pipes – an outer casing pipe and an extracting pipe located inside the outer one (see Figure 1). The process of heat transfer from deep hot rocks to the heat transfer fluid takes place through the casing pipe wall, which means that such system has no drawbacks of the multi-well system. However, owing to a small area of the heat transfer surface (which is actually limited by the geometry of the casing string of pipes), the thermal power of the single-well system is lower than that of the multi-well collection system. At the same time, as was mentioned above, just one well is sufficient to create such heat transfer fluid transport. It reduces considerably the capital costs of creating the energy source and enables employment of existing wells that are currently out of operation (oil and gas, exploratory, research, etc. wells). Therefore, this method for extracting the heat of the Earth's interior is the most promising for use by power-supplying autonomous and standalone consumers.

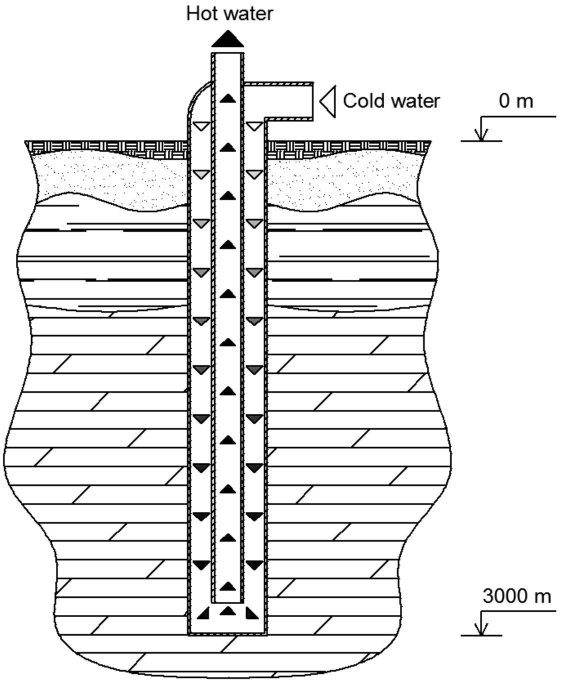

Figure 1: Single-well heat collection system

The common shortcoming of the above systems is local variation of the natural temperature field of the interior, which manifests itself in reducing eventually the temperature potential (cooldown) of rocks in the near-borehole area.

When the interior heat is extracted with a single-well collection system, disruption of the temperature field of the interior occurs along the generatrix of the casing string of pipes. Its variation is orientated in the radial direction from the borehole center, which eventually leads to partial reduction of the system's thermal power [6].

The intensity of the cooldown process decreases with the operation of a single-well collection system. After some time, this process virtually stops. The cooldown process is implemented up to a particular value of impact range r from the borehole axis. As the distance from this range becomes larger, the temperature of deep rocks would virtually equal the temperature at infinite distance from the well, i.e., the natural initial value corresponding to the geothermic gradient [7-10].

This study is dedicated to assessing the dynamics of the Earth's rocks temperature field variation in the near-borehole area during the operation of a similar heat collection system, which involves using an approximation physical simulation. A constant diameter borehole is considered without taking into account additional heat exchange between the heat transfer fluid in the annulus and in the inner pipe. It introduces a marginal error at determination of thermal well power that may be ignored at a first approximation [11].

Simulation of the Earth's Thermal Energy Extraction Using a Single-Well Collection System

Attempts to estimate the value of the temperature impact range r of a single-well heat collection system were made, in particular, in [12-14]. Thus, e.g., according to [13], gradual propagation of the front temperature effect area is determined by equation (1), which, with deep geothermal energy recovery time τ and temperature conductivity *a* of deep rocks specified, enables to determine an approximate value of the temperature impact range r.

$$\frac{a \cdot \tau}{r_c^2} = \frac{\left(\frac{r}{r_w} - 1\right)^2 \left(\frac{r}{r_w} - 2\right)}{36}, \qquad (1)$$

where *a* is temperature conductivity of deep rocks, [m^2/sec];

τ is functioning time of single-well collection system, [sec];

r_w is radius of the borehole, which accommodates the single-well collection system, [m];

r is range of temperature impact, [m].

However, determining the range of temperature impact based on geometry of the collection system and temperature conductivity of the interior does not take into account the temperature variation of the heat transfer fluid and, accordingly, that of the adjacent beds of deep rocks at long-term functioning of the system.

The methodology presented in [12] and [14] considers neither the effect of the heat transfer ratio from the surface of the outer pipe into the moving heat transfer fluid, nor the propagation speed variation of the temperature impact range in the course of time.

Physical simulation of heat transfer processes in heat collection systems of a similar kind are specifically peculiar due to their considerable length (the length to diameter ratio may reach values as high as 10^4 and many-fold larger). Thus, it is virtually impossible, with geometric similarity observed, to ensure, as applied to the well bore, the numerical parity of defining criteria of a thermal process similarity (in this particular case, above all, the Re and Nu numbers) [15, 16]. At the same time, an analysis of known Nu = *f* (Re) relationships [17, 18], not only for the turbulent flow conditions, but also for the transitional mode (see Fig. 2), shows their sufficient convergence right up to the values of Re = 10^5, which gives reason to transfer the simulation results, subject to subsequent conversion, to full-scale conditions.

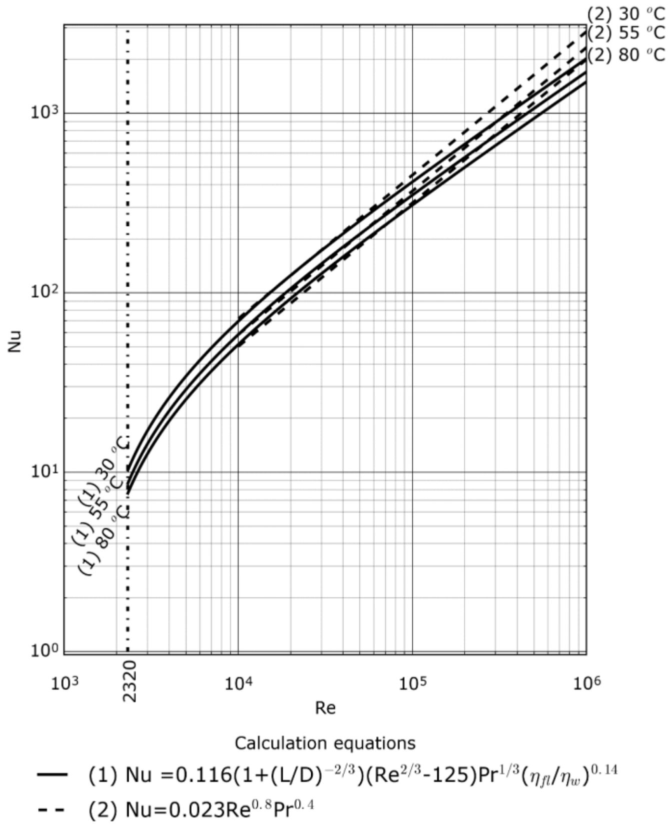

Figure 2. Comparison of Nu = *f* (Re) relationships at transitional and turbulent flow conditions for different water temperature values [19, 20]

By way of example, let us determine the flow conditions and the heat transfer factor for an actual single-well collection system. The inner diameter of the casing string of pipes is 300 mm, the outer diameter of the inner extraction string of pipes is 215 mm, the depth is 1,000 m, and the geothermic gradient is 5 °C/100 m. Wherein the temperature of the heat transfer fluid at the entry into the system will be assumed as $t_1 = 30$ °C. Accordingly, let us assume that the temperature at the exit of the system equals to the temperature of interior rocks at the depth of 1,000 m, $t_2 = 80$ °C. Then, with the average fluid temperature $t_m = 55$ °C and the flow rate $\omega = 0.5$ m/sec, the Reynolds number will be Re = 147,058. Here, the Nusselt number is Nu = 480 (see Fig. 2), which corresponds to the heat transfer factor $\alpha_0 = 2{,}091$ W/(m^2·K).

In the general case, the design of a single-well collection system is made up of the following main elements (see Fig. 3):

- plugging concrete intended for securing the casing string of pipes to the borehole walls;
- casing string of pipes made of steel;
- inner thermally insulated string pipe, along which the heated heat transfer fluid is transported to the well head.

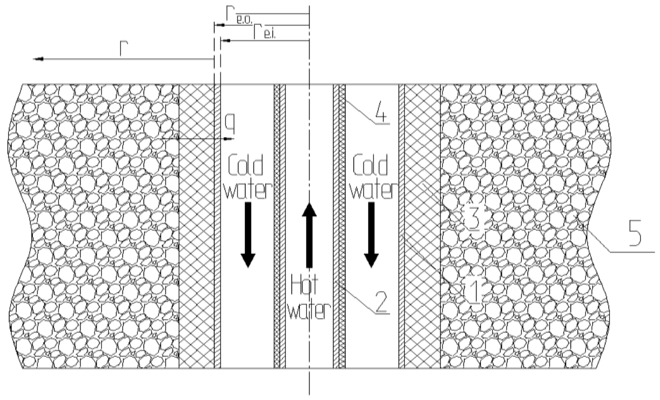

Figure 3: Construction of single-well system for collection of deep geothermal energy: 1) outer string of pipes, 2) inner extraction string of pipes, 3) plugging concrete, 4) thermal insulation of inner extraction pipe, 5) deep rocks, q thermal flux to heat transfer fluid, $r_{e.i.}$ and $r_{e.o.}$ — inner and outer radii of extraction string of pipes, r — range of temperature impact

The thermal flux from the interior per unit of length of a single-well collection system of the previously mentioned design at a given depth will be determined through equation (2).

$$q = \frac{\pi \cdot (t_2 - t_1)}{\frac{1}{2\cdot\lambda_r}\cdot \ln\left(\frac{r}{r_w}\right) + \frac{1}{2\cdot\lambda_{con}}\cdot \ln\left(\frac{r_w}{r_{e.o.}}\right) + \frac{1}{2\cdot\lambda_o}\cdot \ln\left(\frac{r_{e.o.}}{r_{e.i.}}\right) + \frac{1}{\alpha_0 \cdot 2 \cdot r_{e.i.}}} \qquad (2)$$

where:

t_1 is wellbore wall temperature, [°C];

t_2 is temperature of interior rocks at infinity from the borehole, [°C];

λ_r is thermal conductivity factor of deep near-wellbore rocks, [W/m·K];

r is range of temperature impact of single-well collection system, [m];

r_w is borehole wall radius, [m];

λ_{con} is factor of thermal conductivity of plugging rock, [W/m·K];

$r_{e.o.}$ is radius of outer surface of string of casing pipes, [m];

λ_o is thermal conductivity factor of casing string of pipes, [W/m·K];

$r_{e.i.}$ is radius of inner surface of string of casing pipes, [m];

α_o is heat transfer factor of inner surface of casing string, [W/m^{2}K].

Here, the thermal conductivity of plugging rock is close to thermal conductivity of interior rocks, while the thermal conductivity of the steel pipe is an order of magnitude larger than the thermal conductivity of the interior, which means that thermal resistance of the casing pipe may be ignored; then equation (2) may be presented in a simplified form:

$$q = \frac{\pi \cdot (t_2 - t_1)}{\frac{1}{2\cdot\lambda_r}\cdot \ln\left(\frac{r}{r_{e.i.}}\right) + \frac{1}{\alpha_0 \cdot 2 \cdot r_{e.i.}}} = \frac{\pi \cdot (t_2 - t_1)}{R_r + R_\alpha}, \qquad (3)$$

where:

R_r is thermal resistance of interior rocks, (m·K)/W;

R_α is thermal resistance of heat transfer from inner surface of casing pipe of single-well collection system, (m·K)/W.

Let us assume that the solid interior rock thermal conductivity factor, which is the most common on the territory of Russia, equals to 2.0 W/(m·K), and the range of temperature impact of a single-well system equals to 15 m [6]. Then, the denominator in equation (3), which is equal to thermal resistance of heat transfer from the interior to the heat transfer fluid in a single-well collection system R_l, will be:

$$R_1 = R_r + R_\alpha = \frac{1}{2\cdot\lambda_r}\cdot \ln\left(\frac{r}{r_{e.i.}}\right) + \frac{1}{\alpha_0 \cdot 2 \cdot r_{e.i.}} = \frac{1}{2\cdot 2}\cdot \ln\left(\frac{15}{0{,}15}\right) + \frac{1}{2091\cdot 0{,}3} = \qquad (4)$$
$$= 1{,}15 + 1{,}32\cdot 10^{-3}\left[\frac{m\cdot K}{W}\right]$$

As can be seen from equation (4), thermal resistance of heat transfer from inner surface of a casing string of pipes makes 0.14% of the thermal resistance value of heat transfer from the interior to the heat transfer fluid, and this value will generally decrease along with the expansion of the temperature impact range [21].

SUBSTANTIATION OF PHYSICAL SIMULATION FEASIBILITY OF THERMAL ENERGY EXTRACTION FROM EARTH'S INTERIOR

It is possible to explore the way, in which the temperature potential of deep near-borehole rocks reduces on a full-scale system, or by physical simulation of deep heat collection with a single-well system.

Performing full-scale studies on an actual single-well collection system implies creating the same based on a new or existing well, with a large number of additional research wells located at different distances from the primary well and intended for measuring the temperature of interior rocks. This method is extremely complicated, expensive and economically inefficient.

Therefore, the process of cooldown of near-borehole deep rocks should be studied through simulation of the processes taking place in near-borehole deep rocks. As the single-well collection system actually constitutes a "tube-in-tube" type heat exchanger, the task is reduced to simulating thermal processes inside the single-well system and in the mass of rocks of the near-borehole area.

It is technically and economically feasible to create a model on the 1:100 scale, where a single-well collection system, which is 1,000 m deep and has the temperature impact range of 15 m, will be in the form of a cylinder. It will have the radius of 15 cm and the length of 10 m with a central bore of 3 mm in diameter. Here, such cylinder may be made up of serially connected sections, their overall length to correspond to the required value.

Make similar calculations for the above simulation of interior rocks with the following main characteristics of the heat collection process:

- the temperature of heat transfer fluid at the entry into the bore and the interior rock model is 30 °C;
- the temperature of the interior rock channel at the entry into the bore at the beginning of the heat transfer fluid flow is equal to the temperature of the heat transfer fluid (30 °C);
- the geothermic gradient is 5 °C/1 m;
- the heat transfer fluid flow rate varies within the range of 0.5 to 1.5 m/sec (where the minimum value of hydraulic friction of the single-well collection system is achieved).

Thus, e.g., with the average fluid temperature t_{cp} =55 °C and the flow rate 0.5 m/sec, the Reynolds number will be Re = 2,941. Here, the Nusselt number is Nu = 13.83 (see Fig. 2), which corresponds to heat transfer factor $\alpha_к$ = 2,935 W/(m^2·K).

Let us assess the way, in which the above heat transfer factors influence on the process of heat collection in the interior rock model, assuming the range of temperature impact to be r = 15 cm.

$$
\begin{aligned}
R_1 &= \frac{1}{2\cdot\lambda_r}\cdot\ln\left(\frac{r}{r_{b.}}\right)+\frac{1}{\alpha_b\cdot 2\cdot r_{b.}} \\
&= \frac{1}{2\cdot 2}\cdot\ln\left(\frac{0,15}{0,0015}\right)+\frac{1}{2935\cdot 0,003}= , \\
&= (1,15+0,1136)\left[\frac{m\cdot K}{W}\right]
\end{aligned}
\qquad (5)
$$

where r_b is the bore radius in the model.

The results of a similar assessment of the heat transfer thermal resistance in an interior rock model and in full-scale conditions at different flow rates of heat transfer fluids are presented in Table 1.

Table 1. Comparison of the heat transfer thermal resistance in the model and in full-scale conditions at different flow rates of heat transfer fluid

w, m/sec	**0.5**	**0.75**	**1**	**1,5**
$R^{full\text{-}scale}$, m K/W	1.15132	1.15132	1.15132	1.15130
R^{model}, m K /W	1.27333	1.21746	1.19826	1.18228
ΔR/R, %	9.58	5.43	3.91	2.61

As can be seen from Table 1, the average error for determination of heat transfer factor at turbulent flow of the liquid would not exceed 10%.

Based on the previously mentioned, it is possible to distinguish the following stages of an experimental study of the way, in which the near-borehole rocks of the Earth's interior cool down:

- creating a stationary (normal) geothermal field in the model of deep rocks with a given geothermic gradient at 5 °C/1 m;
- ensuring the given flow rate of the heat transfer fluid through the model of rocks;
- determining the dynamics of temperature fields variation in the radial direction from the bore to the outer surface of the string by means of thermal sensors at different heat transfer fluid flow rates. Determination of temperature fields must be exercised throughout the heat transfer fluid cooldown period up to stabilization of this process, with the frequency of registration and recording into the memory of instant temperature values being at least 1 Hz, which contributes to higher accuracy of measurements;
- determining the instant values of temperature variation rates as the first order derivatives dt/dr in

particular points of the mass of rocks surrounding the bore of the single-well heat collection system. Determining the radial distance from the bore to the section with a fixed value of derivative dt/dr corresponding to virtual stabilization of the process, i.e., the range of temperature impact;

- determining the cooldown time, i.e., the period, for which the range of temperature impact is formed. The value obtained may be converted to full-scale conditions subject to a scale factor with applying the Fourier number as one of the criteria for similarity of non-stationary thermal processes, which is the criterion of homochronicity of temperature fields.

CONCLUSION

Exploring the way, in which the temperature potential of near-wellbore rocks of the Earth’s interior reduces, is a complex multi-component problem. At the same time, it is shown that such research can only be carried out based on physical simulation of thermal processes. With the single-well collection system and the near-borehole volume of deep rocks scaled, e.g., at values of 1:100, the accuracy of the held experimental studies remains at an acceptable level (the margin of error is kept within 10%). It considerably simplifies studying the reduction of temperature potential in deep near-borehole rocks.

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REFERENCES

[1] Frolov N.M. “Hydrogeothermy”. 2nd ed., rev. & suppl., Moscow: Nedra, 1976, pp. 280

[2] Yekoladio P.; Bello-Ochende T., Meyer J. Design and optimization of a downhole coaxial heat exchanger for an enhanced geothermal system (EGS). Renewable Energy, Vol. 55, pp. 128-137, 2013.

[3] Olasolo P., M.C. Juárez, M.P. Morales, Sebastiano D´Amico, I.A. “Liarte Enhanced geothermal systems (EGS): A review”. Renewable and Sustainable Energy Reviews, Vol. 56, pp. 133-144, April 2016

[4] Hongbo Shao, Senthil Kabilan, Sean Stephens, Niraj Suresh, Anthon N. Beck, Tamas Varga, Paul F. Martin, Andrew Kuprat, Hun Bok Jung, Wooyong Um, Alain Bonneville, David J. Heldebrant, Kenneth C. Carroll, Joseph Moore, Carlos A. “Fernandez Environmentally friendly, rheoreversible, hydraulic-fracturing fluids for enhanced geothermal systems”. Geothermics, Volume 58, pp. 22-31, November 2015

[5] Linmao Xie, Ki-Bok Min, Yoonho Song “Observations of hydraulic stimulations in seven enhanced geothermal system projects”. Renewable Energy, Volume 79, pp. 56-65, July 2015

[6] Ryzhenkov A.V., A.V. Kurshakov, S.V. Grigoriev, V.V. Bekker, and A.V. Bogachev. “On Possibility of Long-Term Use of Deep Heat of The Earth for Power-Supplying Autonomous Consumers”. Research Journal of Pharmaceutical, Biological and Chemical Sciences, Volume 7(6), pp. 496-504, 2016.

[7] Rybach, L. & Eugster, W. J. “Sustainability aspects of geothermal heat pump operation, with experience”. Switzerland Geothermics, vol. 39, pp. 365 – 369, 2016.

[8] Pahud D. & Matthey B. “Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ”. Energy and Buildings, no. 33, pp. 503 – 507, 2001.

[9] Acuña J., Mogensenb P. & Palma B. “Distributed thermal response tests on a multi-pipe coaxial borehole heat exchanger”. HVAC&R Research, No. 17, pp. 1012-1029, 2011

[10] Bi Y.; Chen L., Wu C. “Ground heat exchanger temperature distribution analysis and experimental verification”. Applied Thermal Engineering, No. 22, pp. 183 – 189, 2002

[11] Ryzhenkov V.A., Kurshakov A.V., Martynov A.V., Grigoriev S.V. & Kutko N.Ye. “On variation of thermal potential of the Earth’s deep rocks in the course of long-term operation of a petrothermal energy sources with the single-well heat collection system”. Natural and engineering sciences, No.3. pp. 321-326, 2012

[12] Lykov, V.A. “Theory of thermal conductivity”. Moscow: Vysshaya Shkola, 1967, pp. 600

[13] Alkhasov A.B. “Geothermal energy generation”. Fizmatlit, 2008, pp. 376

[14] Pekhovich A.I. & Zhidkikh V.M. Calculations of thermal behavior of solid bodies. 2nd edition, updated and revised. – Leningrad: Energy, 1976, pp. 347

[15] Mikheyev M.A. & Mikheyeva I.M. Heat transfer principles. 2nd edition, reprint. Moscow: Energiya, 1977, pp. 344

[16] Mikheyev M.A. Heat transfer principles. Moscow-Leningrad: State Power Engineering Publishing House, 1949, pp. 396

[17] Migay V.K. “Simulation of heat exchange energy engineering equipment”. Leningrad: Energoatomizdat, 1987, pp. 264

[18] Kirpichev M.V., Mikheyev M.A. “Simulation of thermal devices”. Moscow: Publishing House of the USSR

Academy of Sciences, 1936, pp. 320

[19] Greber G., Erk S. & Grigull U. “Heat transfer fundamental”. Moscow: Publishing House of Foreign Literature, 1958, pp. 565

[20] Tsvetkov F.F., Kerimov R.V. & Velichko V.I. “Book of problems on heat-mass transfer”. 2nd edition, updated and revised. Moscow: MPEI Publishing House, 2008, pp.196

[21] Volkov A.V., Ye.M. Shitov, Ye.S., Orlova, A.V. Kuznetsov-Sytinskiy, S.V. Grigoriev, & V.V. Bekker. Raising Efficiency of Petrothermal Source of Energy Through Using Heat Accumulators. Research Journal of Pharmaceutical, Biological and Chemical Sciences, Volume 7(6), pp. 766-773, 2016