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Increasing the efficiency of geothermal energy utilization in oil wells

Zwiększenie efektywności wykorzystania energii geotermalnej w odwiertach naftowych

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ABSTRACT: Based on the application of heat balance equations for flow in the hydraulic channels of the riser pipes and the annulus, the coolant temperature was determined for different ratios of working medium flow rates, oil well depths, and standard tubing string sizes. The extreme nature of the dependence of coolant temperature on its flow rate was established. The coolant temperature increases with increasing well depth according to a nonlinear dependence. The use of a riser string with a larger diameter reduces the coolant temperature at the well outlet. The efficiency of heat extraction increases when well backwashing is implemented. Taking into account the results of the conducted research, a pump-circulation system scheme for extracting thermal energy from an oil well is proposed. The pump-circulation system includes a jet pump with hydraulically separated lines for supplying the injected and mixed flows. The additional circulation circuit created by the jet pump increases the flow rate of the working medium during the lifting of the heated coolant. The procedure for determining the operating mode of the jet pump is implemented using an automated algorithm developed in the Python programming language. The speed of lifting the heated coolant increases with an increase in the injection coefficient of the jet pump while maintaining the same speed and flow rate of the working flow entering the well. Concurrently, the duration of heated coolant transportation decreases, as does the amount of heat loss, while the temperature of the coolant exiting the oil well increases. The operating characteristics of a downhole jet pump are limited by its ability to generate the required pressure. The minimum required flow rate of the working flow, the maximum permissible diameter of the working nozzle, and the depth of placement in the well determine the application range of the jet pump.

Keywords: oil well, geothermal energy, petrothermal well, coolant temperature, heat balance, jet pump, ejection system.

STRESZCZENIE: Na podstawie równań bilansu cieplnego dla przepływu w kanałach hydraulicznych rur wydobywczych oraz w przestrzeni pierścieniowej wyznaczono temperaturę czynnika chłodzącego dla różnych stosunków natężenia przepływu medium roboczego, głębokości odwiertów naftowych oraz standardowych rozmiarów rur wydobywczych. Stwierdzono ekstremalny charakter zależności temperatury czynnika chłodzącego od jego natężenia przepływu. Temperatura czynnika chłodzącego rośnie nieliniowo wraz ze wzrostem głębokości odwiertu. Zastosowanie rury wydobywczej o większej średnicy powoduje obniżenie temperatury czynnika chłodzącego na wylocie z odwiertu. Sprawność odbioru ciepła wzrasta przy zastosowaniu płukania wstecznego odwiertu. Uwzględniając wyniki przeprowadzonych badań, zaproponowano układ pompowo-cyrkulacyjny do odprowadzania energii cieplnej z odwiertu naftowego. Układ ten wykorzystuje pompę strumieniową z hydraulicznie oddzielonymi przewodami doprowadzającymi strumień wtryskiwany i mieszany. Dodatkowy obieg cyrkulacyjny utworzony przez pompę strumieniową zwiększa natężenie przepływu medium roboczego podczas podnoszenia ogrzanego czynnika chłodzącego. Procedura wyznaczania trybu pracy pompy strumieniowej jest realizowana za pomocą zautomatyzowanego algorytmu opracowanego w języku programowania Python. Prędkość podnoszenia ogrzanego czynnika chłodzącego wzrasta wraz ze wzrostem współczynnika wtrysku pompy strumieniowej przy zachowaniu tej samej prędkości i natężenia przepływu strumienia roboczego wpływającego do odwiertu. Jednocześnie skraca się czas transportu podgrzanego płynu chłodzącego, zmniejsza się ilość strat ciepła, a temperatura płynu chłodzącego na wylocie z odwiertu wzrasta. Charakterystyka pracy pompy strumieniowej jest ograniczona jej zdolnością do wytworzenia wymaganego ciśnienia. Minimalne wymagane natężenie przepływu roboczego, maksymalna dopuszczalna średnica dyszy roboczej oraz głębokość umieszczenia w odwiercie determinują zakres zastosowania pompy strumieniowej.

Słowa kluczowe: odwiert naftowy, energia geotermalna, odwiert petrotermalny, temperatura czynnika chłodzącego, bilans cieplny, pompa strumieniowa, system wyrzutu.

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Introduction

According to Precedence Research (Canada, India) (Annual report Code 1769, 2023), the global geothermal energy market size is expected to grow to approximately USD 9.8 billion in 2032, compared to USD 5.99 billion in 2022. Geothermal resources can be integrated into all types of electricity generation systems, ranging from large interconnected continental power grids to local heat generation in small isolated settlements and autonomous buildings. The growth of geothermal energy consumption will contribute to reducing fossil fuel use and greenhouse gas emissions. However, geothermal resources currently account for only 1% of global energy production (Livescu and Dindoruk, 2022). The efficiency of geothermal energy use can be increased through the utilization of decommissioned oil and gas wells.

The concept of using petrothermal energy stored in hot rocks was proposed at Los Alamos Laboratory (USA) in 1970 (Mortensen, 1978; Tester et al., 2006; Sowiżdżał et al., 2021). According to this concept, the main elements of the petrothermal system are injection wells, into which a “cold” working medium is pumped, and production wells, from which the heated coolant is extracted. Currently, there are 29 million inactive wells worldwide, which constitute a source of environmental pollution (Groom, 2020). Utilizing the thermal potential of existing oil and gas wells significantly reduces capital investments in the project, thereby decreasing both the payback period and the cost of geothermal energy extraction. The energy output of oil-thermal wells is insufficient for operating traditional steam turbines, which require working medium temperatures exceeding 160°C (Abesser et al., 2020). However, the use of low-temperature coolants for direct space heating and for the implementation of various thermodynamic processes in agriculture is economically justified. A significant advantage of petrothermal energy utilization lies in the possibility of geothermal heat use rather than electricity generation, within the framework of decarbonization scenarios and the Energy Strategy for global economic development until 2050 (Ejderyan et al., 2020).

Experience from the industrial use of geothermal well systems demonstrates the stability of thermal energy generation. After 20 years of operation of a geothermal well for residential heating (Xi’an, northern China), the average outlet water temperature decreased by only 0.99°C (Deng et al., 2020). Petrothermal energy can also be used in the operation of existing wells. In particular, the application of downhole hydroturbine thermoelectric generators reduces electricity consumption for powering deep pumping equipment and other well-related electrical consumers (Gabdrahmanova and Izmailova, 2019). The advantage of using thermal turbines is the ability to exploit low-temperature wells with geothermal gradients not exceeding 0.02–0.025°C/m and bottomhole temperatures of 45–50°C.

The presence of a large number of inactive oil and gas wells, the stability of geothermal heat generation, and advances in low-temperature coolant technologies highlight the relevance of research aimed at improving the efficiency of petrothermal energy utilization.

The extraction of geothermal energy from decommissioned oil and gas wells involves the use of a single geothermal system, which may be more economical than system employing two wells (injection and production). In such systems, a cold coolant is injected through a tubing string into a well drilled in a hot rock massif. As the coolant moves along the well, it is heated by heat flow from the surrounding rock and directed toward the wellhead. The tubing string used for coolant injection may have a traditional coaxial, single U-shaped, or double U-shaped configuration. The use of idle oil and gas wells allows for the elimination of substantial capital costs associated with the construction and arrangement of geothermal systems (Brown et al., 2024). Under favorable conditions, single-well geothermal systems are 3–6 times more economical than thermal and nuclear power plants (Dzuvaliakov and Zbrueva, 2017).

Current research in geothermal energy development is primarily focused on determining the thermophysical properties of rocks and heat transfer mechanisms within the oil and gas contour (Gnatus et al, 2011), assessing the potential of petrothermal resources (Wagner et al, 2015), and developing techniques and technologies for constructing high-efficiency geothermal power plants (Falcone et al, 2018). Despite the substantial body of research on petrothermal energy deployment, technologies for direct heat extraction during working medium movement in pump-circulation systems of oil and gas wells remain insufficiently studied. Significant heat losses during the heating of the working medium in low-temperature wells limit the effectiveness of petrothermal energy technologies and reduce their economic attractiveness.

The purpose of this research is to determine the influence of petrothermal well design features and flushing regimes on the coolant temperature at the inlet of surface geothermal installations, as well as to develop measures to reduce heat losses in the upward coolant flow. Achieving this objective involves developing an analytical method for determining the coolant temperature at the outlet of a decommissioned well, performing a comparative analysis of the obtained results with data from industrial research, and establishing the influence of design and operational factors on the efficiency of low-temperature geothermal energy utilization. Given the need to improve the efficiency of low-temperature geothermal energy use, an additional objective of the study is to develop and determine the characteristics of a well ejection system aimed at reducing heat losses in the upward flow of heated coolant while maintaining a constant downward flow rate.

Research methods

Methods for studying the efficiency of utilizing low-pressure geothermal energy in oil wells involve the development of a methodology for calculating the coolant temperature in the well and a method for reducing heat losses in the flow of heated coolant during its upward movement in the well.

Methodology for calculating the coolant temperature in the well

When modeling the process of geothermal energy utilization, the following assumptions were made:

- the rock temperature is assumed to be constant along the well and in the near-wellbore zone and is equal to an average value;
- the temperature distribution along the well approaches linearity over time;
- the tubing string in the well is placed concentrically.

Given these assumptions, the proposed model is approximate, has a probabilistic nature, and allows the identification of trends in coolant temperature under the influence of individual operational factors.

In determining the coolant temperature, the following initial data were used:

- specific heat capacity of the coolant (technical water) $C_p = 4190$ J/(kg · °C);
- heat transfer coefficient through the wall of the tubing string $k_t = 58.2$ W/(m^2 · °C);
- heat transfer coefficient through the wall of the casing string $k_\tau = 14–18.6$ W/(m^2 · °C);
- temperature gradient $G_t = 0.04$°C/m;
- coolant temperature at the well inlet $t_1 = 15$°C;
- average temperature of the neutral layer of rocks $t_0 = 14.5$°C;
- casing string diameters: 0.168 m, 0.28 m;
- tubing diameters: 0.0483 m, 0.0603 m, 0.073 m, 0.089 m, 0.1016, 0.1143.

The mass flow rate of the coolant varied in the range from $G = 2$ kg/s to $G = 6$ kg/s, and the well depth varied from $H = 1000$ m to $H = 3000$ m.

The calculation scheme for determining the coolant temperature during direct and reverse well flushing differs in the flow directions (Figure 1).

The heat balance equations for direct well flushing have the form:

$$GC_p(t_2 - t_1) = k_t F_t\left(\frac{t_2 + t_3}{2} - \frac{t_1 + t_2}{2}\right) \tag{1}$$

$$GC_p(t_2 - t_3) =$$
$$= k_\tau F_A\left(t_{ra} - \frac{t_2 + t_3}{2}\right) + k_t F_t\left(\frac{t_1 + t_2}{2} - \frac{t_2 + t_3}{2}\right) \tag{2}$$

where:

G – mass flow rate of the coolant [kg/s],
C_p – specific heat capacity of the coolant [J/(kg · °C)],
t_1, t_2, t_3 – coolant temperature at the well inlet, at the bottom and at the well outlet [°C],
t_{ra} – average rock temperature [°C],
k_t, k_τ – heat transfer coefficients through the walls of the tubing and casing strings, respectively [W/(m^2 · °C)],
F_t, F_c – surface areas of the tubing and casing strings, respectively [m^2].

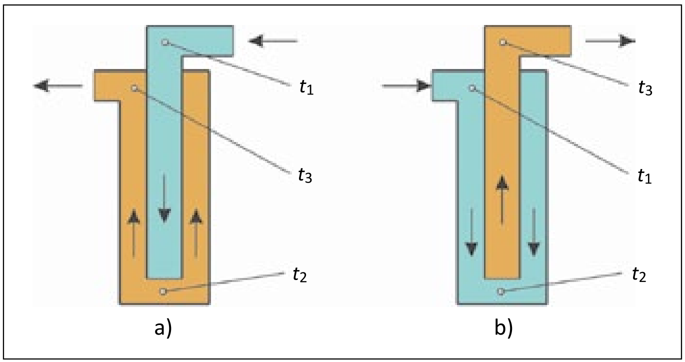


Figure 1. Calculation scheme for determining the coolant temperature during direct (a) and reverse (b) well flushing:
t_1 – coolant temperature at the wellhead inlet,
t_2 – coolant temperature at the bottom of the well,
t_3 – coolant temperature at the wellhead outlet

Equation (1) describes the heat balance of the coolant in the tubing string, whereas equation (2) – in the annulus. The expressions on the left-hand side of equations (1), (2) determine the amount of heat received by the coolant in the tubing string and the annulus, respectively. The expression on the right-hand side of equations (1), (2) determine the amount of heat transferred to the coolant in the tubing string and the annulus. The ratio $(t_1 + t_2)/2$ represents the average coolant temperature in the tubing string, while the ratio $(t_2 + t_3)/2$ – in the annulus.

By jointly solving equations (1), (2), formulas for determining the coolant temperature at the outlet of the annulus in the case of direct well flushing are obtained:

$$t_2 = 0.5A_1 t_3 - (0.5A_1 - 1)t_1 \tag{3}$$

$$t_3 = \frac{A_2 t_{ra} + \left[0.5A_1 + (1 + 0.5A_2)(0.5A_1 - 1)\right] t_1}{0.5A_1(1 + 0.5A_2) + 0.5A_1 + 0.5A_2 - 1} \tag{4}$$

In equations (3), (4), it is denoted:

$$A_1 = \frac{k_t F_t}{GC_p},\ A_2 = \frac{k_\tau F_c}{GC_p} \tag{5}$$

In the case of well backwashing, the heat balance equations take the form:

$$GC_p(t_2 - t_1) = \\ = k_\tau F_c\left(t_{ra} - \frac{t_1 + t_2}{2}\right) + k_t F_t\left(\frac{t_2 + t_3}{2} - \frac{t_1 + t_2}{2}\right) \tag{6}$$

$$GC_p(t_2 - t_3) = k_t F_t\left(\frac{t_2 + t_3}{2} - \frac{t_1 + t_2}{2}\right) \tag{7}$$

Equation (6) describes the heat balance of the coolant in the annulus, and equation (7) – in the tubing string. The expressions on the left-hand side of equations (6), (7) determine the amount of heat received by the coolant in the annulus and in tubing string, respectively.

By jointly solving equations (6), (7), formulas for determining the coolant temperature at the outlet of the annulus in the case of well backwashing is obtained:

$$t_2 = (1 + 0.5A_1)t_3 - 0.5A_1 t_1 \tag{8}$$

$$t_3 = \frac{A_2 t_{ra} - \left[0.5A_1 + 0.5A_2 - 1 - 0.5A_1(1 + 0.5A_2)\right] t_1}{(1 + 0.5A_1)(1 + 0.5A_2) - 0.5A_1} \tag{9}$$

The rock temperature is determined using the linear hypothesis of temperature increase with depth (Havrysh et al., 2019):

$$t_r = t_0 + G_t H \tag{10}$$

where:

t_0 – average temperature of the neutral rock layer [degrees],
G_t – temperature gradient [deg./m],
H – depth of the investigated rock layer [m].

The average rock temperature t_{ra} was defined as the mean value between the temperature at a given depth tr and the near-surface rock temperature.

Method for reducing heat losses in the flow of heated coolant

The traditional coaxial pump-circulation system provides higher efficiency in geothermal energy utilization than a U-shaped column. The coaxial system, however, cannot be used in wells with damaged or leaky casing. In such cases, the use of a U-shaped eliminates the need for costly well overhaul. A U-shaped column is also advisable when it is necessary to limit the rate of geothermal energy utilization.

To reduce heat losses in the upward flow of the heated coolant, a design of a petrothermal pump-circulation system is proposed, the main element of which is a downhole jet pump.

Unlike traditional pump-circulation systems that include a submersible electric centrifugal pump, a jet apparatus does not require placement of a power supply circuit in the well, which increased the reliability and autonomy of the thermal energy extraction process. The decision not to use an electric drive has made it possible to use jet apparatus in shallow wells of the heat pump system (Li et al., 2023). The utilization of geothermal energy in inactive deep oil and gas wells using downhole jet apparatus requires improvement of known pump-circulation systems. The enhancement of the pumping-circulating ejection system represents a development of the application of ejection devices in heat pump systems (Peshcherenko and Pospelov, 2024) and in surface equipment intended for further transformation and preparation for the direct use of geothermal energy (Sharapov et al., 2023).

The main element of the pump-circulation system is a jet pump with a parallel (Panevnyk, 2021) orientation of mixed flows (Figure 2).

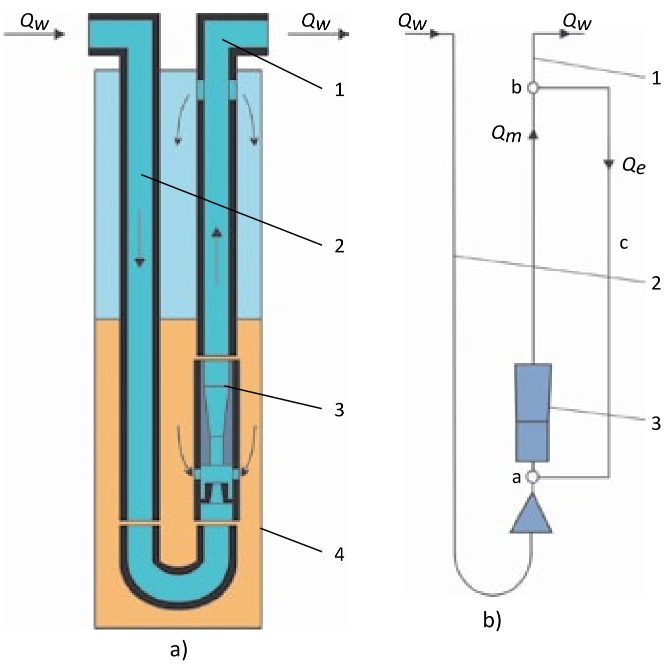


Figure 2. Design (a) and hydraulic diagram (b) of a petrothermal pump-circulation system:
1 – coolant discharge line; 2 – coolant supply line; 3 – jet pump; 4 – well wall.
In Figure (a), the following symbol is indicated: Q_w – working coolant flow rate; in Figure (b) the following symbols are indicated: Q_w – working coolant flow rate, Q_m – mixed coolant flow rate, Q_e – injected coolant flow rate

The proposed scheme for placing a jet pump in a well includes an additional working fluid circulation circuit, similar to the design of an over-bit ejection system intended for the initial opening of productive horizons (Wyrostkiewicz and Panevnyk, 2022) and for eliminating the need for isolation operations (Sudakov et al., 2019) when drilling under conditions of washing solution loss.

The working stream with a flow rate Q_w enters the working nozzle of the jet pump. Due to the high flow velocity at the outlet section of the working nozzle, a low-pressure region is formed, creating conditions for suction of the injected stream. To maintain the operability of the ejection system, the pressure at the outlet section of the working nozzle must exceed the saturated vapor pressure of the liquid (Velychkovych and Panevnyk, 2017). The ascending mixed stream in section ab has a flow rate Q_m, whole the descending injected stream in section bca (Figure 3) has a flow rate Q_e.

In the upper part of the working flow discharge line, radial channels are provided, through which part of the flow with a flow rate Q_e is returned to the well. The presence of an additional circulation circuit abca makes it possible to increase the flow rate in the coolant discharge line compared to the coolant supply line. At the same time, the duration of the upward movement of the heated coolant and the amount of heat loss are reduced.

The coolant temperature at the outlet of the geothermal well depends on the operating mode of the jet pump. The design of the pump-circulation system allows setting the optimal immersion depth of the jet pump, which ensures the maximum coolant temperature at the well outlet. In addition, the characteristics of the jet pump depend on the ratio of geometric dimensions of the flow path elements, the diameter of the lifting tubing and casing, the coolant density, and the capacity of the surface pumping unit. The efficiency of the pump-circulation system can be increased by installing inclined guide elements in the flow path of the jet pump to impart swirl to the mixed flows (Panevnyk, 2022). Instead of a traditional lifting column, a flexible tubing string can be used in the pump-circulation system, which reduces the cost of thermal energy extraction from a petrothermal well.

The increase in the velocity of coolant movement in the tubing connecting the jet pump to the wellhead is given by:

$$\frac{V_p}{V_{p0}} = \frac{4Q_m}{\pi d_c^2} : \frac{4Q_w}{\pi d_c^2} = \frac{Q_m}{Q_w} = \frac{Q_w + Q_e}{Q_w} = \frac{Q_w + Q_w i}{Q_w} = 1 + i \quad (11)$$

where:

V_p, V_{p0} – velocity of upward coolant movement in the tubing when using a jet pump and in its absence, respectively,

Q_m, Q_w – coolant flow rate in the tubing in the upward direction, when using a jet pump and in its absence, respectively,

d_c – inner diameter of the tubing string along which the upward coolant flow moves,

Q_e – injected flow rate,

i – jet pump ejection ratio, $i = Q_i / Q_w$.

Evaluating the efficiency of jet pump application therefore requires determination of the ejection coefficient i or the operating mode of the ejection system.

The operating mode of the ejection system is determined by a system of equations describing the pressure characteristic of the jet pump and its hydraulic system. The pressure characteristic of the jet pump is determined by the well-known equation:

$$h = \frac{\varphi_1^2}{K_p}\left[2\varphi_2 + \left(2\varphi_2 - \frac{1}{\varphi_4^2}\right)\frac{i^2}{K_p - 1} - (2 - \varphi_3^2)\frac{(1+i)^2}{K_p}\right] \quad (12)$$

where:

φ_1, φ_2, φ_3, φ_4 – velocity coefficients for characteristic cross-sections of the jet pump,

K_p – main geometric parameter of the jet pump (ratio of the cross-sectional areas of the mixing chamber and the working nozzle).

The characteristics of the hydraulic system of the jet pump are determined by the pressure values of the mixed P_m, working P_w, and injected P_e flows:

$$P_m = \rho g H_p + \Delta P_p \quad (13)$$

$$P_w = \rho g H_p + \Delta P_w + \Delta P_p \quad (14)$$

$$P_e = \rho g H_p \quad (15)$$

where:

ρ – coolant density,

H_p – depth of jet pump installation in the well,

ΔP_p – linear hydraulic losses in the tubing connecting the jet pump to the wellhead,

ΔP_w – concentrated hydraulic losses in the working nozzle of the jet pump.

Taking into account standard relations for determining linear ΔP_p and concentrated ΔP_w hydraulic losses, the equation describing the hydraulic system characteristics takes the form:

$$h = \left(1 + \frac{d_c^5}{\mu_w^2 \lambda_p H_p d_w^4 (1+i)^2}\right)^{-1} \quad (16)$$

where:

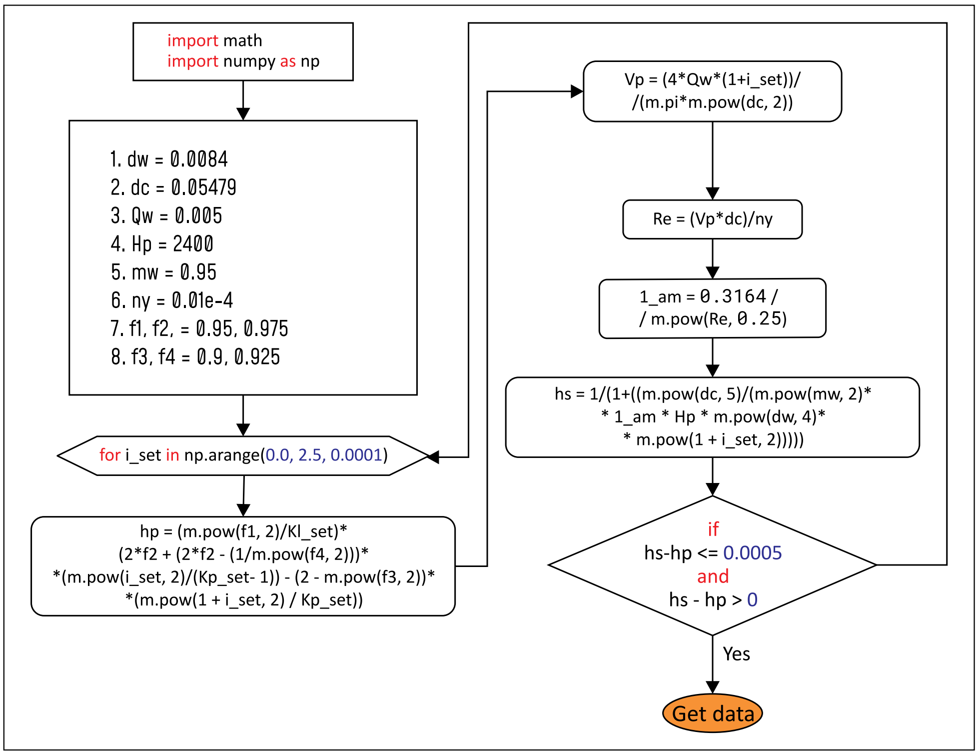
μ_w – flow rate of the working nozzle,

λ_p – Darcy coefficient for the tubing connecting the jet pump to the wellhead,

d_w – diameter of the working nozzle of the jet pump.

Determination of the Darcy coefficient involves a preliminary calculation of the coolant velocity and Reynolds number.

Determination of the jet pump operating mode requires the joint solution of the system of quadratic (Equation (12))



```
import math
import numpy as np
```

```
1. dw = 0.0084
2. dc = 0.05479
3. Qw = 0.005
4. Hp = 2400
5. mw = 0.95
6. ny = 0.01e-4
7. f1, f2, = 0.95, 0.975
8. f3, f4 = 0.9, 0.925
```

```
for i_set in np.arange(0.0, 2.5, 0.0001)
```

```
hp = (m.pow(f1, 2)/Kl_set)*
(2*f2 + (2*f2 - (1/m.pow(f4, 2)))*
*(m.pow(i_set, 2)/(Kp_set- 1)) - (2 - m.pow(f3, 2))*
*(m.pow(1 + i_set, 2) / Kp_set))
```

```
Vp = (4*Qw*(1+i_set))/
/(m.pi*m.pow(dc, 2))
```

```
Re = (Vp*dc)/ny
```

```
1_am = 0.3164 /
/ m.pow(Re, 0.25)
```

```
hs = 1/(1+((m.pow(dc, 5)/(m.pow(mw, 2)*
* 1_am * Hp * m.pow(dw, 4)*
* m.pow(1 + i_set, 2)))))
```

```
if
hs-hp <= 0.0005
and
hs - hp > 0
```

Figure 3. Sequence of calculation procedures

and fractional-rational (Equation (16)) equations. Due to the significant number of mathematical operations involved in determining the operating point of the pumping unit, an automated algorithm was developed, implemented using the Python programming language (Figure 3).

The Python programming language was selected due to its suitability for developing interfaces for visualizing calculation results and facilitating their interpretation and analysis. The NumPy library was used as the basis of the computational block, providing efficient generation of numerical sequences with high accuracy. The loop body includes a series of mathematical expressions and dependencies responsible for determining the hydraulic and pressure characteristics of the jet pump, such as the hydraulic resistance coefficient, pressure losses, and flow parameters. The calculation termination condition is implemented using an if-else construct, which verifies result accuracy based on an absolute error or convergence criterion and controls whether the calculated parameters remain within a physically permissible positive range. When the requires conditions are met, the algorithm outputs the calculation results, representing the coordinates of the pumping unit operating point in terms of the injection coefficient and relative pressure.

Research results and discussion

The results of the conducted research make it possible to determine the coolant temperature for different well designs and flushing modes, as well as the operating mode of a petrothermal pump-circulation system intended to reduce heat losses during the upward movement of the coolant.

Determination of the coolant temperature for different designs and well flushing modes

The relationship between calculated and experimental values of the coolant temperature at the well outlet was analyzed using the results of industrial studies of oil, gas, and geothermal wells. For the analysis of direct and reverse well flushing processes, industrial data from the Karadag 189 well (Crimea, gas condensate field) (Starodub et al., 2012) and the HGP-A well (Hawaii) (Morita et al., 1992) were used, respectively. The characteristic parameters of the wells taken for analysis are presented in Table 1.

The coolant temperature at the well outlet for direct and reverse flushing was calculated using equations (1)–(5). A comparison of the calculated and experimental values of the coolant temperatures at the well outlet is presented in Table 2.

It should be noted that the additional increase in the coolant temperature in the Karadag 189 well is caused by bit operation at the bottomhole. Unlike the HGP-A well, the Karadag 189 well used for comparative analysis was investigated directly during operational drilling. In this case, heating of the coolant (flushing solution) occurred not only due to the heat flow from the heated rock massif but also as a result of friction between the rock and the bit cutters during its operation on the face.

Table 1. Characteristic parameters of wells

Parameter name	Well name	
	Karadag well 189	HGP-A well
Depth [m]	3675	876.5
Casing diameter [m]	0.299	0.178
Tubing diameter [m]	0.14	0.089
Heat carrier flow rate [kg/s]	30	1.333
Temperature gradient [°C/m]	0.01992	0.10903

Table 2. Comparative analysis of the determined coolant temperature at the well outlet

Well name	Washing method	Inlet temperature, t_1 [°C]	Outlet temperature, t_3 [°C]		
			experimental, t_{3e}	calculated, t_{3c}	error, δt_3 [%]
Karadag (Crimea)	direct	18	33.0	29.8	9.7
HGP-A (Hawaii)	reverse	25	43.6	47.2	–7.6

The temperature in the bit operation zone can reach up to 600°C (Kolesnyk et al., 2020). This additional heating of the coolant during bit operation on the face is not taken into account in the calculation methodology, which explains the significant excess of the experimental values of the coolant temperature at the outlet of the Karadag 189 well compared to the calculated values.

Determination of coolant temperature for different well designs and flushing modes

The influence of well design and flushing mode on the coolant temperature was analyzed using equations (1)–(5) (Figure 4). The dependence of temperature on coolant flow rate exhibits an extreme character (Figures 4a, 4b).

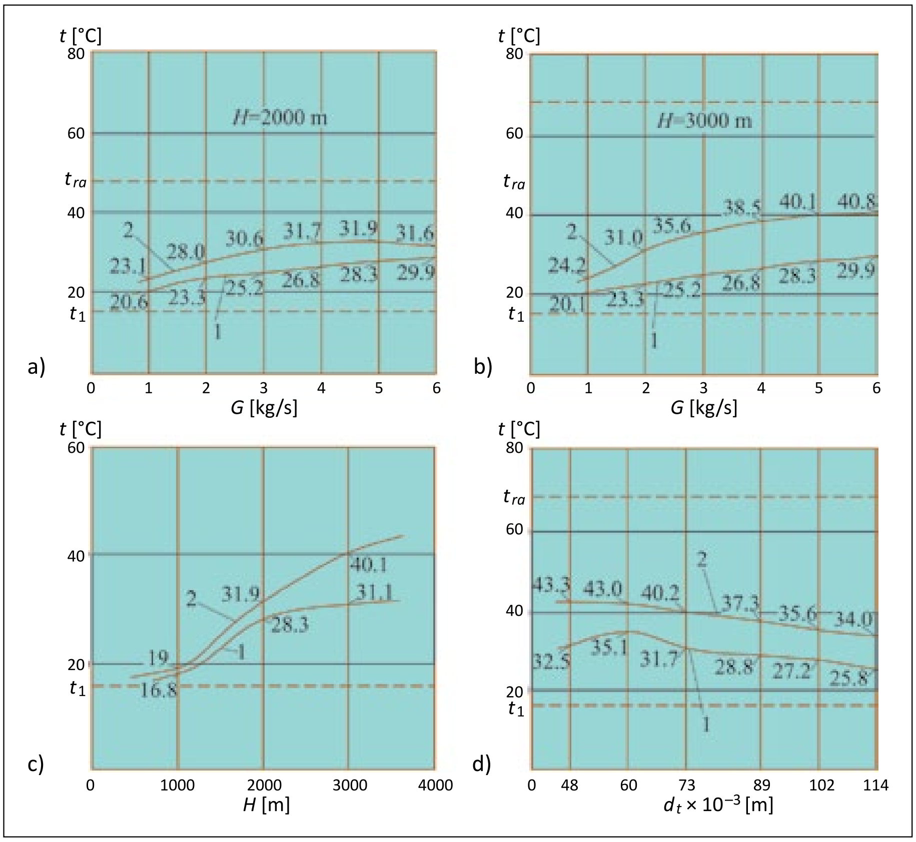


Figure 4. Influence of operational factors on coolant temperature for direct 1 and reverse 2 well flushing: a) dependence of coolant temperature on flow rate for a well depth of 2000 m, b) dependence of coolant temperature on flow rate for a well depth of 3000 m, c) dependence of coolant temperature on well depth, d) dependence of coolant temperature on riser pipe diameter

As the flow rate increases, the residence time of the coolant in the well and the amount of energy absorbed decrease. At the same time, the upward velocity of the coolant increases and heat losses during transport to the wellhead decrease. The coexistence of these two opposing processes leads to the presence of a maximum in the temperature-flow rate dependence. This trend is observed for both analyzed well depths.

The dependence of coolant temperature on well depth (Figure 4c) exhibits a nonlinear increasing character. With increasing depth, both the rock temperature and the amount of energy transferred to the coolant increase. Rock temperature is the dominant factor determining the amount of energy absorbed by the coolant. In addition, increasing well depth increases the duration of coolant residence in the high-temperature zone, thereby increasing the amount of geothermal energy received.

Changes in the diameter of the riser pipes lead to a redistribution of the cross-sectional areas of the coolant supply and return channels in the well (Figure 4d). As a result, the velocities of downward and upward flows and the durations of heating and transport processes change. An increase in the diameter of the riser pipe column causes a decrease in the residence time of the coolant the high-temperature zone and an increase in the duration of its upward movement. Consequently, a nonlinear inverse dependence of coolant temperature on riser pipe diameter is observed.

The determining factor influencing coolant heating temperature is the flushing method. Regardless of coolant flow rate, well depth, and pipe diameter, thermal energy utilization is more efficient when the working medium is directed into the annulus. This feature of coolant heating is likely associated with the ratio of cross-sectional areas of the annulus and tubing string channels, as well as with the higher temperature difference between the working fluid and the surrounding rocks in this case.

Reducing heat losses during the lifting heated coolant is therefore by shortening the duration of upward flow while maintaining the duration of the downward flow time required for heat acquisition.

Determination of the operating mode of a petrothermal pump-circulation system designed to reduce coolant heat losses in the well

The use of an ejection system makes it possible to reduce the duration of upward flow and the associated heat losses during coolant transport to the wellhead. Regardless of well depth, coolant flow rate at the well inlet, and tubing diameter, the application of an ejection system allows you the preservation of geothermal energy accumulated by the coolant.

According to the obtained results, increasing the working flow rate of the jet pump from $Q_w = 0.005$ m^3/s to $Q_w = 0.01$ m^3/s increases the ejection coefficient from $i = 0.22$ to $i = 0.32$. The upward flow velocity, according to relation (11), increases by factors of 1.22 and 1.32, respectively.

The applicability limits of the pump-circulation system are determined by the pressure characteristics of the jet pump. The pressure generated by the jet pump is used to overcome hydrostatic pressure and hydraulic losses in the lifting column connecting the jet pump to the wellhead. The limiting pressure of the jet pump corresponds to an injection coefficient value $i = 0$. The minimum required operating flow rate of the jet pump can be determined from equation (16) by substituting the relative pressure value $h = h_{\max}$ and the injection coefficient $i = 0$. The limiting relationships between the diameter of the working nozzle, the depth of jet pump installation, and the operating flow rate define the application range of the geothermal jet pump (Figure 5).

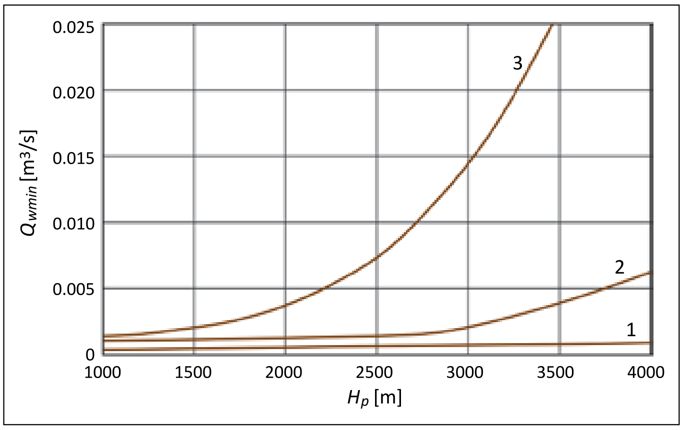


Figure 5. Dependence of the minimum required working flow rate on the depth of jet pump installation for different working nozzle diameters: 1 – $d_w = 0.007412$ m; 2 – $d_w = 0.0084$ m; 3 – $d_w = 0.00953$ m

According to the obtained dependencies, the minimum required operating flow rate is directly proportional to both the diameter of the working nozzle and the depth of jet pump installation. These relationships enable improved efficiency in designing a downhole jet pump structure for a given installation depth and coolant flow rate.

Conclusions

1. An analytical model of heat exchange between counter-coaxial flows and surrounding rock with a linear temperature distribution was developed based on a system of heat balance equations for the coolant in the tubing string and the annulus, taking into account the hydrodynamic and thermophysical characteristics of the components of a single-well geothermal system. The developed model

makes it possible to assess the efficiency of low-temperature geothermal energy utilization during direct and reverse flushing of decommissioned oil and gas wells.

2. In the process of studying the developed analytical model, the influence of design and operational factors on the efficiency of low-temperature geothermal energy utilization was established:
   - an increasing trend in coolant temperature for direct flushing and extreme dependence for reverse flushing were observed when the mass flow rate varied in the range from 1 kg/s to 6 kg/s;
   - an increase in well depth from 1000 m to 3000 m leads to an increase in coolant temperature by a factor of 1.85 for direct flushing and 2.11 for backwashing;
   - an inverse dependence of coolant temperature on the diameter of the tubing string was established;
   - within the studied range of design and operating parameters, backwashing provides higher efficiency in the utilization of low-temperature geothermal energy.
3. A well ejection system was developed to reduce the duration of upward flow movement and decrease heat losses in the coolant flow. The system is implemented in the form of a jet pump with hydraulically separated suction and pressure lines, a sequential switching scheme, and a parallel orientation of mixed flows. The solution of the system of operator equations for determining the operating parameters of the pump-circulation system is implemented using an automated algorithm developed in the Python programming language. An increase in flow velocity and a reduction in the duration of upward flow movement by 1.22–1.32 times were obtained. An increasing nonlinear dependence of the minimum required flow rate of the ejection system on the depth of the jet pump installation in the well and the diameter of its working nozzle was established.

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