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NEW AND RENEWABLE ENERGY SOURCES

A Hybrid Solar−Geothermal Heat- and Hot-Water Supply System

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Abstract—The cooling of rock formations when extracting heat by a borehole heat exchanger and the restoration of the thermal field in the rock during the idle time of the well have been investigated. The heat in the rock during the summer downtime of the well is partially restored due to the influx of heat from the outside formation. The radius of the rock cooling front around the borehole in the heating period can reach 6−8 m. The temperature on the borehole wall is restored by approximately 50% in one month and by 80−85% in summer. Hybrid technology is proposed for the extraction and accumulation of thermal energy from the upper layers of the earth's crust comprised of a shallow borehole heat exchanger, a heat pump, and solar collectors. The technology provides for both the extraction of heat from the rock during the heating period and transmission of this heat to the heating system with a heat pump and the restoration of the temperature field around the well during the interheating period by accumulating in the rock formation the heat fed to the borehole heat exchanger with hot water from the storage tank. This system was implemented in Makhachkala at the test site of the Joint Institute for High Temperatures, Russian Academy of Sciences, for supplying heat and hot water to cottage-type houses. The main components of the system are solar collectors with a total area of 20 m², a heat-insulated hot water storage tank with a built-in heat exchanger, a 15-kW heat pump, and a 100-m deep borehole heat exchanger. The test results have demonstrated high efficiency of the system for supplying heat to low-power consumers not covered by central heating.

Keywords: low-temperature heat, heat transfer, heat pump, solar thermal collector, well, heat exchanger, intermediate heat-transfer medium, rock, renewable energy sources

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Low-temperature heat of the Earth's ground is a ubiquitous and environmentally clean heat source widely used in many developed countries in heat supply systems that use heat pumps. For the extraction of this kind of heat, ground heat exchangers are used [1−5].

To successfully implement heat pump−based heat supply systems equipped with ground heat exchangers, it is necessary to develop heat exchangers of the optimal designs, to investigate the reciprocal influence of the heat pump (HP) and the ground heat exchanger, and to optimize the operating conditions of the plant as a whole. The heat exchangers can be placed in the ground both horizontally at a depth of approximately 3 m and vertically (borehole heat exchangers). Vertical ground heat exchangers are most efficient. As a ground heat exchanger, a vertical borehole may serve (Fig. 1); an extra heat-insulated pipe of a smaller diameter is placed inside it. The intermediate heat-transfer medium (water) goes down the annular space of the heat exchanger and extracts the heat from the surrounding rock formation and, after being heated, rises up the internal pipe.

STUDY OF THE HEAT EXTRACTION FROM ROCK FORMATIONS BY A BOREHOLE HEAT EXCHANGER

The circulation of the intermediate heat-transfer medium in a ground heat exchanger affects the thermal field around the well. The diameter of the thermal field perturbation zone depends on the diameter of the well, the intensity and time of the ground heat exchanger's operation, and the temperature and thermophysical properties of the rock formations and the intermediate heat-transfer medium.
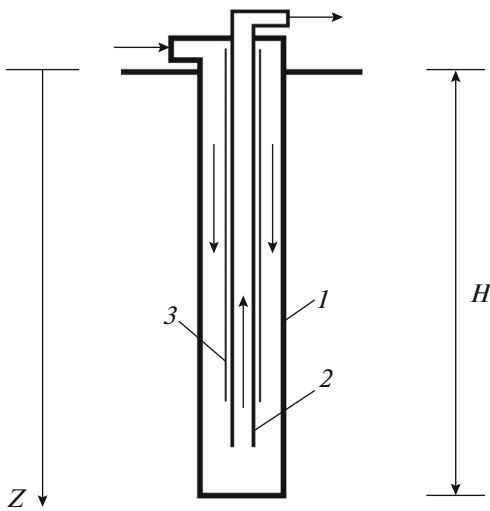
The heat transfer process in a vertical ground heat exchanger is described by the equation

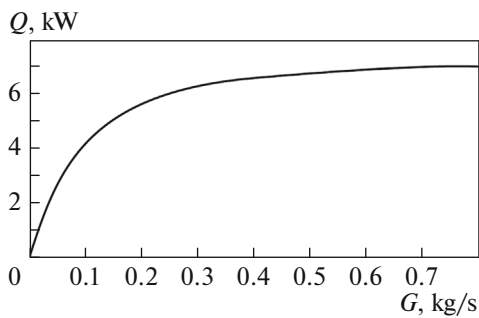$$\frac{dt_1}{dZ} = \frac{k}{Gc_p}(t_0 + \mathrm{G}gZ - t_1) \qquad (1)$$

at the boundary condition

$$t_1(Z = 0) = t_\mathrm{m},$$

where t_1 is the temperature of the intermediate heat-transfer medium (°C), Z is the vertical coordinate (m), k is the linear coefficient of the heat transfer from the

Fig. 1. Vertical ground heat exchanger: (*1*) outer tube string, (*2*) tubing string, and (*3*) heat insulation; (*H*) heat-exchanger depth (m) and (*Z*) vertical coordinate (m).

Fig. 2. Heat extraction Q of the ground heat exchanger as a function of the mass flow rate G of the heat-transfer medium.

rock to the intermediate heat-transfer medium (W/(m K)), G is the mass flow rate of the intermediate heat-transfer medium (kg/s), c_p is the thermal capacity of the intermediate heat-transfer medium (J/(kg K)), t_0 is the temperature of the neutral layer (°C), Gg is the geothermal gradient (°C/m), and t_m is the temperature of the intermediate heat-transfer medium at the heat exchanger inlet.

Solving Eq. (1), one can obtain the final formula for the change in the temperature of the intermediate heat-transfer medium through the depth of the ground heat exchanger as

$$t_1 = t_0 + \text{Gg}Z - \frac{\text{Gg}Gc_p}{k}$$
$$+ \left(t_m - t_0 + \frac{\text{Gg}Gc_p}{k}\right)\exp\left(\frac{kZ}{Gc_p}\right).$$

The circulation of the intermediate heat-transfer medium in a vertical ground heat exchanger affects the thermal field around the well due to the temperature difference between the intermediate heat-transfer medium and the rock formations through which the well is bored. The diameter of the zone of the thermal condition perturbation depends on the diameter of the well, the intensity and time of the ground heat exchanger's operation, and the temperature and thermophysical properties of the rock formations and the intermediate heat-transfer medium.

Theoretically, under circulation of the intermediate heat-transfer medium, the temperature of the rock formations must change at an infinitely great distance from the well. However, in practice, a boundary can always be determined in the bed beyond which the bed preserves its natural temperature.

The effective radius R of the circle inside which the temperature of the rock around the well deviates from the natural distribution can be found by solving the equation of thermal conductivity. In the case in question when the radius of perturbation is much shorter than the depth of the well, we can consider the radial problem for which a detailed solution is provided in a previous work of the authors [6]:

$$R = 2.405\sqrt{a\tau},$$

where a is the temperature conductivity of the rock (m²/s) and τ is the operation time of the well (s).

Then, the linear heat transfer coefficient can be determined by the formula

$$k = \frac{\pi}{\frac{1}{2\lambda_r}\ln\frac{2R}{d_3} + \frac{1}{2\lambda_c}\ln\frac{d_3}{d_2} + \frac{1}{2\lambda_m}\ln\frac{d_2}{d_1} + \frac{1}{\alpha d_1}},$$

where d_3 is the well bore by the drill bit (m); d_2 and d_1 are the inner and outer diameters of the outer pipe string; λ_r, λ_c, and λ_m are the thermal conductivity coefficients of the rock, cement ring, and metal, respectively (W/(m K)); and α is the coefficient of the heat transfer from the inner wall of the outer pipe string to the intermediate heat-transfer medium (W/(m² K).

During the operation of the heat exchanger, the efficiency of the heat extraction from the rock decreases, which is caused by a gradual increase in the effective radius R and a reduction in the heat transfer coefficient k. A 100-m deep borehole heat exchanger being operated for several days is practically equipotent in terms of the heat extraction to a 200-m deep heat exchanger that is continuously operated during the entire heating period. The calculations show that the optimal flow rate of the intermediate heat-transfer medium is 0.5–0.6 kg/s (Fig. 2). A further increase in the flow rate does not practically lead to an increase in the heat extraction from the rock.

The thermal energy extracted from a ground heat exchanger linearly depends on the depth of the heat

exchanger (Fig. 3). The specific heat extraction q from the rock formation per each meter of the heat exchanger depth is $q = 33$ W/m for a 200-m deep heat exchanger operated for 150 days and $q = 60$ W/m for a 100-m deep heat exchanger operated for 1 day.

The obtained data suggest that a heat-pump–based heat supply system with two shallow ground heat exchangers in vertical boreholes that operate alternately in a cycle mode when one well is operated for 1–2 days, while the other is at the standstill to restore the temperature field around it.

The necessity of frequent changeovers of the circulating flow from one well to the other is a significant drawback of a heat-pump–based heat supply system with two wells. However, the capitals costs of a heat-pump–based heat supply system with one 200-m deep well exceed the total costs of two wells 100 m deep each. Furthermore, the operating costs related to the pumping of the heat-transfer medium are higher in a deep well owing to a twofold increase in the frictional head loss through the height of the heat exchanger.

Studies of the cooling of the rock formation during the extraction of heat by a borehole heat exchanger and the restoration of the thermal field in the rock during the idle time of the well in the interheating period have confirmed that the temperature field in the rock during the idle time in summer is restored only partially due to the influx of heat from the rock formations outside the cooling zone [7, 8]. The radius of the rock cooling front in the heating period can reach 6–8 m. It is impossible to completely restore the temperature field around the well during its idle time. The temperature on the borehole wall is restored in a month by approximately 50% and above and by 80–85% in summer; far from the borehole, the restoration process is somewhat delayed reaching lower values. Under such conditions, the problem of complete restoration of the thermal field in the rock around the borehole during its idle time in summer arises.

HYBRID SOLAR–GEOTHERMAL TECHNOLOGY

The technological systems that use renewable energy sources of two and more types have the best prospects for the uninterruptable power supply to the consumers. There are renewable energy sources of one or two types in practically all regions of Russia—with some regions being rich in renewable sources of all types—the commercial operation of which can be economically feasible.

A hybrid solar–geothermal technology for the hot water- and heat supply to low-power consumers not covered by the central heating (Fig. 4) [9] has been developed and patented. This technology comprises solar energy collectors *1*, heat exchanger *3*, storage tank *2*, heat pump *9*, and borehole heat exchanger *14*. The heat-transfer medium (an antifreeze) circulates
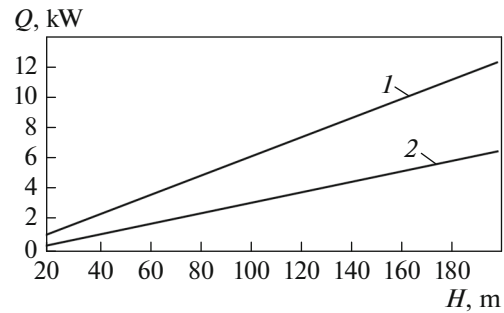

Fig. 3. Heat extraction Q as a function of the heat exchanger depth H at $G = 0.5$ kg/s and operation time of the well of (*1*) 1 day and (*2*) 150 days.
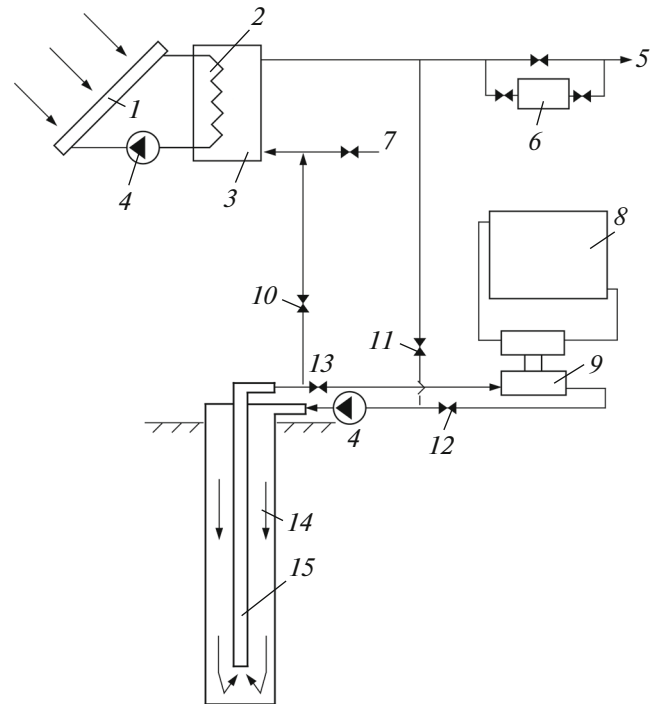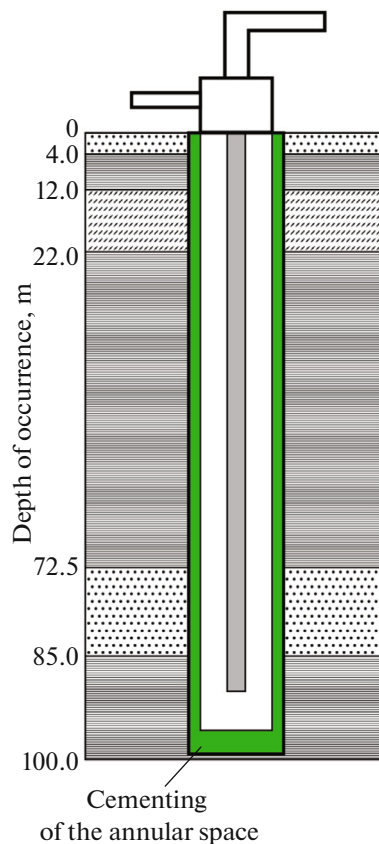

Fig. 4. Solar–geothermal heat- and hot-water supply system: (*1*) solar collectors, (*2*) heat exchanger, (*3*) heat-insulated hot-water storage tank, (*4*) circulating pump, (*5*) hot-water supply line, (*6*) electric heater, (*7*) makeup water from the water conduit, (*8*) power unit of the low-temperature heating, (*9*) heat pump, (*10–13*) valves, (*14*) borehole heat exchanger, and (*15*) heat-insulated tubing string.

through a solar collector where it is heated by solar energy and then transmits thermal energy to water through heat exchanger *3* mounted into storage tank *2*. In the storage tank, hot water is stored until the time it is consumed; therefore, the tank has to be thoroughly heat-insulated. In the primary circuit, where the solar collector is installed, natural or forced heat-transfer medium circulation can be applied. Electric heater *6* is mounted in the hot water supply line. If the temperature in the storage tank falls below the preset tempera-

Fig. 5. Design of the borehole heat exchanger. Rock formations through the depth of occurrence (m): (0–4) sand, (4–12) clay, (12–22) argillaceous sand, (22.0–72.5) clay, (72.5–85.0) sand, and (85–100) clay.

In the summer season, the excess thermal energy in the form of hot water from the storage tank is forwarded to the well for the complete restoration of the temperature in the surrounding rock formation.

In the interheating periods, valves *12* and *13* are closed; with valves *10* and *11* open, the hot water from the storage tank is pumped by a circulating pump into the annular space of the borehole where, as water goes down, the heat exchange with the surrounding formation occurs. Then, the cooled water is fed though the central heat-insulated tube string back into the storage tank. And vice versa, valves *12* and *13* are open and valves *10* and *11* are closed in the heating period.

EXPERIMENTAL SOLAR–GEOTHERMAL SYSTEM

A hybrid solar–geothermal heat and hot water supply system for cottage-type houses was constructed on the test site of the Joint Institute for High Temperatures, Russian Academy of Sciences, in Makhachkala. The system comprises a 100-m deep borehole heat exchanger[1] to extract heat from the rock formation (Fig. 5), 20 solar collectors with a total area of 20 m², a heat-insulated hot water storage tank with a volume of 1.2 m³ with a built-in heat exchanger, a hot water line, and a power unit of the low-temperature heating with a 15-kW heat pump and a circulating pump to pump the intermediate heat-transfer medium.

The system uses new-generation flat solar collectors developed at the Institute for Problems of Geothermal Research and Renewable Energy, a branch of the Joint Institute for High Temperatures, Russian Academy of Sciences (IPGVE OIVT RAN), and manufactured by NPP Resurs-M scientific industrial enterprise. The technical characteristics of the solar collectors are as follows:

Outer dimensions (excluding the pipe branches), mm	1500 × 700 × 60
Absorber area, m²	0.98
Weight (dry), kg	10.5
Working pressure, MPa	0.6
Volume of the absorber plate channels, dm³/m²	1.2
Performance	0.7

In the collectors, advanced heat-resistant polymer materials are used, such as cellular polycarbonate and polypropylene. The collectors consist of a metal tube-

ture due to cloudy weather for a long time or few sunlight hours in winter, the electric heater is switched on and heats water up to the preset temperature.

The power unit of the solar collector is operated year round and supplies the consumers with hot water, while the power unit of the low-temperature floor-heating system with a heat pump and a 100–200-m deep borehole heat exchanger is put into operation only in the heating period.

In the heat pump cycle, cold water at a temperature of 5°C goes down the annular space of the borehole heat exchanger and extracts low-temperature heat from the surrounding rock formation. Then, water heated to 10–15°C depending on the borehole depth rises up the central tube string to the surface. To prevent the reverse heat flux, the central tube string is heat-insulated from the outside. On the surface, water from the borehole enters the heat pump evaporator where the low-boiling working medium is heated and evaporated. Downstream from the evaporator, the cooled water is returned to the borehole. During the heating season, the rock formation surrounding the borehole is gradually cooled under constant circulation of water in the borehole.

in-sheet adsorber and a transparent coating of 4-mm-thick cellular polycarbonate. The protection of the back side is made of cellular polypropylene; mineral wool is used as the heat insulation. The side rails of the collector are manufactured of custom-designed aluminum sections. For the best implemented project, the collector was awarded a gold medal at the 9th Moscow International Show of Innovations and Investments. Currently, such collectors are being widely used in the south of Russia in solar water-heating plants for various applications.

The storage tank can hold a 3-day reserve of hot water for four persons. Inside the tank, a metal heat exchanger is installed that, together with the collectors, forms the closed primary circuit filled with a nonfreezing liquid. This ensures the operability of the system in the winter season. For long periods lacking in solar radiation, the system is provided with a backup electric water heater that is automatically switched on as the temperature in the hot-water supply system falls below the preset value.

The ground coupled storage is a vertical borehole with the following characteristics:

Depth, m	100
Diameter, mm	146
Inner PVC tube diameter, mm	54
Tube thickness, mm	7
Annular clearance, mm	38

The heat-transfer medium (water) is fed year round into the annular clearance between the tubing string and the borehole. In the heating periods, heat is extracted from the rock formation; in the inter-heating period, the thermal field in the rock around the borehole is restored. Inline with the borehole, a 15-kW MSR-J043WHC "water–water" heat pump is installed.

The solar collectors are designed to supply hot water in the winter period when the sunshine is minimal. As a result of the thermal design calculations, the area and the number of the collectors were increased somewhat. In the summer period, the excess thermal energy in the form of hot water from the storage tank is fed into the well for the complete restoration of the temperature in the rock around the well.

The solar collectors were tested under a constant flow rate of the heat-transfer medium. This is the most widely applied operating mode for solar water heating systems in which the circulation of the heat-transfer medium is affected by a pump. The tests were conducted on sunny days from September 10 to September 25, 2019. In the course of the tests, the temperature of the heat-transfer medium at the collector inlets and outlets, the solar radiation flux density, and the outside temperature were measured. The collectors numbered 20; their total area was 20 m^2. The circulating pump output was 0.08 kg/s. The collectors in the system were connected in parallel; the consumption rate of the heat-transfer medium through a collector was 0.004 kg/s. The system was operated to store heat in the storage tank. During the tests of the collectors, heat was not extracted to supply heat and hot water and was not transmitted to the ground coupled storage either.

According to the test results, the daily output of a collector on a sunny September day equaled 14.24 MJ/m^2 at a total daily solar radiation on the collector surface measured in the course of the tests of 23.4 MJ/m^2. Consequently, the daily average performance of the collectors was 0.62 with a daily average temperature of the heat-transfer medium in the collectors of approximately 56°C.

Simultaneously, trial pumping of the heat-transfer medium into the borehole heat exchanger was conducted. Before that, the ground around the borehole was not heated by pumping the heat-transfer medium, and the rock had the natural temperature of the borehole that gradually increased from the wellhead to the bottom from 15.0 to 18.5°C. The heat exchanger was fed with artesian water with a temperature of 29°C drawn for household use and drinking out of a separate 400-m-deep well on the test site of the Joint Institute for High Temperature. The water was pumped at a rate of 0.33 kg/s; at the well outlet, the temperature of the pumped-in water decreased to 21°C, which is evidence of successful accumulation of heat in the rock.

We should note that, to restore the temperature in the rock in shallow wells in the summer period, surface water preliminarily heated by solar heat in an outdoor pool can be successfully used.

The thermal energy generated by solar collectors is consumed completely; in the summer period, part of the thermal energy, which is irretrievably lost in solar systems of other designs, is stored in the proposed system in the ground coupled storage and fed in the heating period by the heat pump to heat the houses.

The heat-pump–based heat supply systems with vertical ground heat exchangers can be successfully applied to develop environmentally clean decentralized heat and hot water supply systems and to supply heat to rural consumers. The borehole heat exchangers do not require allocation of considerable land parcels and can be constructed beneath house footings or in close proximity to the house. The widespread application of these heat-supply technologies will allow for the solution of not only complicated problems related to the purchase and delivery of energy carriers to remote residential areas but also some social problems in the countryside.

The surface soil layers are a rather universal and ubiquitously accessible source of low-temperature heat; in Russia, there are unlimited possibilities of applying heat-pump–based heat supply technologies that use vertical ground heat exchangers. Currently, in the country there exist more than 30 million individ-

ual heat generators comprised, as a rule, of low-performance equipment that cause increased emissions of pollutants and have to be rejected in the near future. The widespread introduction of solar–geothermal heat-supply systems that use vertical borehole heat exchangers will be a promising way to solve the problem.

CONCLUSIONS

(1) According to the results of tests, the hybrid technology for the extraction and accumulation of thermal energy of the upper layers of the earth's crust comprised of a shallow borehole heat exchanger, a heat pump, and solar collectors proposed for the heat- and hot-water supply of cottage-type houses and implemented on the test site of the Joint Institute for High Temperatures in Makhachkala has demonstrated high efficiency in supplying heat to low-power consumers not covered by central heating.

(2) The final choice of the hybrid heat-pump–based heat-supply system, its operating conditions, and the depth and number of borehole heat exchangers depend on the thermal power demand and the results of the technical and economic feasibility study considering the capital and operating costs as well as geological and thermophysical properties of the rock in the borehole.

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