МРНТИ 27.35.25
УДК 532.546.6

https://doi.org/10.51889/7670.2022.18.32.011

GRAVITY EFFECT ON WELL SCREENS ALIGNMENT DURING THE IN-SITU LEACHING

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Abstract

The production of a mineral via in-situ leaching method in the conditions of a rollfront deposit is accompanied by many problems associated with the impossibility of direct observation of the process. This article discusses the problem of the influence of the density heterogeneity of the injected solution on the efficiency of well screen operation. As a result of the influence of gravitational forces, with a non-uniform distribution of the density of the liquid, the effect of a "fall" of solutions occurs, which significantly reduces the efficiency of mining under conditions of well screen located at the same level and the remoteness of the lower aquiclude from the lower boundary of the well screen. The problem was investigated on the basis of mathematical modeling using finite difference schemes. The calculation was carried out for a hexagonal pattern with six injection and one production wells. The results showed that the change in the lowering level of solutions depending on the distance between the wells and the density of the injected leach solution is linear. These results make it possible to determine the effective location of well screens at various values of the density of the injected solution.

Keywords: mathematical modeling, mineral extraction, in-situ leaching method, filtration theory, gravitational effects, wells, well screen.

Аңдатпа

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ЖЕРАСТЫ ҰҢҒЫМАЛЫ ШАЙМАЛАУ БАРЫСЫНДА ГРАВИТАЦИЯНЫҢ ҰҢҒЫМА ФИЛЬТРЛАРЫНЫҢ ОРНАЛАСУЫНА ӘСЕРІ

Қабатты-инфильтрациялық кен орны жағдайында жер асты ұңғымалы шаймалау әдісімен пайдалы қазбаны өндіру, процесті тікелей бақылаудың мүмкін еместігімен байланысты көптеген мәселелермен қатар жүреді. Бұл мақалада айдалынатын ерітіндінің тығыздығының гетерогенділігінің ұңғыманың фильтрінің жұмысының тиімділігіне әсер ету мәселесі қарастырылады. Гравитациялық күштердің әсерінен сұйықтықтың тығыздығының біркелкі бөлінбеуі кезінде ерітінділердің «түсу» әсері пайда болады, ұңғыма фильтрлары бір деңгейде орналасқан және фильтрдың төменгі шекарасы өткізбейтін төменгі қабаттан қашық орналасқан жағдайда, фильтрлардың орналасқан жерінде кен өндіру тиімділігін айтарлықтай төмендейді. Мәселе ақырғы айырмашылық схемаларын қолданып математикалық модельдеу негізінде зерттелді. Есептеу алты айдау және бір өндіру ұңғымасы бар алтыбұрышты (гексагоналды) орналасу схемасы үшін жүргізілді. Нәтижелер ұңғымалар арасындағы қашықтыққа және айдалатын сілтісіздендіру ерітіндісінің тығыздығына байланысты ерітінділерінің түсу деңгейінің өзгеруі сызықты екенін көрсетті. Бұл нәтижелер айдалатын ерітіндінің тығыздығының әртүрлі мәндерінде ұңғыма сүзгілерінің тиімді орналасуын анықтауға мүмкіндік береді.

Түйін сөздер: математикалық модельдеу, минералды өндіру, жерасты шаймалау әдісі, фильтрация теориясы, гравитациялық эффектілер, ұңғымалар, ұңғыма фильтрлары.

Аннотация

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ВЛИЯНИЕ ГРАВИТАЦИИ НА РАСПОЛОЖЕНИЕ ФИЛЬТРОВ СКВАЖИН ПРИ ПОДЗЕМНОМ СКВАЖИННОМ ВЫЩЕЛАЧИВАНИИ

Добыча минерала методом подземного скважинного выщелачивания в условиях пластово-инфильтрационного месторождения сопровождается множеством задач, связанных с невозможностью прямого наблюдения за процессом. В данной статье рассматривается задача влияния неоднородности плотности закачиваемого раствора на эффективность работы фильтров скважин. В результате воздействия гравитационных сил, при неоднородном распределении плотности жидкости возникает эффект «падения» растворов что значительно снижает эффективность отработки при условиях расположения фильтров на одном уровне и отдаленности нижнего водоупора от нижней границы фильтра скважины. Задача была исследована на основе математического моделирования с применением конечно-разностных схем. Расчет был проведен для шестиугольной (гексагональной) схемы расположения с шестью закачными и одной откачной скважинами. Результаты показали, что изменение уровня понижения растворов в зависимости от расстояния между скважинами и плотности закачиваемого выщелачивающего раствора является линейным. Данные результаты позволяют определить эффективное расположение фильтров скважин при различных значениях плотности закачиваемого раствора.

Ключевые слова: математическое моделирование, добыча минералов, метод подземного скважинного выщелачивания, теория фильтрации, гравитационные эффекты, скважины, фильтры скважин.

Introduction

In-situ leaching (ISL) is an economically viable and environmentally friendly method of uranium mining. The extraction of the mineral by the ISL method is carried out from the host rock using a chemical solution that converts solid uranium into a dissolved form, then the dissolved uranium is extracted to the surface using a network of wells [1]. The use of this method is possible with certain properties of the host rock. The main condition is the permeability of the rock to deliver the solution to the rock and further dissolution of uranium [2]. Deposits with such characteristics are called infiltration and are divided into two types [3]:

1. reservoir-infiltration, formed as a result of the transfer of minerals along artesian infiltration-hydrodynamic systems. The continuous flow of groundwater directly contributes to the formation of the tongue-shaped form of the ore deposit. This form of deposits is called rollfront. Rollfront deposits in most cases are low concentrated, which is largely convenient for applying the ISL method;
2. soil-infiltration, formed in static infiltration-hydrodynamic systems.

Production by the ISL method is mainly used for reservoir-infiltration fields. In the conditions of soil-infiltration deposits, the full application of the ISL method is possible only for the following types:

1. Khiagdinsky (Khiagdinsky ore field in Buryatia, RF);
2. Semizbaysko-Dalmatovsky (Semizbay in the Akmola region of the Republic of Kazakhstan, Malinovskoye in the Kemerovo region of the Russian Federation and the Dalmatovskaya group of deposits in the Kurgan region of the Russian Federation);
3. Devladovsky (Devladovsky group of deposits of the so-called Ukrainian shield).

Rollfront deposits are conditionally divided into two parts: frontal and rear (Figure 1). The front part has the maximum thickness, is characterized by a high concentration of uranium and is called the “bag part”. The rear part of the roll is usually low power and is called "wings". Between the wings there is an oxidized zone with a significantly low or zero mineral concentration [3].

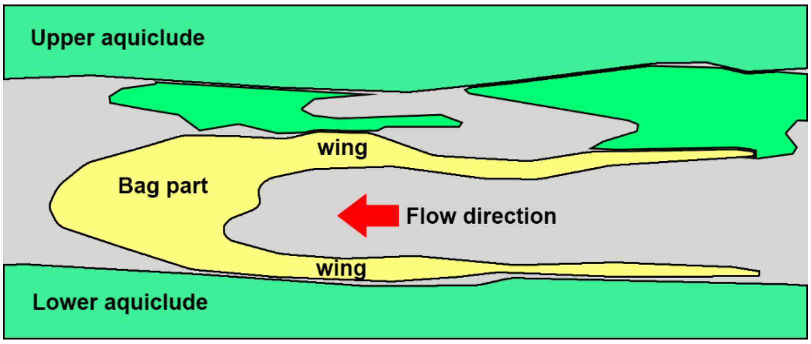

Figure 1. Illustration of the shape and arrangement of the elements of the ore-bearing formation

An aquiclude is an impermeable layer, usually represented by clayey rocks [4]. The upper and lower aquiclude prevents groundwater from flowing into the depths or to the surface, which ensures the movement of the mineral front through successive leaching and sedimentation. The shape of a rollfront deposit is also determined by the direction of groundwater flow, i.e. the bag part of the deposit is directed along the flow of groundwater [5].

The injection of the solution into the formation is provided with well screens. At the same time, in the production wells, the screens provide reverse movement, i.e. from the reservoir to the wells for further withdrawal of the dissolved mineral to the surface. An important requirement for screens is the separation of mechanical impurities in the form of rock particles and the screen itself. During production by the ISL method, the following requirements are imposed on the screens of technological wells [6]:

1. resistance to the effects of the applied leaching reagents;
2. mechanical strength to reduce the impact of hydrodynamic pressure;
3. optimal filtration characteristics - ensuring the penetration of productive and leaching solutions, with minimal penetration of rock particles;
4. resistance to the formation of mechanical and chemical clogging during the entire period of operation of the technological block;
5. providing the necessary throughput volume of solutions to reduce the cost of operating the field.

The maximum length of the screen is limited by mechanical strength, in practice it does not exceed 8 meters, while the distance between the upper and lower aquicludes can reach up to 20 meters [7]. Accordingly, for complete coverage of the ore deposit, additional wells are placed nearby with screens installed at different levels. In the rear part of the roll, the use of several production wells at a close distance is not profitable due to the low uranium content. In this regard, the problem arises of determining the optimal location of the screens along the well.

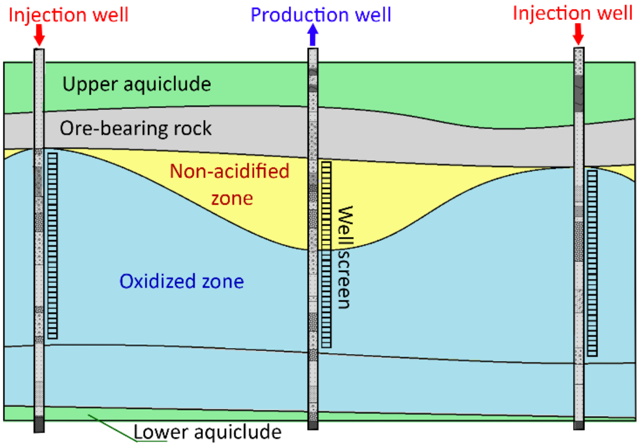

Figure 2. Influence of the density of solutions on the arrangement of screens due to gravitational forces

On the other hand, the density of the leaching solution lies in the range from 1000 to 1050 kg/m3 and differs from the density of formation waters. It was shown in [8] that the difference in the densities of the solution and formation waters leads to a lowering of the level of the flow of the solution in the rock due to gravity.

In addition, an increase in the distance between wells or the absence of a bottom aquiclude also affects the level of fluid flow in the formation, as a result of which it is necessary to adjust the location of the well screens. In this regard, the task arises of studying these factors for the location of screens along the height of the wells (Figure 2).

Problem statement and research methods

A three-dimensional area is considered with injection wells located at the vertices of a regular hexagon and one production well in its center (Figure 3). The fluid flow in the reservoir, taking into account changes in fluid density and gravitational forces, is described by the following equations [8]:

$$\frac{\partial \rho}{\partial t} + \varphi\, U\mathrm{grad}(\rho) = 0 \quad (1)$$

$$div(U\varphi) + \frac{gk_{zz}}{\mu}\frac{\partial \rho}{\partial z} = -\frac{q_{inj}\delta(x - x_{inj}, y - y_{inj}) + q_{prod}\delta(x - x_{prod}, y - y_{prod})}{\rho} \quad (2)$$

$$U\varphi = -\frac{k}{\mu}\,(\mathrm{grad}(P) + \rho\, g) \quad (3)$$

where,

ρ - liquid density [kg/m^3], U - filtration rate [m/s], φ - porosity coefficient, g - gravity acceleration [m/s^2], k - permeability tensor [m^2], q_{inj}, q_{prod} - flow rates of injecting and extracting wells [m^3/s], $\delta(x\text{-}x_{inj}, y\text{-}y_{inj})$,

$\delta(x\text{-}x_{prod}, y\text{-}y_{prod})$ - Dirac delta function for location of injecting and extracting wells, P - pressure [Pa] .

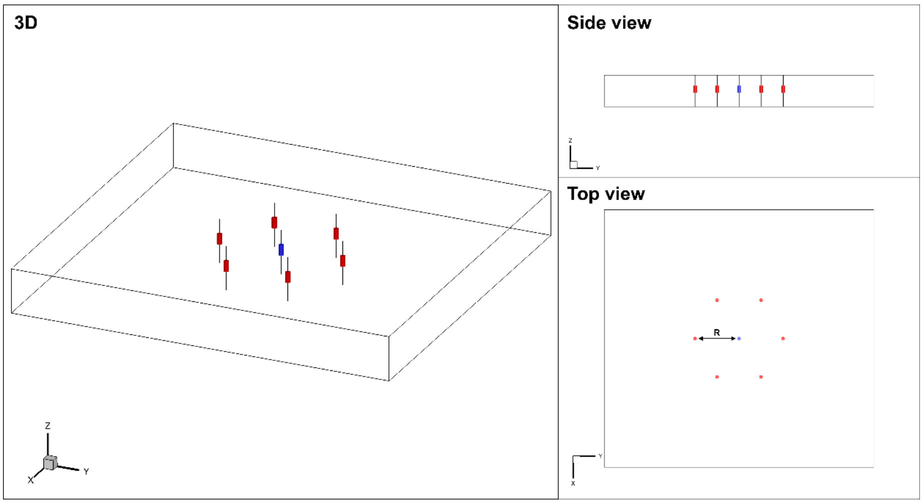

Figure 3. Computation area with wells (red – injection wells, blue – production wells, well size does not correspond to scale)

Let us assume that the rock is limited by the lower and upper aquicludes, and therefore the no-flow condition is applied at these boundaries:

$$\frac{\partial P(x,y,z_t)}{\partial z} = \frac{\partial P(x,y,z_b)}{\partial z} = 0 \tag{4}$$

At the remaining boundaries of the region, the pressure is equal to the hydrostatic pressure and the Dirichlet condition is applied:

$$P(x_e,y,z) = P(x_w,y,z) = P(x,y_s,z) = P(x,y_n,z) = \rho g z \tag{5}$$

In production, to prevent spreading beyond the boundaries of the block and impoverishment of solutions by groundwater, the sums of flow rates of injection and production wells are equalized. When solving this problem, the same conditions were set:

$$\sum_{i=1}^{6} q_{inj_i} = -\,q_{prod}$$
$$q_{inj_i} = \frac{q_{prod}}{6} \tag{6}$$

At the initial moment of time, the formation water density is constant and equal to 1000 kg/m^3. The density of the injected solution (ρ_{inj}) depends on the value of the concentration of the reagent and varies in the range of 1000-1050 kg/m^3, where the value of 1050 kg/m^3 corresponds to the density of the solution at an acidity of 30 g/l and the condition of leaching of 1% of the mining material.

The distance between the injection and production wells (R) is shown in Figure 3, and is also the radius of the circumscribed circle of the hexagon.

Thus, this paper investigates (i) the effect of fluid density and (ii) the distance between injection and production wells on the drawdown level of the injected fluid. The solution for each value of density (ρ_{inj}) and distance between wells (R) is calculated separately.

Algorithm

The algorithm for solving the problem consists of the following steps:

1. Entering the density of the injected solution (ρ_{inj}) and the distance between wells (R);
2. Construction of the computational domain and placement of wells at a given distance R;
3. Determination of the distribution of the density of the solution in the reservoir from equation (1);
4. Determining the distribution of the velocity field from equation (2);
5. Based on certain values of the velocity, the construction of streamlines of the solution in the reservoir using the Pollock method [9]. Streamline - a curve (str_i) consisting of N_p points, the direction of the tangent to which at each point coincides with the direction of the fluid particle velocity at this point [10] (Figure 4);

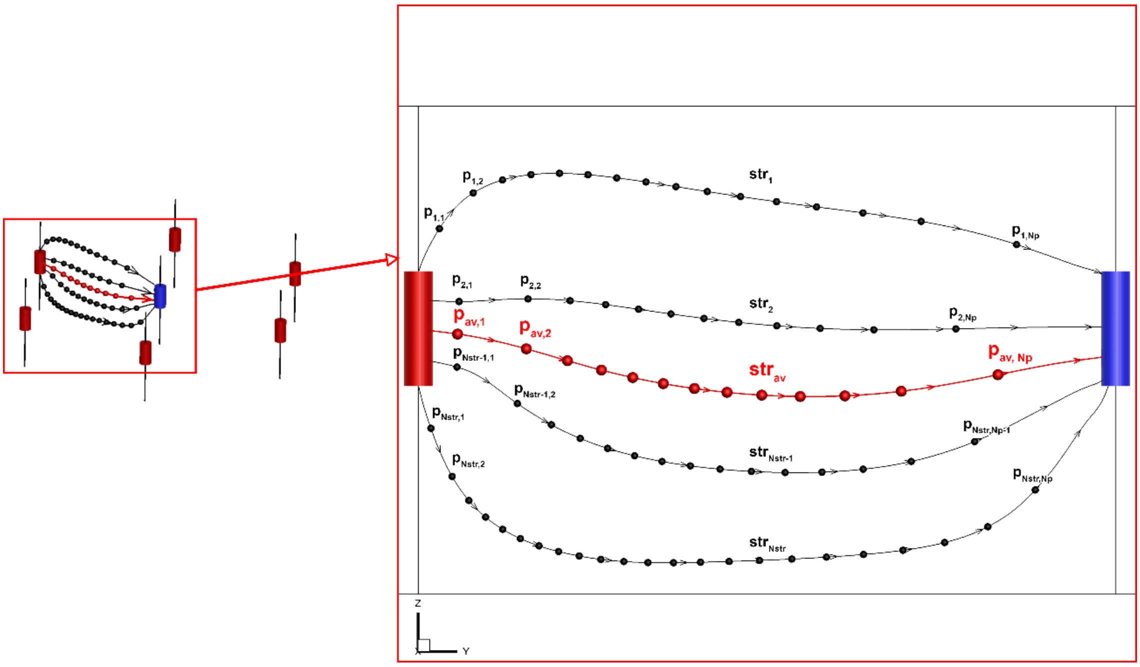

Figure 4. Illustration of streamlines (str_i) with points ($p_{i,j}$) along them

6. Calculation of the "arithmetic mean" streamline. According to Figure 4 and formula 7, for each value of density and distance between wells, the average depth of the streamlines is calculated:

$$
\begin{gathered}
str_i\left(p_{i,1}, p_{i,2} \dots p_{i,N_p}\right) = f(U_x, U_y, U_z) \\
p_{i,j}(x_{i,j}, y_{i,j}, z_{i,j}) \\
str_{av}(p_{av,1}, p_{av,2} \cdots p_{av,N_p}) \\
p_{av,j}(x_{av,j}, y_{av,j}, z_{av,j}) \\
x_{av,j} = x_{i,j} \\
y_{av,j} = y_{i,j} \\
z_{av,j} = \frac{z_{1,j} + z_{2,j} + \cdots + z_{N_{str},j}}{N_{str}} \\
i = 1 \dots N_{str}, j = 1 \dots N_p
\end{gathered} \quad (7)
$$

7. Calculation of the deviation (decrease level - H_d) averaged over the depth of the streamlines (str_{av}) for density values (ρ_{inj}) 1010-1050 kg/m^3 from the "arithmetic average" over the depth of the streamlines (str_{av}) for the injected density (ρ_{inj}) 1000 kg /m^3;

8. Calculation of the maximum decrease level (H_{max}) for each density of the injected solution (ρ_{inj}) and distance between wells (R).

Results and discussions

The distribution of pressure and streamlines in the specified area for the density (ρ_{inj}=1050 kg/m^3) of the injected solution is shown in Figure 5.

Due to the symmetry of the pressure and velocity fields, for qualitative and quantitative analysis, it is sufficient to consider the change in the average streamline in the area between the injection and production wells (as shown in Figure 6).

As can be seen from Figure 6, an increase in the density of the injected solution leads to a drop in the level of the streamlines under the action of gravitational forces. This effect leads to an increase in the time of development of the deposit, which affects the efficiency of production.

The dependence of the levels of "arithmetic average" streamlines (H_d) on the distance between wells for different values of the density of the injected mud is shown in Figure 7.

As can be seen from Figure 7, an increase in the density of the injected solution leads to an increase in the magnitude of the streamline drawdown level.

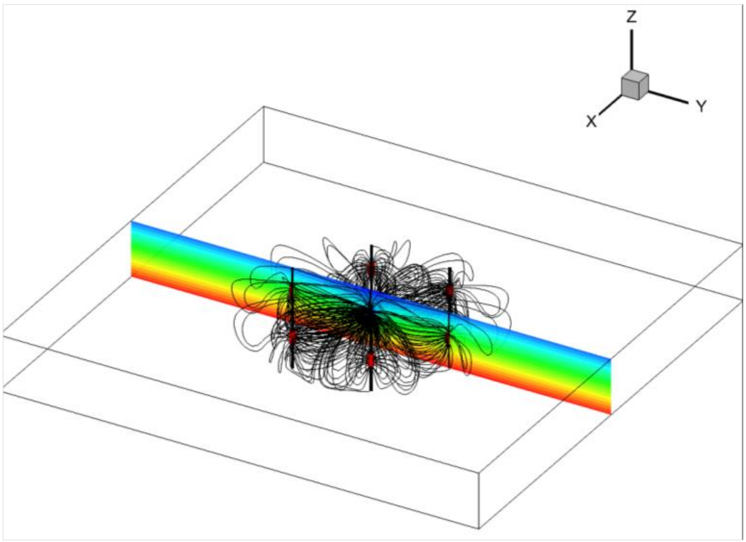

Figure 5. Distributions of pressure in the slice and streamlines for case when ρ_{inj}=1050 kg/m^3

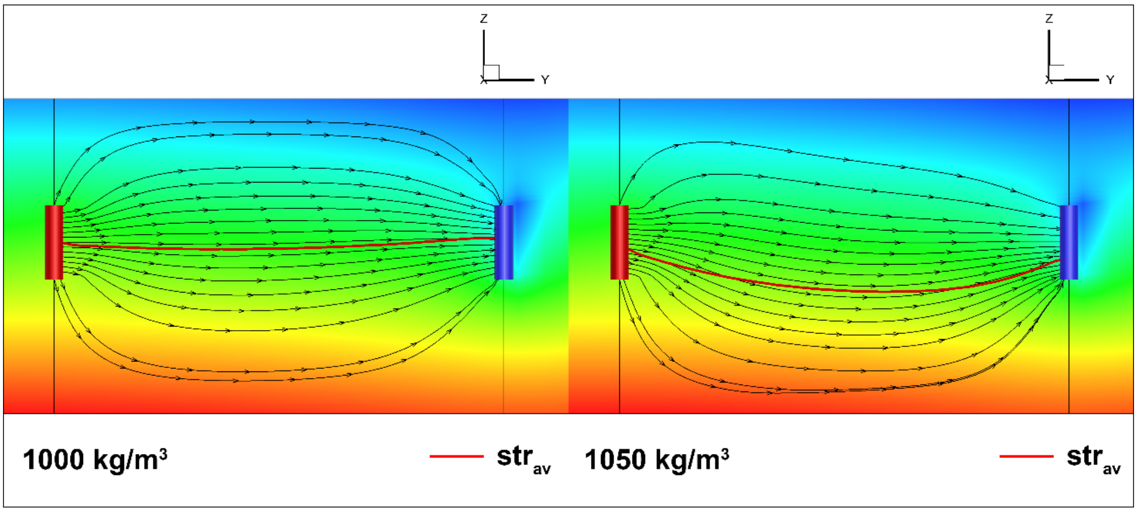

Figure 6. Distribution of streamlines and pressure along the shear between pumping and injection wells for values of 1000 kg/m^3 and 1050 kg/m^3

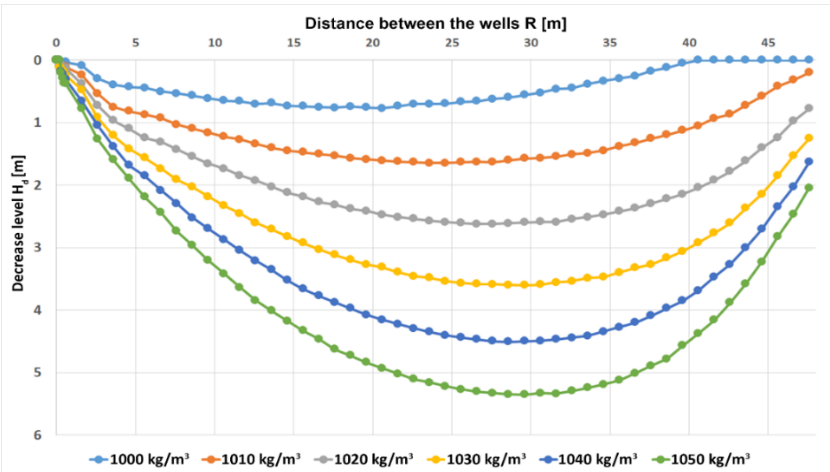

Figure 7. Dependence of the levels of "arithmetic average" streamlines (H_d) on the distance between wells for different values of the density of the injected solution (ρ_{inj})

A comparative analysis of the dependences of the maximum value of the decrease in the level of the average streamlines on the distance between the wells for various values of the fluid density is shown in Figure 8.

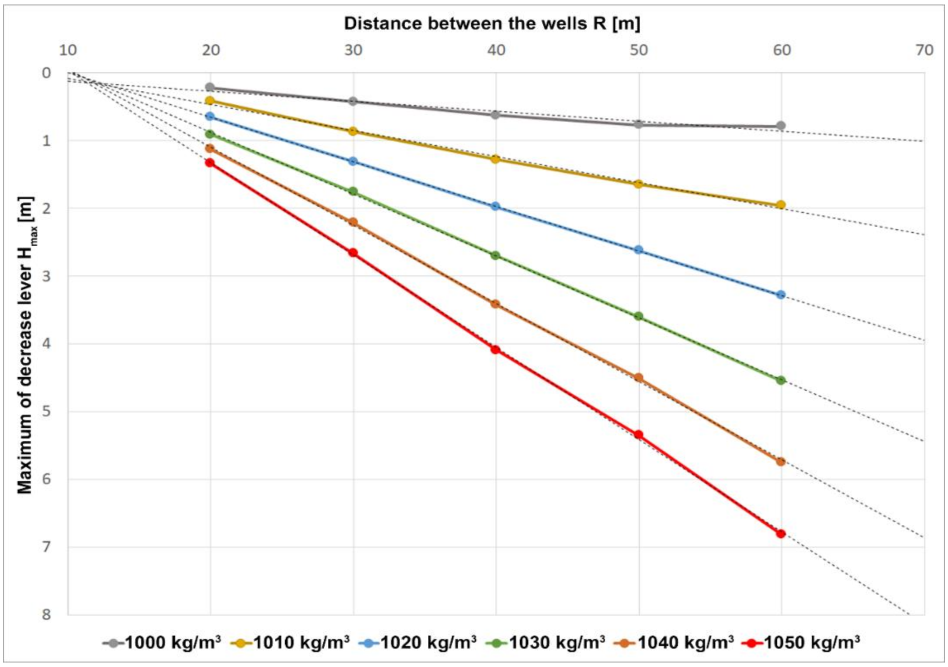

Figure 8. Dependence of the maximum depth of fall (H_{max})
on the distance between wells (R) at different densities of the injected solution (ρ_{inj})

As can be seen from Figure 8, the dependence of the change in the maxima of the drawdown levels on the distance between the wells for different values of the fluid density is linear. The level of decrease in the average streamline at a solution density of 1000 g/m^3 and a distance between wells of 60 meters does not exceed 1 meter, while at a solution density of 1050 g/m^3.

Conclusion

Under the conditions of reservoir-infiltration deposits, where the thickness of the deposit is heterogeneous along the reservoir, the location of the well screens in height is one of the main tasks for increasing the efficiency of uranium mining by the ISL method. Depending on the thickness of the deposit, multi-layer screens or several closely spaced wells with different levels of screens are used.

In this paper, we studied the change in the depth of the flow drop at different values of the density of the solution, and also investigated the effect of the distance between the injection and production wells on the depth of the decrease in flow from the injection well at different values of the density of the solution.

To minimize the influence of reservoir filtration characteristics on the fluid flow in the rock, in this work, the porous medium under consideration was considered homogeneous and isotropic. The influence of the anisotropy of the medium on determining the effective location of wells is the task of the next work.

The paper shows that the gravitational effect increases with increasing density of the solution, which leads to the descent of the solution. An increase in the distance between the pumping and injection wells also leads to a decrease in the average streamline. Thus, when well screens are installed at the same level in height, the flow from the injection well is bent, part of the productive solution goes down beyond the operating area of the production well screen. This, in turn, leads to a decrease in the injectivity of the injection well, and, accordingly, the efficiency of field development decreases.

Taking into account all the above-mentioned main factors, in this work, the dependence of the change in the maximum depth of fall for various values of the density of the injected solution and the distance between the wells, which is linear, was established.

Acknowledgments. *The study was carried out within the framework of a grant financing project "Digital technology for the efficient positioning and management of technological wells for uranium extraction with In-Situ Leaching method" (AP08052470).*

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