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Compression of liquids from the operating wells to the surface applying the sequential approximation

Sprężanie cieczy z odwiertów eksploatacyjnych na powierzchnię z zastosowaniem metody sekwencyjnej aproksymacji

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ABSTRACT: The article discusses the issue of pushing water to the surface by injecting gas into the dome of a water pressure system. The layer is completely filled with liquid. This requires the creation of underground gas storages in the central upper part of the water pressure system. For this purpose, the water must be pressurized from the drilled and unloaded wells. A sequential approximation method is used to solve the problem, and formation of the reservoir occurs due to the compression of the fluid through the operating wells. Fluids and gases that enrich the water pressure system, field system and parameters are known. The boundaries of the latter are the contours of the pressure and the flow. Over time, the water pressure in the reservoir has been determined by changing the sum of the volume of the cavity at the edge of the reservoir, the capacity of the created gas and the amount of injected gas. Under the conditions considered, the movement of water in the areas bounded by the contour of the discharge and flow can be considered as radial. Since this area is not very large, the elasticity of the water and the porosity of the reservoir can be ignored. This issue can be considered as the filtration of incompressible fluid in a non-deformable bed. With a relatively small change in flow rate due to the constant pressure in the discharge circuit, the water compressed by the gas flows freely through the wellhead of the discharge well.

Key words: underground gas storage, dome-shaped, water pressure, flow contour, operating well, injection wells, pressure loss, gas-water contour, water trap.

STRESZCZENIE: W artykule omówiono problem wydobywania wody na powierzchnię poprzez zatłaczanie gazu do systemu ciśnieniowego wody zlokalizowanego w obrębie struktury o kształcie kopuły. Warstwa jest całkowicie wypełniona cieczą. Wymaga to utworzenia podziemnych zbiorników gazu w centralnej strefie wyższej części systemu ciśnieniowego wody. W tym celu woda odbierana z otworów odwierconych w strefach zmniejszonego ciśnienia musi być sprężana. W celu rozwiązania problemu stosuje się metodę sekwencyjnej aproksymacji, w wyniku której tworzenie się złoża następuje na skutek sprężania płynu poprzez odwierty robocze. Znane są ciecze i gazy, które wzbogacają system ciśnieniowy wody, system złożowy i jego parametry. System złożowy ograniczony jest wyznaczonymi konturami ciśnienia i przepływu. Z czasem ciśnienie wody w złożu zostało ustalone w wyniku zmiany sumy objętości kawerny w brzeżnej części złoża, pojemności wytworzonego gazu i ilości wtłaczanego gazu. W rozważanych warunkach ruch wody w obszarach ograniczonych konturem odbioru i przepływu ma charakter radialny. Mając na uwadze, że obszar ten nie jest zbyt duży, można zignorować własności elastyczne wody i porowatość zbiornika. Zagadnienie to można rozpatrywać jako filtrację nieściśliwego płynu w niezdeformowanym złożu. Przy stosunkowo niewielkiej zmianie natężenia przepływu, spowodowanej stałym ciśnieniem w obwodzie odbiorczym, woda sprężona przez gaz przepływa swobodnie przez głowicę odwiertu roboczego.

Słowa kluczowe: podziemny magazyn gazu, kształt kopuły, ciśnienie wody, kontur przepływu, odwiert produkcyjny, odwierty zatłaczające, strata ciśnienia, kontur gazowo-wodny, pułapka wodna.

Introduction

The article examines the schematic field water pressure system. The layer is completely filled with hydrocarbon field. An underground gas storage is required in the central upper part of the dome-shaped water pressure field. To this end, the gas must be pumped into the central part of the dome, from where the water is pumped out by special wells drilled and unloaded for this purpose. These wells are located in the form of a circular battery along the radius R_{vs}. The liquid is compressed until the

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gas-water contact reaches AB state. Subsequent compression is not profitable, because in this case the gas exceeds the water trap and spreads across the bed.

water pressure in the flow circuit – by p_{vs}; specific gravity of water – γ_w; the height of the water trap – H; the radius of the discharge well – R_d (Figure 1).

The goal of the work

As is well known, one of the methods to store gas is the creation of underground gas condensate fields (UGCF). Some of these reservoirs are created in depleted gas condensate fields. During pumping gas to these reservoirs for the purpose of further extraction, the old methods used will not fully realize the extraction. The article presents a two-stage method of operation of such wells.

In the first stage, dry gas is injected into the upper layers, while in the second stage gas and remaining gas condensate are extracted from the lower layers of reservoir.

The proposed method will increase the oil recovery by extraction of the remaining condensate located in the lower reservoir. Liquids and gases that enrich the water pressure system, field system and parameters are known. The boundaries of the latter are the contours of the press and the flow. It is necessary to determine the pressure in the reservoir. Gas is quite compressible, and when you stack it vertically you find that the pressure exerted by the gas stacked above it changes via both linear and nonlinear mechanisms. The primary nonlinear mechanism is called “compressibility” (symbol “Z”) which is fundamentally a measure of the amount that a gas deviates from ideal gas behavior. Air is very nearly an ideal gas where $Z = 1.0$. Methane and CO_2 exhibit distinctly nonlinear (and often nontrivial) response to applied force. Let us call the injection well around the discharge and the flow contours wells circular (Aslanov, 2001; Rubin, 2018).

Under the conditions considered, the movement of water in the areas bounded by the contour of the discharge and flow can be considered as radial. Since this area is not very large, the elasticity of water and the porosity of the environment can be ignored, and this issue can be considered as the infiltration of incompressible fluid in a non-deformable bed (Jafarov et al., 2013; Ismayilov et al., 2018).

Let us indicate the volume of the cavity in the gaseous part of the edge of the field by Ω_g; gas-water contact $F = F(Z)$; in this case the pressure of the gaseous part of the field – by $\bar{p}_g$; the period since the gas injection – t; the decrease in the water level calculated from the highest point of the cover – Z; porosity of the gaseous part of the field – by m; when $Z = H$ gas –water contact – by F_a; In the AB case, the average radius of water withdrawal – by R_{av}; dynamic viscosity coefficient of water – μ_w; R_0 and R_{vs} of the bed; the power of the gaseous part between the radii and the contours – by h; conductivity – K;

Performance of work

When creating UGS in depleted and watered oil fields and oil and gas condensate fields, cyclic operation is necessary due to the physicochemical interaction of compressed gas in the reservoir with residual oil, leading to phase transformations – the gas dissolves in the residual oil, significantly reducing its viscosity and density. In turn, high-molecular hydrocarbons of the paraffin series are dissolved in oil, while oil, in general, acquires greater mobility. When gas is taken from the UGS, this previously stationary oil will be filtered along with gas and water to the well and there will be an increase in oil recovery of the already depleted field in which the UGS is being created. Thus, the technical and economic characteristics of the UGS will increase due to the additional oil produced, the increase in the use of the pore volume of the reservoir for underground gas storage and saving of reservoir energy during gas extraction from the UGS, thus increasing the potential of the UGS (Mustafayev and Aliyeva, 2015; Aliyeva, 2019).

However, in the process of lifting a two-phase three-component (gas–oil–water) gas-liquid mixture (GWS), significant phenomena occur in the pumping and compressor pipes (tubing), negatively affecting the operational characteristics of UGS:

- there is a change in the thermodynamic parameters of the GWS, because the reservoir and surface parameters of pressure (p), volume (V), temperature (T) are sharply different;
- reverse phase transformations occur in the tubing in the extracted products (oil degassing, the appearance of the third phase – crystallization of refractory paraffins);
- nonequilibrium coarse-dispersed systems are formed: gas and oil–water (direct and reverse) emulsions. Nonequilibrium coarse water–oil hydrophobic (reverse) emulsions differ sharply, not additively, in viscosity characteristics from the initial components and have a negative effect on gas and liquid production;
- the formation of asphalt-resin-paraffin deposits (ASF) on the walls of tubing, as well as field pipelines leads to a decrease in their flow section and to an increase in friction losses of reservoir energy.

All this leads to a decrease in depression in the reservoir and a decrease in the flow rate of the well for gas and liquid, which reduces the efficiency of UGS in depleted oil and gas condensate fields (Shchelkachev and Lapuk, 1949; Miralamov et al., 2013).

Let us use a sequential approach to solve the problem. We assume the calculations as follows. We use a small-time interval at $\Delta t = t_e - t_b$ (where t_e and t_b are the end and beginning of the section) and the t_e time near the end of the section with the volume of space outside the gaseous part of the file Ω_w (Aliyeva, 2019; Mustafayev et al., 2019).

$$\bar{p}_g = \frac{\int_{t_n}^{s} q_g P_{at} dt + p_w \Omega_w}{\Omega_w} \tag{1}$$

$$P_{at} = \frac{P_w \Omega_0 - P' \Omega_w}{Q} \tag{2}$$

$$P' = P_w - \gamma_w Z - \Delta P \tag{3}$$

We find the formula p – pressure p_0 in the gaseous part of the field at the time of the final cut, t_e – pressure and volume Ω_0 – in the gaseous part of the field at the time of the initial cut, $k = \Omega(Z)\,\mu_w(H - Z)$, we define p_{vs}.

$$q_k = \frac{2\pi kh\Delta pn}{\mu_w \ln \dfrac{R_{sa}^{2n} - R_b^{2n}}{nR_{sa}^n + R_b^{n-1} R_e}} \tag{4}$$

According to the formula t_e, we find the yield sum of the compressed water at the end of the cut-off time. Then we determine the change in the volume $\Delta\Omega$ of the cavity at the edge of the gaseous part of the field over time. However, it should be noted that the average consumption of the liquid Δt in a small period of time is equal to the arithmetic mean of the initial and final sections (Mustafayev et al., 2017).

$$\Delta\Omega = \frac{q_w + q_k}{2} \Delta t \tag{5}$$

The new value of the outer space volume is: $\Omega'_w = \Omega_0 + \Delta\Omega$.

We repeat the calculation as described above until the values of assumed Ω_w and Ω'_w obtained are not equal or the calculations that can be assumed differ in accuracy. Then we work with the following values of Δt and Ω_w and assume the initial Ω_0 and p_w values of $\bar{p}_0$ and Ω_w in the same way in the report.

By squeezing the liquid from water trap of the operating wells with gas, it is possible to create underground reservoirs under different boundary conditions in the press contours (Aliyeva, 2016; Ismayilov et al., 2018). In the general case $q_w = q_w(t)$.

This shows that the consumption of gas injected into the water trap is well known. Boundary conditions in the flow contour are p_{vs} = const. The presence of a constant pressure in the discharge circuit results in the gas flowing freely through the wellhead of the discharge well at a relatively small change in flow rate.

In the following case, gas reservoirs are created by squeezing the liquid from the working wells in the water pressure system of the field, and in this case the injected gas consumption is known. It is necessary to calculate the creation of the reservoir. To do this, we will perform calculations.

The scheme of the field water pressure system is given in Figure 1.

We assume the following data for the calculations. The porosity of the field is 20%, the coefficient of permeability is 1,5 Darcy, the dynamic coefficient of water viscosity, μ_w, is 1 centipoise, reservoir thickness is 20 m, pressure in the discharge contour, R_{dc}, is 6 MPa, pressure in the contour of the feeding area, P_{fc}, is 6 MPa, radius of the discharge contour, R_{dc}, is 3000 m, specific gravity of water, γ_w, is 1000 kg/m^3, water trap height – 55 m, radius of the emptied well, R_w, is 0,1 m, average radius of fixed water intake, $R_a = R_b$, is 500 m, constant consumption of injected gas, q_g, is 10^6 m^3/day, radius of contour of feeding area, R_c, is 19,47 km, number of operating wells – 40, number of pressure wells – 20.

Let us calculate the value of:

$$q_s = \Delta P \cdot A_0 \tag{6}$$

$$A_0 = \frac{2\pi khn''}{\mu_w \ln \dfrac{R_{ca}^{2n'} - R_b^{2n'}}{n' R_{ca}^{n'} R_b^{n''-1} R_c}} = \tag{7}$$

$$= \frac{2 \cdot 3.14 \cdot 1.5 \cdot 2000 \cdot 40 \cdot 0.864 \cdot 10}{2.3 \cdot 33.5 \cdot 10} = 845\,\mathrm{m}^3 / \mathrm{day}$$

The results of the above calculations are given in Table 1.

According to Table 1, the dependencies $p_w = \bar{p}_w(t)$ and $Z = Z(t)$ were set up (Figure 2).

Table 1. Basic data characterizing gas storage facilities created by displacement of water from operating wells

Tabela 1. Podstawowe dane charakteryzujące zbiorniki gazu powstałe w wyniku wypierania wody z odwiertów eksploatacyjnych

$t_e - t_b = \Delta t$	Ω_w	$\bar{p}_w$	Z	Δp	A_0	q_c	$\Delta\Omega$	Ω''_w
[days]	[10^6 m^3]	[MPa]	[m]	[at]	[m^3/day, at]	[m^3/day]	[10^6 m^3]	[10^6 m^3]
60 – 0 = 60	0.840	7.150	5.35	16.56	845	13.900	0.840	0.840
120 – 60 = 60	1.675	7.165	7.45	16.41	845	13.600	0.834	1.674
180 – 120 = 60	2.507	7.180	9.05	16.39	845	13.830	0.831	2.505
240 – 180 = 60	3.336	7.192	10.5	16.37	845	13.820	0.830	3.335
300 – 240 = 60	4.160	7.202	11.7	16.35	845	13.810	0.828	4.163
360 – 300 = 60	4.990	7.212	12.9	16.33	845	13.800	0.827	4.990

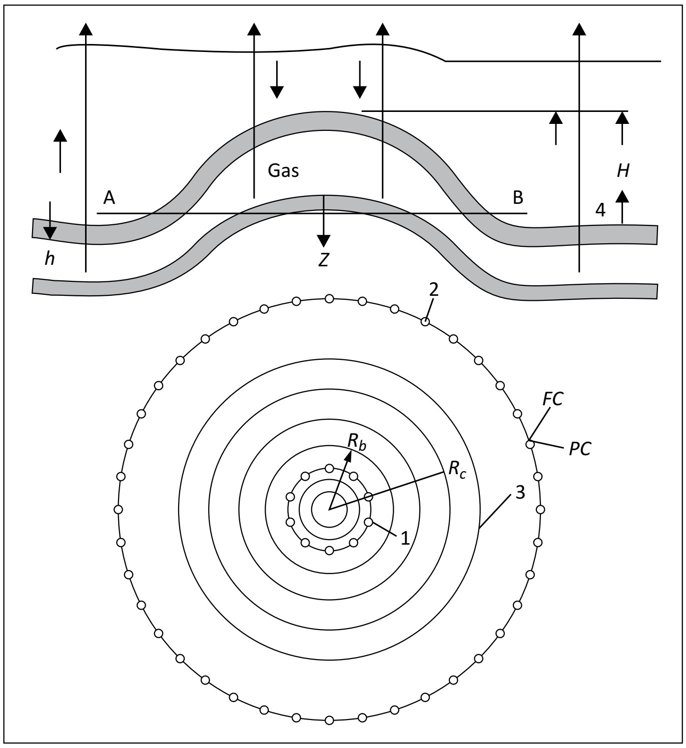

Figure 1. Scheme of the field water pressure system: 1 – injection wells; 2 – operating wells; 3 – contour lines; 4 – waterproof bed cover; *FC* – flow contour; *PC* – pressure contour; R_b – radius of injection well battery ($R_b = R_0$); H – the height of the water trap; h – formation water height; A–B – the lowest possible level of gas-water contour; Z – compression rate

Rysunek 1. Schemat systemu ciśnieniowego wody złożowej: 1 – odwierty zatłaczające; 2 – odwierty eksploatacyjne; 3 – izolinie; 4 – nieprzepuszczalna warstwa pokrywająca złoże; *FC* – kontur przepływu; *PC* – kontur ciśnienia; R_b – promień grupy odwiertów zatłaczających ($R_b = R_0$); H – amplituda pułapki; h – interwał konturującej wody złożowej; A–B – najniższy możliwy poziom konturu gazowo-wodnego; Z – wielkość kompresji

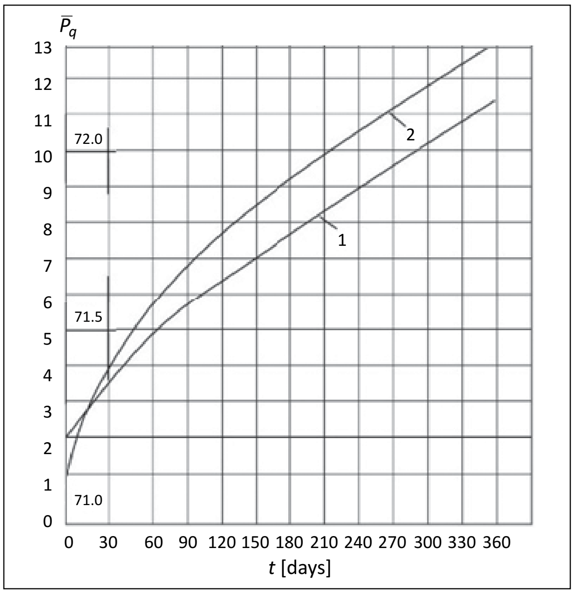

Figure 2. Dependence curves; 1 – $P_q = P_q(t)$; 2 – $Z = Z(t)$

Rysunek 2. Krzywe zależności; 1 – $P_q = P_q(t)$; 2 – $Z = Z(t)$

As it can be seen from the calculation, if reservoir formation is the result of fluid displacement through the operating wells, then the storage capacity of the reservoir at a stable gas injection rate is almost constant ($d\Omega_w/at$).

$1 - \bar{p}_w(t)$; $2 - Z = Z(t)$

Based on the above (Table 1), gas storage capacity can be calculated using formula (1), (Aslanov, 2001; Aliyeva, 2018):

$$\Delta\bar{\Omega} = \Delta\tau \frac{\left[-1+\alpha(1-\bar{Z}_0)+\dfrac{\bar{Q}_0}{2}+\dfrac{\bar{Q}_1}{\Omega_0}\right]}{1+\dfrac{1}{2}\Delta\tau\left(\dfrac{\alpha\beta_1}{F_0}+\dfrac{\bar{Q}_1}{\bar{\Omega}_0^2}\right)} \tag{8}$$

Here:

$$\beta_1 = \frac{\Omega_k}{HF_k m};\ \Omega_k = \int_0^n FmdZ;\ \Omega_q = \int_0^z FmdZ; \tag{9}$$

$$\bar{\Omega} = \frac{\Omega_q}{\Omega_k};\ \bar{Z} = \frac{Z}{H}$$

$$\bar{F} = \frac{F}{F_k} \tag{10}$$

$$\alpha = \frac{\gamma_w H}{\rho_{dc}} \tag{11}$$

$$q_0 = \frac{2\pi kh\rho_{dc}n}{\mu_w \ln\dfrac{R_{dc}^{2n}-R_b^{2n}}{nR_{dc}^n R_b^{n-1}R_q}} \tag{12}$$

$$\Omega_k / q_0 = T \tag{13}$$

$$\tau = t / T \tag{14}$$

$$Q = \int_0^t q_g p_{at} \tag{15}$$

$$Q = q_g p_{at} t \tag{16}$$

at – constant;

the initial data for the calculation has been carried out according to the formula (13) in the previous example $t = 60$ days; $\Omega_n = 0.84 \cdot 10^6$ m^3; $p_n = 7.15$ MPa; $Z_n = 5.35$ m; $F_m = 32 \cdot 10^4$ m^2; $\Omega_k = 56.5 \cdot 10^6$ m^3; $F_k = 616 \cdot 10^6$ m^2 was carried out according to the initial data.

To perform the calculations, it is necessary to compile an auxiliary Table 2.

$$\alpha = \frac{1000\cdot 55}{60\cdot 10^4} = 0.092$$

$$\beta_1 = \frac{56.5\cdot 10^6}{55\cdot 6.16\cdot 10^6\cdot 0.2} = 0.833$$

$$\bar{Z}_0 = \frac{5.35}{55} = 0.00975$$

$$q_0 = \frac{2\cdot 3.14\cdot 1.5\cdot 2000\cdot 60\cdot 40\cdot 0.864\cdot 10^5}{2.3\cdot 33.5\cdot 10^6} = 50\,700 \text{ m}^3/\text{day}$$

$$\bar{\Omega}_0 = \frac{0.84\cdot 10^6}{56.5\cdot 10^6} = 0.01487$$

$$\bar{F}_0 = \frac{32\cdot 10^6}{0.2\cdot 6.16\cdot 10^6} = 0.257$$

$$T = \frac{56.5 \cdot 10^6}{5.07 \cdot 10^4} = 1113 \text{ day}$$

Table 2. Values of t, τ and $\overline{Q}$
Tabela 2. Wartości t, τ i $\overline{Q}$

T [days]	τ	$\overline{Q}$	*T* [days]	τ	$\overline{Q}$
0	0	0.0177	180	0.1617	0.0708
60	0.0539	0.0354	240	0.2156	0.0885
120	0.1078	0.0531	300	0.2695	0.1062

$$\Delta\overline{Q} = \frac{0.0539\left[1 + 0.092(1 - 0.0975) + \dfrac{0.0177 + 0.0354}{2 \cdot 0.01487}\right]}{1 + \dfrac{1}{2} 0.0539\left(0.257\dfrac{0.092 \cdot 0.833}{0.257} + \dfrac{0.0354}{(0.01487)^2}\right)} = $$

$$= 0.0088$$

$$\overline{\Omega}_1 = 0.01487 + 0.0088 = 0.02377$$

$$\overline{\Omega}_1 = 56.5 \cdot 10^6 \cdot 0.02377 = 1.34 \cdot 10^6 \text{ m}^3$$

$$Z_1 = 6.7 \text{ m}$$

$$\overline{Z}_1 = 6.7 / 55 = 0.122$$

$$\overline{F}_1 = \frac{40.0 \cdot 10^4}{0.2 \cdot 616 \cdot 10^6} = 0.322$$

$$p_g = 8.95 \text{ MPa}$$

In the next calculations, let us take the values of Ω, Z, and $\overline{F}_1$ as the initial values and follow the same procedure. The results of the calculations and comparison with the data obtained by the sequential approximation method (Table 1) are given in Table 3. It can be seen from Table 3 that $\Delta\tau = 0.0539$ is obtained by the sequential approximation method.

The relative error in the accepted values Ω and p_g is too large at the beginning of the calculation and reaches 20 and 24.9%, respectively. Then these values decrease and when $t = 300$ days they amount to 2.4 and 2.61%, respectively.

To increase the accuracy of the report, it is necessary to reduce the value of $\Delta\tau$ to $\Delta\tau = 1.01$ ... 0.005, which in turn significantly increases the volume of calculations. However, in modern computing, all operations can be performed quickly and at a very low value of $\Delta\tau$.

At the bottom of the pressure wells, the pressure at the calculated value of pg is as high as the pressure from the well to the gas–water contour during gas filtration.

Conclusion

The development of UGS, underground CO_2 storage and the storage of other gases, including compressed air and halogen, will play a key role as energy technologies evolve in the coming decades. Many of the issues that arise during the planning and construction phases of UGS sites have been covered, including important and related aspects of safety and public confidence. The lessons learned from ongoing research into CO_2 storage may provide valuable input into the planning, development and ultimately decommissioning procedures for UGS facilities that are emerging in the UK. This publication should, therefore, prove of interest to developers, planners and local communities as we encounter new issues in the energy landscape of the twenty-first century. The presence of a constant pressure in the flow contour results in the gas flowing freely from the wellhead of the working well at a relatively small flow rate, and the formation of a reservoir occurs by compressing the fluid through the working wells.

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Nomenclature

Ω_g – volume of the cavity,
$\overline{p}_g$ – pressure of the gaseous part,
t – the period since the gas injection,
Z – compression rate,
F_a – gas–water contact area,

Table 3. Ω calculated by the formula (1) and the corresponding values Z, F_m, p_g
Tabela 3. Ω obliczone według wzoru (1) oraz odpowiadające im wartości Z, F_m, p_g

t_c	Ω	Z	F	$\overline{p}_g$	$\dfrac{(\Omega_g - \Omega)\cdot 100}{\Omega_g}$	$\dfrac{(p_g - p)\cdot 100}{p_g}$
[days]	[10^6 m^3]	[m]	[10^4 m^2]	[MPa]	[%]	[%]
0	0.84	5.35	32.0	7.15	0	0
60	1.34	6.70	40.0	8.95	20,00	24.90
120	2.15	8.45	50.0	8.37	14.30	16.60
180	3.07	10.0	60.0	7.82	8.00	8.74
240	3.99	11.5	69.0	7.52	4.08	4.83
300	4.87	12.7	76.0	7.40	2.40	2.61

R_{av} – the average radius of water,
μ_w – dynamic viscosity coefficient of water,
K – conductivity,
n – number of working wells,
h – the power of the gaseous part between the radii and the contours,
p_{vs} – water pressure in the flow circuit,
H – the height of the water trap,
R_d – the radius of the discharge well,
P_{fc} – pressure in the contour of the feeding area,
FC – flow contour,
PC – pressure contour,
R_b – radius of pressure well battery,
q_g – constant consumption of injected gas,
γ_w – specific water gravity.

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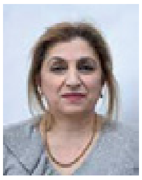

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