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Physical Modelling of Temperature's Potential Decrease for Near-Wellbore Rocks during Extraction of Thermal Energy

A.V. Volkov, A.V. Ryzhenkov, A.V. Kurshakov, S.V. Grigoriev, and V.V. Bekker

National Research University "Moscow Power Engineering Institute"
14, Krasnokazarmennaya Str., Moscow-111250, Russia.

Abstract

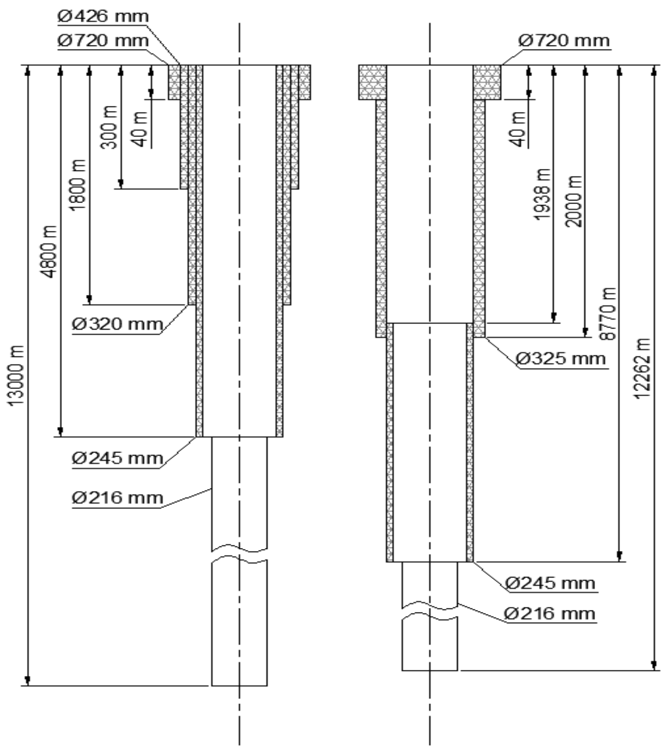
A selection of a single-well system for extraction of geothermal energy has been justified as the most promising solution for supplying energy to autonomous consumers. Description of physical modelling of the temperature potential decrease (cooldown) process for near-wellbore rocks of the Earth during extraction of thermal energy has been provided. Geometrical characteristics of the Earth's rocks model performed on 1:100 scale to the actual system have been justified. The content and the schematic diagram of the unique test rig designed for modelling of the cooldown process for near-wellbore rocks have been provided, and the functional characteristics of the test rig have been described. The selection of thermal and physical characteristics of the rocks model included in the test rig has been justified. Individual results of studies performed with the test rig have been provided.

Keywords: Renewable energy sources, geothermal energy, single-well system for extraction of geothermal energy, physical modelling of the ground cooldown.

INTRODUCTION

Today, deep thermal energy (petrothermal energy) of the Earth's hot dry rocks is one of the most promising renewable energy sources. Numerous studies [1–3] demonstrate the possibility for extraction of geothermal energy anywhere irrespective of climatic, geographical and seasonal factors, thus making a substantial difference between that source of energy and other renewable energy sources (RES). However, the use of the Earth's petrothermal energy presents certain difficulties.

That primarily relats to drilling relatively deep (up to 10 km) wells. As a rule, deep wells have a sectional structure [4]. The example of such a well is presented in figure 1 [5]. Today, the drilling depth is the major factor limiting the accessibility of deep geothermal energy of required temperature level anywhere on the planet. It is known that the existing technologies allow superdeep drilling to the depths up to 12 km [6]. Well drilling technologies to shallow depths (3–5) km are well-proven and relatively cheap. However, drilling accounts for 70–80 % of the capital costs on the creation of a power supply source and 40–60 % on a heat supply source [7].



a) project b) actual

Figure 1: Design of Kola Superdeep Borehole

The utilization of the Earth's petrothermal energy involves the creation of a ground circulation system which enables collection and transportation of thermal energy to the surface [8].

Water is used as a traditional heat transfer fluid in the systems for collection and transportation of deep geothermal energy, although recently attention has also been given to alternative working fluids (low-boiling fluids, freons, etc.).

Alternative working fluids are used to reduce the hydraulic resistance of a deep thermal energy collection system as they more easily pass through a branched deep collector formed through hydraulic fracturing. Thus, at the same created injection pressure of the heat transfer fluid though the collector the water flow is twice as little as the flow, for instance, of carbon dioxide [9].

The duration of deep geothermal energy extraction at a fixed location is estimated at 100–300 years subject to maintaining an optimum flow of a heat transfer fluid [10].

Today, 2 implementation variants are used for the extraction of petrothermal resources:

- open method of extraction of geothermal energy is widely used in the USA and European countries [11]; it involves drilling of two and more wells (injection and production), as well as arrangement of a water-permeable areas between them at various depths with required temperature potential [12];
- closed method of extraction of geothermal energy utilizes a single-well double-pipe heat exchanger [13, 14]. In this case, the heat transfer fluid is circulated over the closed-loop system in the tube side and shell side of the heat exchanger.

The permeable area at the "open" collection method may be made as a cavity with broken rock formed by an explosion or a multitude of crevices formed by hydraulic fracturing. The heat exchanger is delivered to the injection well, penetrates through the heated rock and then rises through the production well to the surface in the liquid or vaporized state.

The advantage of such method is that it provides the maximum possible heat transfer surface between the heat transfer fluid and the heated rock and, consequently, the maximum heat output. The drawbacks include the need for two and more vertical and directional wells, possible losses of substantial volumes of the heat transfer fluid, the need for substantial capacities to overcome hydraulic resistance, and the requirement for measures to protect equipment from aggressive action of the heat transfer fluid transported to the surface. The hydraulic fracturing takes up from 12 hours [15] (collector of 336 m^3) to 6 days (formation of a deep collector of 35 million m^3). In this case, the heat transfer area of existing collectors formed through hydraulic fracturing amounts to 1.5 km^2 [16].

The advantages of the "closed" method of collection of geothermal energy include the need for only one non-directional well, low hydraulic resistance, absence of contamination of the heat transfer fluid with corrosive compounds, thus making this method the most promising option. The closed method is less studied and the examples of its utilization include projects in Japan and Germany [17].

It should be pointed out that the drawbacks of this method include much smaller heat transfer area and a reduction of temperature potential of the near-wellbore rocks of the Earth at sustained operation of a single-well system for collection of geothermal energy [18]. This fact leads to the change in the thermal output of a single-well collection system and, consequently, to a reduction in its efficiency. This process is virtually endless and actually depends on the intensity of thermal energy extraction by the heat transfer fluid from the Earth's depths. In this regard, the intensity is determined primarily by the flow of the heat transfer fluid, its temperature at the inlet of the single-well collection system, and the thermal and physical properties of the near-wellbore rocks of the Earth. The dynamic profile of the temperature potential variation of the near-wellbore rocks of the Earth will allow optimizing the operation of the thermal equipment substantially increasing the useful life of the single-well collection system at acceptable thermal output.

Today, various researchers are making attempts to only mathematically evaluate the reduction in the temperature potential over time. However, mathematical models do not always allow obtaining a result which is adequate to the actual (full-scale) single-well collection system. This paper makes an attempt to create a physical model of a single-well collection system for experimental studying of the cooldown process for near-wellbore rocks.

DESCRIPTION OF EXPERIMENTAL IMPLEMENTATION OF THE COOLDOWN PROCESS FOR NEAR-WELLBORE ROCKS OF THE EARTH DURING THE USE OF A SINGLE-WELL SYSTEM FOR COLLECTION OF GEOTHERMAL ENERGY

A single-well system for extraction of geothermal energy with the near-well rocks is made as a cylinder of unlimited radial section dimensions with initial reserve of thermal energy which can be transported to the surface. However, for creation of a physical model the final geometrical dimensions are required; it is reasonable to select them based on the 1:100 scale of the model to the full-scale system.

For estimation of the temperature effect radius of a single-well collection system a simplified procedure described in [19] can be used which helps to identify an approximate value of the temperature effect radius. Propagation of the temperature perturbation front over time as per [19) is determined by equation (1).

$$\tau_n = \frac{(R-1)^2 \cdot (R+2)}{36} \qquad (1)$$

where, R is a non-dimensional distance from the borehole axis to the temperature effect boundary of a single-well collection system which is defined as a ratio of the radius at a distance from the well to the radius of the borehole $\frac{r}{r_b}$ where a single-well system for collection of geothermal energy is located.

τ_n is the non-dimensional time determined by the equation (2);

$$\tau_n = \frac{a \cdot \tau}{r_b^2} \qquad (2)$$

where, a – the temperature conductivity of the rocks, m^2/s;

τ – the operation time of a single-well collection system, s;

r_b – the radius of the borehole where a single-well collection system is located, m.

Therefore, the equation (1) taking into account (1) can be presented as the equation (3):

$$\frac{a \cdot \tau}{r_b^2} = \frac{\left(\frac{r}{r_b} - 1\right)^2 \cdot \left(\frac{r}{r_b} + 2\right)}{36} \qquad (3)$$

Based on the analysis of the equation (3), assuming 300 mm mean radius of the borehole, it has been established that the temperature effect radius of a single-well system for collection of deep thermal energy at sustained operation of the system will be equal to ca. 13 m. Therefore, the physical model on 1:100 scale to the full-scale single-well system can be made as a cylinder with external radius above 0.13 m and a channel located along the centre of the cylinder 3 mm in diameter. In this case, the cylinder length influences only on the temperature potential of the thermal energy contained in the rocks considering geothermal gradient (the characteristic which describes the variation of the rocks temperature as depth increases, expressed in $^{o}C/m$).

In view of the foregoing, the geometrical characteristics of the Earth's rocks model have been identified. This model is the main element for performing physical modelling of the temperature potential's variation of the near-wellbore rocks of the Earth.

The Earth's rocks model is made as a cylinder with the diameter of 0.32 m and the total length of 10 m composed of serially connected 4 parts, 2.5 m long each. At the centre of the cylinder a channel 3 mm in diameter is located, which is used to transport the heat transfer fluid at a specified temperature. The geometrical characteristics of the Earth's rocks model are selected based on 1:100 scale to the full-scale (actual) single-well collection system 1,000 long and located in the well 300 mm in diameter.

For positioning the rocks model, it is necessary to envision a stand with equipment attachment system and weight load control; for transportation of the heat exchange fluid through the rocks model, it is necessary to provide a pump and a tank in which a constant temperature of the heat exchange fluid is maintained, and also the measuring equipment and the required number of temperature sensors. The listed equipment operating in tandem represents a test rig for modelling of the cooldown process for near-wellbore rocks of the Earth which structurally consists of the following main elements (the schematic diagram of the test rig is presented in figure 2):

– the Earth's rocks model;
– stand with the equipment attachment system and weight load control;
– heat exchange fluid supply and flow control system;
– heating and temperature control system for the rocks model;
– measuring module located on the control board including temperature sensors and a measurement automation system (the module is controlled by a special software).

The stand with the equipment attachment system provides equal distribution of load on the floor structure of the room where the test rig is located. The heat exchange fluid supply and flow control system provide transportation of the heat exchange fluid through the rocks model at a specified velocity and temperature enabling to study the effect of the initial temperature of the heat exchange fluid on the intensity of cooldown of various types of rocks and the effect of the heat exchange fluid velocity on the cooldown of the Earth's rocks. The heating and temperature control system for the rocks model enables to set the required temperature gradient for the external surface of each part of the rocks model.

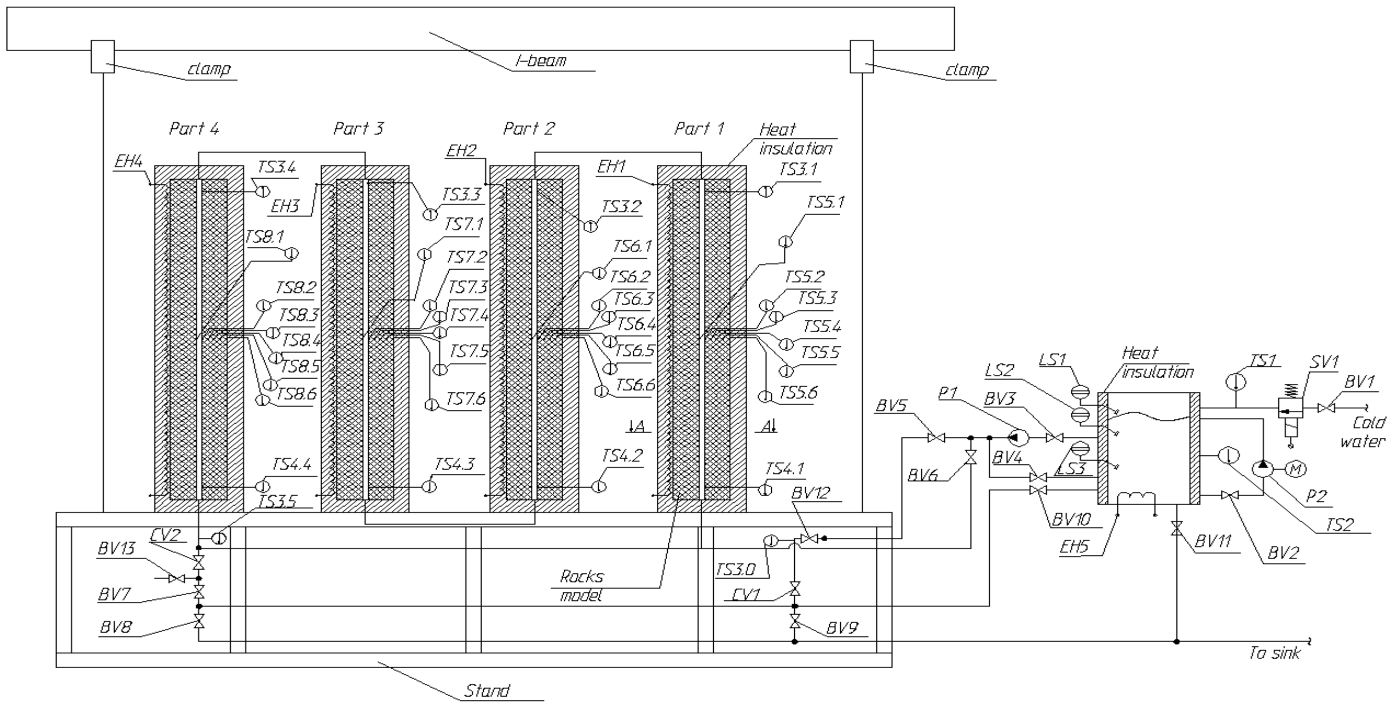


Figure 2: Schematic diagram of the test rig for modelling of the cooldown process for near-wellbore rocks of the Earth: SV1 – solenoid valve, BV1-BV13 – ball valves, P1 – supply pump, P2 – circulation pump, EH1-EH4 – band electric heaters, EH5 – tube electric heaters, LS1-LS3 – level sensors, CV1-CV2 – needle valves, TS1 – water temperature sensor for cold water supply system, TS2 – water temperature sensor in the tank, TS3.0 – water temperature sensor at the inlet of part 1, TS3.1-TS3.4 and TS4.1-TS4.4 temperature sensors for the channel wall at the inlet and outlet of parts 1-4, TS5.1-TS5.6, TS6.1-TS6.6, TS7.1-TS7.6 and TS8.1-TS8.6 - temperature sensors for the rocks in parts 1-4, TS3.5 – temperature sensor for water at the rocks model outlet.

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Registration of all the values measured during the experimental study is provided by the measuring module which combines the analogue input systems for temperature sensors, the automation system and the control board.

The measuring module of the test rig for modelling of the cooldown process for near-wellbore rocks of the Earth is designed to perform the following main functions:

- control of the heating and temperature control system for the rocks model;
- heating and temperature control for the water supplied to the first part of the rocks model;
- control of the heat exchange fluid supply and flow control system;
- collection, processing and archiving of records from sensors and instruments.

All components comprising the electric part of the test rig can be conventionally split into three groups:

- actuated equipment (heating elements, pumps, valves);
- testing and measuring equipment (level sensors, temperature sensors);
- automation system equipment which ensures interaction of the actuated equipment and the testing and measuring equipment, automated performance of measurements, display and archiving of the current parameters.

Setting of all initial parameters of the experimental study, visual control of the equipment operation and archiving of the measured values are performed with a software installed at the operator's workstation (see figure 3).

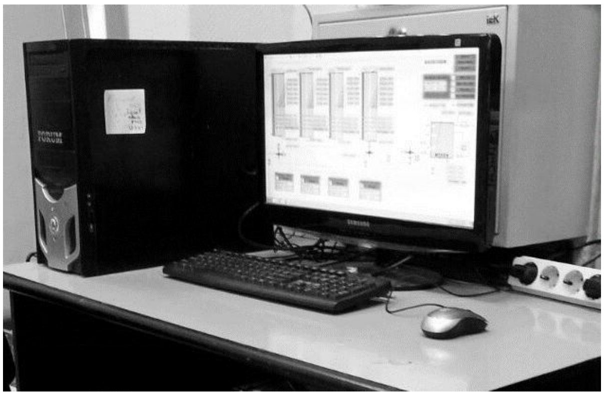

Figure 3: Photo of the test rig operator's workstation configuration

When selecting materials for production of the rocks model, studies were performed to define the main thermal and physical characteristics of the hard rock samples typical for the territory of Russia. It was identified that at the depths up to 10 km the Earth's rocks consist mainly of granites and basalts; whereby the studies performed demonstrated that the examined samples of these materials have the following typical characteristics:

- the heat conductivity factor varies in the range from 0.551 W/(m·K) to 1.751 W/(m·K);
- the average density varies in the range from 1,731 to 3,110 kg/m^3;
- the average heat capacity of granite and basalt samples of various types varies in the range from 690.5 J/(kg·K) to 871.5 J/(kg·K).

It should be noted that pressure has almost no effect on the heat conductivity factor of granite [20]. Figure 4 shows an example of the variation of the granite heat conductivity factor of 2 W/(m*°C) at normal atmospheric pressure versus the pressure at the corresponding depth.

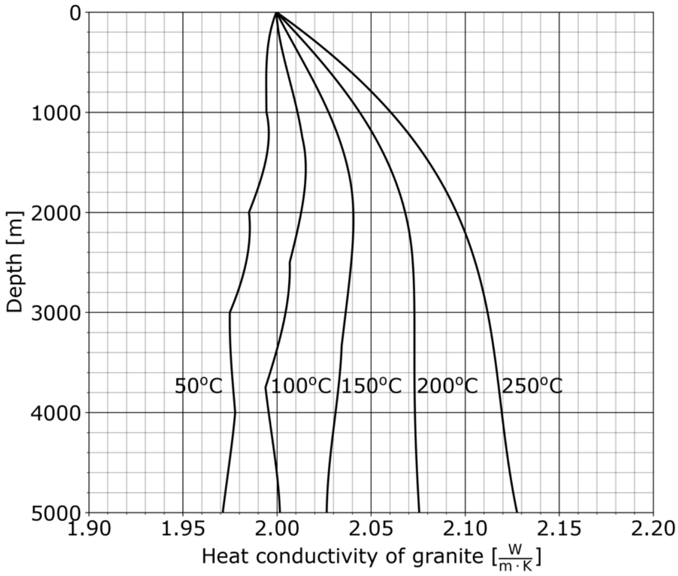

Figure 4: Variation of the granite heat conductivity factor of 2 W/(m*°C) at normal atmospheric pressure versus the pressure at the corresponding depth

EXAMPLES OF SOME RELATIONSHIPS RECEIVED WHEN USING THE TEST RIG

Due to the fact that propagation of the temperature perturbation in the near-wellbore rocks occurs in the radial direction (radially), 6 precision temperature sensors in the middle of the rocks model parts are located as follows: the first and the second sensors are located at the channel surface, the sixth sensor is located on the outer surface of the part, three sensors are located between the second and the sixth sensors, where the distances from the channel surface to each of the three intermediate sensors are equal to 10 mm, 27 mm and 73 mm, respectively. Such location of the temperature sensors enables to identify the time variation of temperature patterns at the centre of each part.

Moreover, the temperature sensors are located at the heat transfer fluid inlet and outlet of each part of the rocks model which enables to register the variation of the heat transfer fluid temperature at its heating. The initial temperature field of the rocks model is provided by the electric heaters located on the outer surface of each part, where each heater has its own power supply which enables to set the required temperature gradient at the surface of the parts.

Presented above temperature sensor configuration in the central radial sections of the rocks model parts and the registration of the temperature values over time enable to perform various experimental studies of the impact caused by the heat transfer fluid flowing through the channel on the temperature field of the rocks model.

Figure 5, as an example, shows the variation of temperature of the rocks near the rocks model channel in the middle of each part at the heat transfer fluid velocity 0.75 m/s and geothermal gradient 5 ºC/1 m (which corresponds to geothermal gradient 5ºC/100 m in full-scale conditions).

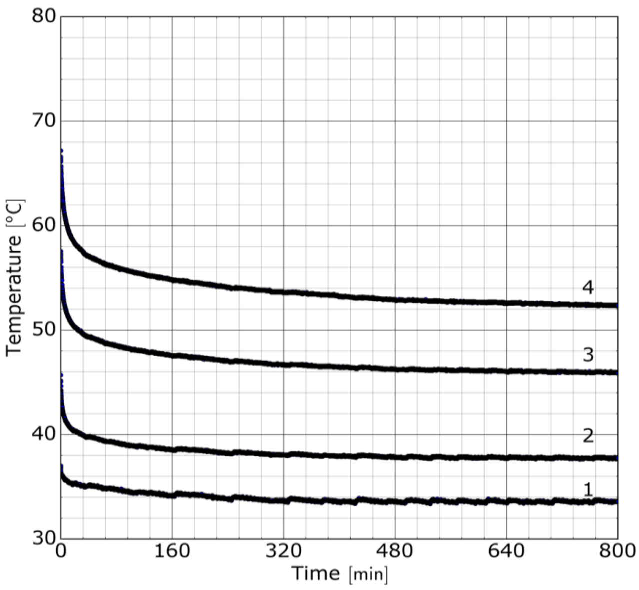

Figure 5: Variation of temperature of the rocks near the model channel in parts No. I–IV at v_{water} = 0.75 m/s and T_{in}^{water} = 30 °C: 1 – part No. 1, 2 – part No. 2, 3 – part No. 3, 4 – part No. 4

Relationships presented in figure 5 can be obtained at various heat transfer fluid velocities, namely from 0.1 to 1.5 m/s. At high velocities there is a considerable increase of hydraulic resistance both of the full-scale system and the heat transfer fluid transportation system of the test rig, whereby studies in such modes are impractical.

Variation of the heat transfer fluid velocity in the test rig enables to determine the relationship between the water temperature at the model outlet and velocity. The example of such relationship at the water temperature at the model inlet 25 and 30 ºC and at the similar geothermal gradient (5 ºC/1 m) is presented in figure 6.

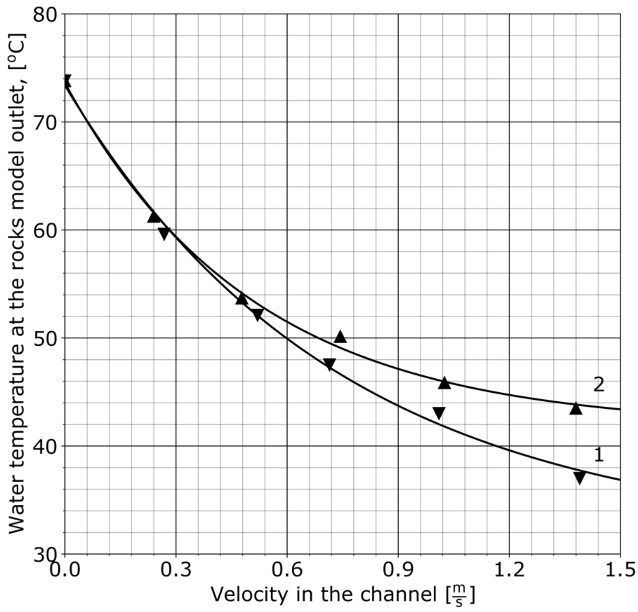

Figure 6: Relationship between the heat transfer fluid temperature at the test rig outlet and the water velocity: 1 – at the water temperature of 30 ºC at the model inlet, 2 – at the water temperature of 25 ºC at the model inlet

The hard rocks model described can be fabricated from various materials both from natural hard rocks of the Earth (basalt, granite, shale) and loose ones when using a special rigging. The length of the rocks model is determined by the economic and technical capabilities. When using short (less than 5 m) models, the studies can be performed sequentially setting final parameters of the previous iteration as initial parameters for each iteration. This way, it is possible to model single-well systems for collection of geothermal energy of almost unlimited length.

CONCLUSION

The provided universal experimental implementation of the physical modelling of the cooldown process for near-wellbore rocks of the Earth when using a single-well system for collection of geothermal energy based on the rocks model in 1:100 scale enables to perform the following types of studies with possibility to apply the results to the full-scale system, namely:

- the intensity of temperature variations for a mass of various rocks in different parts of the temperature effect zone, including near the outer surface of the well;
- the effect of the heat transfer fluid velocity on the cooldown of the Earth's rocks;
- the effect of the initial temperature of the heat transfer fluid on the intensity of cooldown of various types of rocks.

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REFERENCES

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

[2] Yuan Feng, Xi Chen & Xi Frank Xu, Current status and potentials of enhanced geothermal system in China: A review, Renewable and Sustainable Energy Reviews, Volume 33, pp. 214-223, 2014

[3] P. Olasolo, M.C. Juárez, J. Olasolo, M.P. Morales & D. Valdani, Economic analysis of Enhanced Geothermal Systems (EGS). A review of software packages for estimating and simulating costs, Applied Thermal Engineering, Volume 104, pp. 647-658, 2016

[4] G. S. Kaldal, M. T. Jonsson, H. Palsson & S. N. Karlsdottir Structural modeling of the casings in high temperature geothermal wells. Geothermics, Volume 55, pp. 126-137, 2015

[5] P.V. Orlov & N.P Laverov. Kola Superdeep Borehole. Scientific results and research experience. Moscow: MF “TECHNONEFTEGAZ”, 1998, pp. 260.

[6] H. Kern, T. Popp & F.F. Gorbatsevich et al. Seismic properties of rocks of Kola Superdeep Borehole and their homologs at the surface in conditions adequate to the deep ones. Bulletin of MSTU, No. 2, pp. 263-266, 2007

[7] Keith Yost, Amanda Valentin & Herbert H. Einstein Estimating cost and time of wellbore drilling for Engineered Geothermal Systems (EGS) – Considering uncertainties. Geothermics, Volume 53, pp. 85-99 2015

[8] Ryzhenkov V.A., Kurshakov A.V., Anahov I.P., Martynov A.V. & Grigoriev S.V. Utilization of the deep geothermal energy for supplying energy to isolated and remote consumers. Energetik, No. 5 pp. 29-32, 2012

[9] K. Pruess, Enhanced geothermal systems (EGS) using CO2 as working fluid—A novel approach for generating renewable energy with simultaneous sequestration of carbon, Geothermics, vol 35 pp. 351-367, 2006

[10] G. Axelsson, Sustainable geothermal utilization – Case histories; definitions; research issues and modelling, Geothermics, vol 39, pp. 283-291, 2010

[11] C. R. Chamorro, J. L. García-Cuesta, M. E. Mondéjar & A. Pérez-Madrazo Enhanced geothermal systems in Europe: An estimation and comparison of the technical and sustainable potentials. Energy, Volume 65, pp. 250-263, 2014

[12] N.A. Gnatus, V.A. Ryzhenkov, A.V. Martynov, H.E. Krutko & S.V. Grigoriev, Utilization if petrothermal (deep) heat of the Earth for supplying energy to autonomous consumers. Energy supply and water treatment, No. 3, pp. 23-27, 2012

[13] M. Le Lous, F. Larroque, A. Dupuy & A. Moignard, Thermal performance of a deep borehole heat exchanger: Insights from a synthetic coupled heat and flow model, Geothermics, Volume 57, pp. 157-172, 2015

[14] R. A. Beier, J. Acuña, P. Mogensen & B. Palm, Transient heat transfer in a coaxial borehole heat exchanger, Geothermics, Volume 51, pp. 470-482, 2014

[15] G. Zimmermann, I. Moeck & G. Blöcher, Cyclic waterfrac stimulation to develop an Enhanced Geothermal System (EGS)—Conceptual design and experimental results, Geothermics, vol. 39, pp. 59-69, 2010

[16] P. Heidinger, J. Dornstädter &A. Fabritius, HDR economic modelling: HDRec software, Geothermics, vol. 35, pp. 683-710 2006

[17] Geothermische Kraftwerke nach dem System GEOHIL/GEO-STORM. Projekt Worms. H.Hildebrand, Geohil Engeneering AG 08/06/2004. http://www.geohil.com (accessed date 30.10.2015).

[18] A.V. Ryzhenkov, A.V. Kurshakov, S.V. Grigoriev, V.V. Bekker, & 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

[19] A.B. Alhasov, Geothermal power engineering: Problems, resources, technologies. Moscow: FIZMATLIT, 2008, pp. 376.

[20] S.N. Emirov & A.E. Ramazanova Thermal properties of solid bodies under high pressures and temperatures. Earth sciences, No. 1 pp. 37-42, 2009