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Raising Efficiency of Petrothermal Source of Energy Through Using Heat Accumulators.

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ABSTRACT

The key data is presented on efficiency of extraction of deep geothermal energy. A schematic diagram is presented of a source of energy based on the Earth's heat. The main concepts, characteristics and fields of heat accumulators are presented. A classification and characteristics of heat-accumulating materials used in heat accumulators are presented, along with their advantages and disadvantages. A type of heat accumulator is chosen to be used with a petrothermal energy source, and the efficiency of the energy source is determined.

Keywords: petrothermal, heat, energy.

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INTRODUCTION

The XXI century is characterized by accelerated development of industrial production, as well as scientific improvement and innovative growth. However, along with the above positive aspects, issues arise of depletion of conventional energy sources, as well as negative impact produced by their use on natural environment, which casts a doubt on further development, or even the very existence of our planet. Stricter requirements to conservation of environment lead to search for new energy sources [1].

Huge amounts of energy are consumed in the world every year: on average, 9 to 20 billion tons of hydrocarbon fuel is burnt annually, 78% of all the consumed energy accounted for fossil fuels (34% - oil, 25% - coal, 19% - natural gas), 5% – NPP, 6% - HPP, 11% - other sources of energy [1].

At the same time, today, the opportunities of obtaining energy from natural renewable energy sources – solar energy, energy of wind, energy of biomass, energy of smaller rivers, tidal energy, wave energy, as well as energy determined by the difference of temperatures at different depths of the ocean, and geothermal energy – are not used to the full extent. Besides, RES include, among others, various waste and sources of low-potential energy combined with heat pumps [2]. High environmental safety and renewability are the main advantages of RES. According to the expert estimations, Russia's economic potential makes 270 mln tons of reference fuel (t.r.f.)/year [3-4]:

- geothermal energy – 115 mln t.r.f./year;
- smaller hydroelectric plants – 65,2 mln t.r.f./year;
- low-potential heat – 36 mln t.r.f./year;
- biomass – 35 mln t.r.f./year;
- solar energy – 12,5 mln t.r.f./year;
- wind energy – 10 mln t.r.f./year.

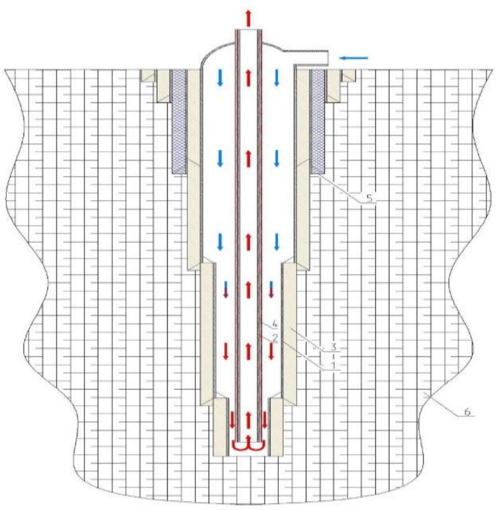
However, the aforesaid non-conventional energy sources are characterized by considerable heterogeneity of distribution over the territory of Russia, and dependence on climatic and seasonal factors. The most promising for uninterrupted electric power supply of autonomous consumers is petrothermal energy of the Earth's interior (the heat of dry rocks of the Earth located at depths over 2,000 m).

The thermal characteristic of deep rocks is temperature gradient, which is expressed in a rise of temperature of deep rocks with increase of depth. On average, this parameter is about 30-60 ^{0}C per km, but in some cases may reach 100 ^{0}C per km of depth [5]. Therefore, at the depth of 3 km, the temperature of rocks amounts to 90 to 180 ^{0}C, while at depths to 7,000 m, the temperature of interior may be within the range of 210 to 420^{0}C. This temperature potential is sufficient for supplying different consumers with thermal and electric power energy.

Description of single-well collection system for geothermal heat and its energy scheme

For extraction of thermal energy, it is sufficient to have one well, where a single-well collection system is created, which looks like two coaxial empty cylinders formed by an outer (casing) string of pipes and an inner extracting pipe [6]. While flowing along the annulus, the heat transfer fluid is heated, whereupon it comes into the extraction pipe in the lower part of the system and is transported up to the surface to energy-generating equipment. The schematic diagram of the single-well collection system is presented in fig. 1.

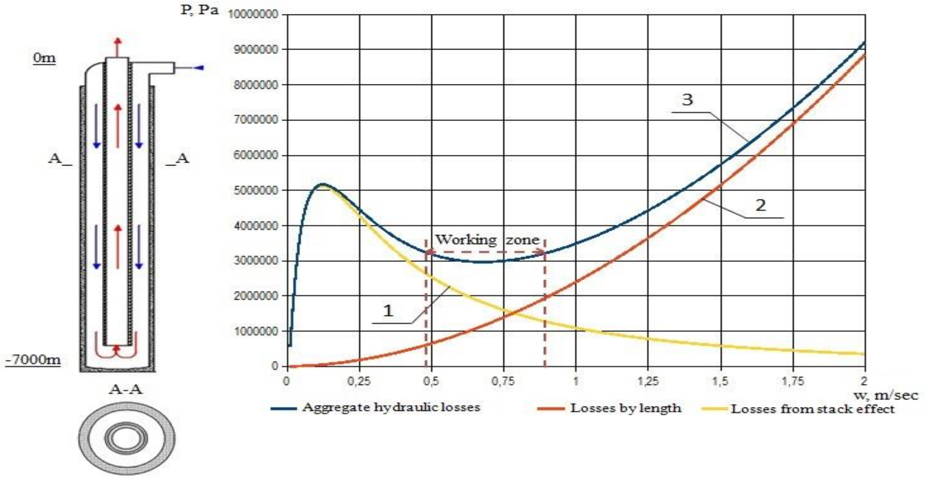
Cold heat transfer fluid, when coming into the annulus, may, under certain conditions, have a temperature below the temperature of deep rocks surrounding the well, which could result in cooldown of the heat transfer fluid. To prevent this from happening, the single-well system is thermally insulated with thermal insulating plugging concrete to a depth, where the temperature of the heat transfer fluid corresponds to the temperature of surrounding deep rocks.



1-outer (casing) string of pipes, 2-inner extraction string of pipes, 3-plugging concrete, 4-thermal insulation of inner extraction pipe, 5-thermal insulating plugging concrete, 6-deep rocks

Fig. 1 – Structural design of single-well system for collection of deep geothermal energy

As the single-well collection system is rather long (its aggregate length can be as large as 14 km), it has a considerable hydraulic friction, which directly affects the amount of electric energy spent on pumping the heat transfer fluid. The hydraulic friction of the single-well system consists of the friction along the length of the system, local frictions and the stack effect arising due to the difference in the density of the heat transfer fluid in the upper and lower parts of the collection system. For a long system, local frictions make a marginal contribution to the overall value of hydraulic friction. An example of variation of hydraulic friction at different flow rates of heat transfer fluid is presented in fig. 2. As can be seen from fig. 2, on the resulting curve of hydraulic losses depending on the heat transfer fluid flow rate, one can distinguish the values, at which the expenses related to own needs will be kept to the minimum; there, the heat transfer fluid flow rates lie within the range of 0.5 to 0.8 m/sec. As the geometry of the collection system (the diameter of the casing and the inner coaxial string of pipes) is limited by possibilities of existing drilling technologies, the optimum heat transfer fluid flow rate actually determines the optimum flow rate of the medium, at which the maximum efficiency of the single-well collection system will be achieved.

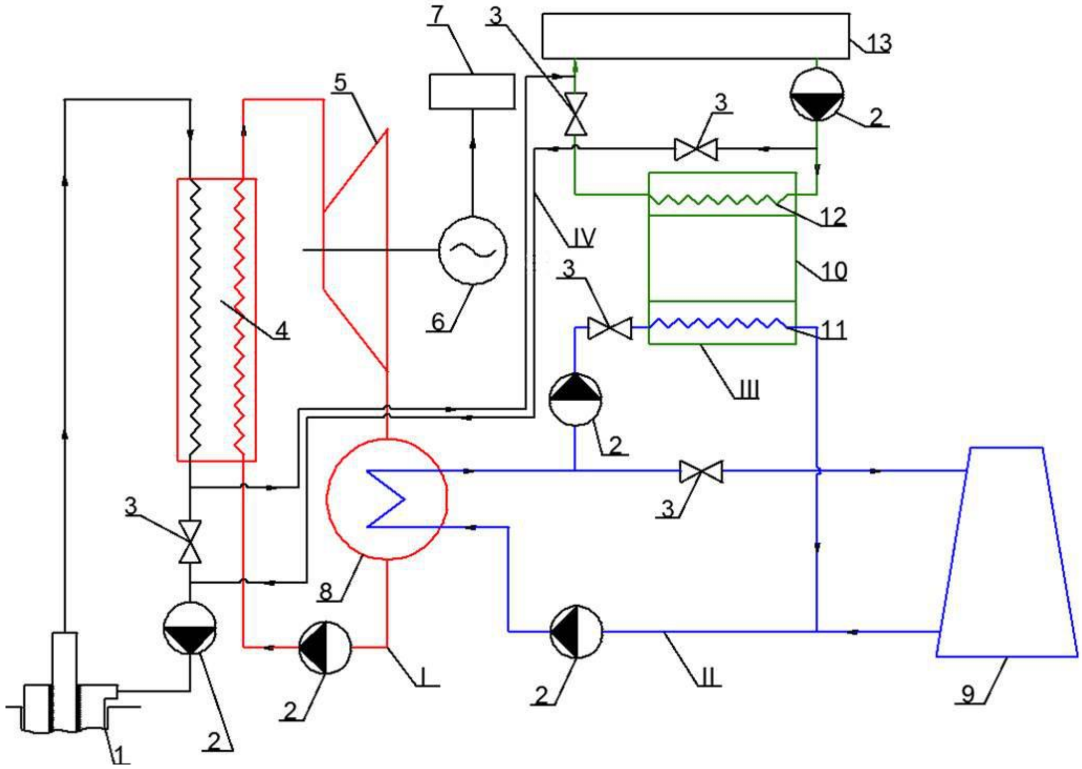


1-pressure losses for compensation of difference of density of heat transfer fluid in the upper and lower parts of single-well collection system, 2-pressure losses along the length of single-well collection system, 3-aggregate hydraulic losses of single-well system for collection of deep geothermal energy

Fig. 2 – Example of effect produced by the flow rate of heat transfer fluid along the single-well collection system on hydraulic friction of the system at the depth of 7000 m and temperature gradient 5 °C/100m

As the depth of the well drilling affects the capital costs considerably (making up to 70% of initial cost), when creating an energy source of this kind, one must use the minimum accessible depths, with the temperature of rocks sufficient for generation of thermal and electric energy.

It is expedient to generate electric energy using turbines based on low-boiling working media (LBWM), as the required temperature of the heat transfer fluid at the output of the single-well system would in this case be 90^0C, or higher. Given the aforesaid, the specialists of the NRU MPEI have developed a schematic diagram for generation of thermal and electric energy based on using petrothermal heat (fig. 3).



I-Working circuit of a turbine based on low-boiling working media (LBWM), II-Cooling circuit of a turbine based on LBWM, III-Cooling circuit of a turbine using a heat-pumping system (HPS), IV-Circuit of direct thermal supply of consumers 1–Well heat exchanger, 2–Circulation pump, 3–Shutoff and control valves, 4–Evaporator of a turbine based on low-boiling working medium (LBWM), 5-LBWM-based turbine, 6-Generator, 7-Consumer, 8-Condenser of a turbine based on LBWM, 9 – Cooling tower, 10-Heat-pumping system, 11-Evaporator of heat-pumping system, 12-Condenser of heat-pumping system, 13-Consumer of thermal energy.

Fig. 3 – Schematic diagram of a double-circuit petrothermal TPP, with the closed method of extraction of deep geothermal energy

In the diagram presented in fig. 3, the heat-supplying plant is constituted by a heat-pump system (HPS) and a circuit connected to the heat transfer fluid from the single-well system for collection and transportation of deep geothermal energy. The HPS is installed on the turbine's cooling circuit. This solution enables to efficiently use the heat of the condenser of the turbine in low-boiling working medium. However, in case of a failure of heat pumping equipment due to mechanical malfunctions or seasonal decrease of thermal load of consumers, a separate cooling plant of the turbine condensation circuit must be provided, which may be constituted by a cooling tower.

Comparing and selection of heat accumulators to raise the efficiency of petrothermal source of energy

With the thermal power of the HPS insufficient, the takeoff of the heat may occur directly from the thermal heat fluid of the single-well collection system, which enables to cover peak loads in case of a considerable fall of the ambient temperature compared to the designed values. Yet, in this case, the amount of heat brought to the turbine evaporator would be lower, which, in its turn, would adversely affect the service life of the turbine equipment. For peak loads to be covered, the schematic diagram must provide for a heat accumulating device installed upstream of the turbine evaporator for accumulation of excessive heat at the periods of the minimum consumption of electric and thermal energy, and for release of thermal energy at the periods of its maximum consumption. Using a heat accumulator will enable:

- to raise reliability of power-supplying of consumers;
- to ensure continuous designed operating conditions for the turbine equipment;
- to decrease the installed thermal power of the single-well collection system owing to covering the peaks of consumption of thermal energy;
- to ensure continuous flow rate of heat transfer medium in the single-well collection system, which would be the optimum in terms of expenses related to own needs.

As of today, there exist various heat accumulating devices, which are used both in industry and in systems of supplying power to consumers [7-8]. Conventionally, a heat accumulator (HA) may be regarded as a system made up of two main components: a structure containing a heat accumulating material (HAM), and an outer layer of thermal insulation. The efficiency of operation of the HA is mostly determined by the value of specific stored energy and the rate of the cooldown of HAM in the standby mode. This determines two main directions in selection of HA for the energy source based on the Earth's petrochemical energy:

- selection of the optimum combinations of thermal insulation materials for the HA,
- selection of HAM based on its properties.

At present, a large number of thermal insulating materials are commercially produced and developed for construction and other needs. These include organic cotton wool, loose, aerated materials, in particular, various models of foamed polyurethanes. Besides, as an insulating layer of HA, there may be used expanded perlite sand, aerated concretes, basaltic fiber, asbestos, materials of expanded rocks and others. As a rule, the thermal insulating material is chosen based on conditions of assuring the required level of losses and cost. In some cases, thermal insulation is subject to specific requirements, including those on weight and dimensions, and vibration resistance, which makes necessary development of its new types.

By the type of processes unfolding in HA, they distinguish thermal capacity accumulation, thermal-chemical accumulation and accumulation through using the heat of phase transition [7,9].

In case of thermal capacity accumulation, the amount of accumulated energy depends on the temperature, by which the heat accumulating material is heated, and its specific thermal capacity.

Today, there are widely used [9] both solid accumulators and those, where water or steam act as the working medium. The cost-efficiency of their application in systems of power-supplying autonomous consumers, in particular, involving use of renewable energy sources, has been confirmed on multiple occasions [7,10,11,12]. Heat accumulators using water may have a specific stored energy above 300 kJ/kg owing to high specific thermal capacity of water (4.187 kJ/(kg·K)). Besides, for accumulation of heat, metals, natural and artificial rocks, chemical compounds may be used, whose specific thermal capacity is lower than that of water and generally lies within the range of 0.5..2 kJ/(kg·K). Yet, due to the possibility of heating up to high temperatures, such systems may have a specific stored energy at 180…1.440 kJ/kg.

Systems operating based on the thermal capacity principle of energy accumulation are characterized by a low value of specific stored energy, or a considerable difference in temperatures of the charged and discharged HA [9], which results in considerable limitations on the scope of application of such heat accumulators.

There are known systems involving use of the thermal-chemical method of accumulation, which have no such shortcomings. At the same time, the HAM used therein are characterized by values of specific stored energy at 250…1,000 kJ/kg [13]. The heat is stored through production of a chemical or chemical-physical process resulting in obtaining energy-saturated products, where the energy brought to the system from the primary energy source is stored.

At present, widely used are compositions based on sodium sulfate [14], aluminosilicates or hydrates of salts [13]. The shortcoming of the systems based thereon lies in unstable physical and chemical properties in the course of melting/solidification, as well as a high cost of both the thermal chemical HAM, as such, and the corrosion-resistant elements of the HA structure. E.g., one of significant flaws of mirabilite (Glauber salt – $Na_2SO_4{\cdot}10H_2O$), apart from its being prone to overcooling, is the nature of the melting process, which results in stratification of solid and liquid phases, with precipitation of residue. This entails a smaller enthalpy of phase transition with an increase in the number of "melting-crystallization" cycles, and reduces the efficiency of heat exchange related to precipitation of solid phase onto the heat transfer surface. The reversibility of phase transition is stabilized with introducing additives acting as crystallization nodules into the mass of the HAM.

Aluminosilicates are used in HA owing to a high attainable specific surface area (600 m^2 per gram), volume of pores (0.8 cm^3 per gram) and diameter of pores (4.7 nm) [13,15]. Hydrates of salts are used in HA owing to their availability and a wide temperature range. Such HA are charged-discharged in the course of dehydration and hydration. Today, the most widespread HAM are: potassium chloride hexahydrate ($CaCl_2$ $6H_2O$), barium hydroxide octahydrate ($Ba(OH)_2{\cdot}8H_2O$), and anhydrous lithium nitrate ($LiNO_3$), as these are able to absorb water with a high heat release.

The advantage of heat accumulators of thermal-chemical type, compared to thermal capacity ones, is their better weight and dimension parameters, with a wide selection of possible working temperature ranges.

The third method of accumulation of thermal energy is based on using phase-change materials (PCM) [16]. The advantage of structures of HA based on them is a small range of temperature variation at charge-discharge and a high value of specific stored energy 200...1,000 kJ/kg depending on the material. Widely used are such materials as ceresin, paraffin, wax, crystalline hydrates [17,18,19].

Paraffins have the heat of phase transition at 144...189 MJ/m^3. Their important shortcoming is low thermal capacity (about 2 kJ/kg·K) and thermal conductivity in the solid state. Hence, the popularity of structures of HA with capsules of metals accommodating the HAM, as such, which enables to increase the area of the surface of interaction between the HAM and the heat transfer fluid.

Using hydrates of salts as PCM is associated with solving a number of technical problems. As a rule, melting leads to formation of a liquid saturate phase and a slid phase in the form of hydrate of the same salt, which would precipitate as a residue. Besides, melts of hydrates of salts are prone to overcooling followed by explosive crystallization, which can lead to mechanical damage of HA. To ensure crystallization with low overcooling of fluid, it is necessary to use substances acting as primary crystallization nodules. To block separation of phases, either thickening agents are used, or intense agitation in the course of heat exchange, which is not always convenient at operation. Another shortcoming of crystalline hydrates is their high corrosive activity [13,15].

Alloys of light metals, as well as their compounds (hydrides, fluorides, silicates) have the highest values of heat of phase transition among all the PCM [15]. However, phase transitions of these materials occur at temperatures of 300...3,000°C, which imposes limitations on possibilities of their practical application in thermal supply systems. Among their shortcomings, one can name a considerable variation of volume at melting and release of hydrogen by hydrides in the course of charging of the HA.

Characterized by specific properties is sodium acetate (CH_3COONa), which, when subjected to mechanical impact in the liquid state, result in phase transition involving release of heat, causing its conversion into the solid state (the reverse transition is possible, if heated to 85°C). Heat released in the material may be controlled with crystallization arranged at appropriate time through mechanical impact. However, the relatively low temperature of heat release (under 50°C) limits its applicability. Special materials are known to be used, which raise the temperature of exothermal reaction to 60…70°C and the heat of phase transition (crystallization) to 300 kJ/kg [18].

One of the key characteristics of PCM is the temperature range of their operation, which determines possible options of their application. Traditionally, they distinguish 4 groups of materials and HA based thereon [20]:

1. accumulators for generation of cold (T < 20°C);
2. low-temperature accumulators (20°C ≤ T < 200°C);
3. medium-temperature accumulators (200°C ≤ T ≤ 500°C);
4. high-temperature accumulators (T > 500°C).

Additionally, HA are classified according to the temporal factor of their application – the duration of the charge-discharge cycle. They are divided into hourly and daily accumulators of short-term action and seasonal accumulators of long-term action. The duration of a cycle of operation of a short-term action accumulator would not exceed 24 hours. In seasonal accumulators of long-term action, the duration of the charge-discharge process may reach a year. In terms of design, the main difference between the above-mentioned types of heat accumulators is their overall dimensions, which is determined by the necessity of accumulation of different amounts of heat.

CONCLUSIONS

Given the aforesaid, the most promising (for application in the thermal arrangement of an energy source based on petrothermal energy) are thermal energy accumulators based on phase transition, which is due to the following factors:

- permanent temperature of heat transfer fluid downstream of the heat accumulator in case of the latter's discharge, which ensures uninterrupted operation of the thermal arrangement of the energy source;
- sufficient density of thermal energy being stored;
- low cost of phase-change material and simple design of heat accumulator.

Therefore, application of heat accumulators based on phase transition enables to meet the above requirements and to raise the efficiency of using the Earth's deep geothermal energy.

Under the performed theoretical calculation of efficiency of energy source with the Earth's petrothermal energy used based on a turbine with LBWM, with the temperature of the heat transfer fluid at the output of the single-well collection system being 120^0C will be 58.3%, and with the fluid transfer fluid temperature rising up to 140^0C, would increase to 59.8%. Therefore, using the deep geothermal energy enables to efficiently solve the problems of power-supplying remote and standalone consumers, improve energy security and reduce the environmental load.

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