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IMPLEMENTATION OF NEW TECHNOLOGY IS A RELIABLE METHOD OF EXTRACTING RESERVES REMAINING IN HYDROCARBON DEPOSITS

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The prospects for further increase in oil production determined the introduction of new advanced technologies at all stages of the geological exploration process, drilling of wells, extraction and processing of hydrocarbons. On exploited deposits located at the late and final stages of development, in areas with developed infrastructure, the task of increasing oil recovery is particularly relevant. The increase in the total oil extraction in the fields by only a few percent allows us to obtain additionally millions of tons of oil and gas condensate.

The oil reservoir is a multifactorial dynamic dissipative system and possesses all the properties of nonlinear self-organizing systems. To order the physicochemical processes in the formation in the parametric resonance mode, it is sufficient to periodically apply pressure to the formation by wide-band pulses from an independent nonlinear source. Such an independent well source is a plasma-pulse generator with an energy of about one kilojoule and a frequency spectrum from a few hertz to several kilohertz with a period of elastic vibrations 1-2 times per minute.

The authors of the proposed technology suggest using an underwater electric explosion of conductors, in which the process of formation of a conducting channel is a successive chain of phase transformations of a metal under the influence of a pulsed current and then a breakdown of the hydromedia along the products of the explosion. A typical process of initiating a discharge is the breakdown of the interelectrode gap in a liquid under the influence of an electrical voltage that appears on the electrodes when a charged capacitor is connected to them through a conductor initiating an explosion.

The application of the plasma-pulse effect equipment on the productive reservoir ensures an increase of oil and gas production rate and injectivity of injection wells by a factor of 2-6 and an improvement in the oil-water ratio of the produced fluid.

Key words: oil reservoir, remaining reserves, low-porosity and low-permeability reservoirs, plasma-pulse effect, water cut

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Introduction. Modern methods of oil fields development by a system of drilled wells with the use of various methods of intensifying hydrocarbon inflows, with all their huge economic efficiency and rapid return on investment, have a significant drawback, which consists in the fact that the degree of deposit recovery even under the most favorable conditions, does not exceed 50 % of geological reserves, and from deposits with hard-to-recover reserves (low-porosity and low-permeability reservoirs containing high-viscosity oil, significantly water-flooded reservoirs, etc.) ranges from 2 to 10 %.

Possible ways to solve the problem. The analysis of physical-chemical processes occurring on the bed during development of the deposit starting from the drilling stage and opening of productive formations, application of methods for maintaining the reservoir pressure, usage of all possible reagents for increasing hydrocarbon movability in the formation, restriction of water breakthrough and other technology preventing formation of insoluble salts and paraffin deposits in the reservoir and near well bore area, which limit the oil movability and decrease reservoir permeability, shows that the processes occurring in reservoir can be successfully managed and controlled. This enables to optimize the formation development process and increase hydrocarbon recovery coefficient [2, 5, 9, 12, 15-19, 28, 29, 31, 32].

What are the reasons for the decline in hydrocarbon production?

The first is depletion of the reservoir energy. The applied methods of pumping water, gas and other carriers tend to increase the intensity of the formation fluid, but due to the differences in mobility of oil, gas and water in the reservoir, as well as due to anisotropy of the formation parameters, the rate of hydrocarbon movement to the producing wells is not the same. This leads to the formation of washed zones and areas of high residual oil saturation (bypassed oil).

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The second reason is a decrease in the total permeability of productive formation and, consequently, a decrease in well production rates, as well as an increase of water-flooded product, as the characteristics of the wells in the production and injection wells and the formation as a whole deteriorate in the process of reservoir development (formation damage, saline deposit, paraffins, etc.).

The most difficult task is additional extraction of hard-to-recover hydrocarbon reserves, including from deposits located at the late and final stages of development process.

In the theory of «synchronization of dynamical systems» under the dynamic material, to which any productive deposit can be attributed, are meant environments which physical parameters (density, viscosity, elasticity, rigidity, electromagnetic and physical properties) vary in time as well as in space. This applies to two or more different media, which, on the one hand, mutually penetrate each other, and on the other hand, make movements relative to one another, in particular oscillations (academician I.I.Blekhman of the USSR Academy of Sciences).

Each hydrocarbon deposit must be considered as a complex multifactorial nonlinear dynamical system in which constant changes occur. Often, as a result of the long-term exploitation of the deposit and permanent technogenic intervention in the oil production process, it is necessary to apply quickly the methods and technical means for the optimal management of physicochemical processes in the reservoir [4, 17].

There is a correlation relationship between filtration flows and wave acoustic and electromagnetic fields. The synchronized rhythmic hydrodynamic field is an acoustic characteristic of oil-saturated systems.

A number of researchers [15, 17, 22-24] explain these phenomena by the nonlinearity of the interaction of physical media. It becomes quite obvious that, depending on the degree of energy generation in the formation, geophysical fields measurements can provide information on reversible or irreversible processes in the reservoir.

The study of the properties of the geological section with the mass, density, and velocity of propagation of elastic vibrations (longitudinal, transverse, and other types of waves) characteristic for each formation allows us to conclude that the attenuation of elastic vibrations of different frequencies in a section composed of rocks differing in porosity, permeability, concentration of clay material, saturation with gas, oil or water, should be different [23, 24].

Each saturated reservoir has its own stationary (dominant) circular frequency of free resonance oscillations, which cannot be determined, since it varies in time and space, and a process of disordered oscillations constantly occurs at the expense of the working agent injected into the formation to maintain reservoir pressure and energy coming from the outside (tides, natural and technogenic earthquakes, etc.). All this occurs in a nonlinear dissipative system, the form and properties of its oscillations are determined by the system itself (*the self-oscillatory regime* – A.A.Andronov, 1929).

Since the nature itself is essentially non-linear (academician of RAS R.F.Ganiev), the circular steady-state frequency of free resonance oscillations depends on the initial conditions, namely, the disturbing forces, and in this case, there appears a recurrent force per unit mass, which equals the disturbing force (academician of the USSR Academy of Sciences, I.I.Blekhman) [4].

Such phenomena are typical for nonequilibrium elastic self-oscillatory systems. When exposed to a gas-liquid medium, turbulent stresses play the role of vibrational forces (the Reynolds equation). The emerging bubble medium acquires different properties. In each complex complicated disordered system, the reflection, refraction, and absorption coefficients of elastic vibrations change their parameters and characteristics, and all acoustic oscillations in such a medium become low-frequency (academicians of the Russian Academy of Sciences A.S.Alekseyev, V.E.Nakoryakov) [20].

If such a medium is acted upon by wide band periodic pulses of the same strength, spaced apart for equal time intervals, then the medium begins to form shock pulses due to self-modulation, and in this case, there will appear a recurrent force, referred to unit mass, and equal to the disturbing force. The resulting elastic shock wave begins to stretch and compress the medium, propagating ra-

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dially horizontally from the oscillation source and causing the Rebinder effect (P.A.Rebinder – academician of the USSR Academy of Sciences).

The fundamental studies performed at the Scientific Center for Nonlinear Wave Mechanics and Technology of the Russian Academy of Sciences in the field of nonlinear wave mechanics of hydromechanical systems under the guidance of Academician R.V. Ganiev on the basis of new phenomena and effects discovered in the process of creating wave technology allow efficiently produce resonant pumping of energy into the processed media, thereby intensifying the technological processes (up to several dozen times) [15, 22].

The theory of self-organization shows that the trajectory in phase space, describing the evolution of a system with a complex internal structure, is very sensitive to small oscillations, possessing many bifurcation points (self-organization) of open systems, their transition from chaos to order and vice versa [17].

The studies of many Russian and foreign scientists, including B.P.Belousov, A.M.Zhabotinsky, E.Lorentz, and others, have shown that in nonequilibrium systems, i.e. in media with some feeding, autowaves can propagate, and disordered oscillations can self-organize with a periodic effect on them [15, 17]. In such a situation, the role of small quantities and effects greatly increases, which, being involved in right time, allow us to control the processes of self-organization, directing them in the desired way. Small effects play the role of a trigger for hidden reserves of systems [17, 23, 24].

Thus, the oil reservoir can be considered as an open dissipative nonlinear system, ready for self-organization and containing a huge source of unrecognized and therefore unclaimed energy, which in the course of operation is inextricably non-linearly connected with the producing and injection wells.

Modeling of non-linear processes occurring in the reservoir allows us to consider the productive reservoir as a set of oscillatory systems (a non-linear oscillator in a nonequilibrium elastic medium), which can be influenced by external forced oscillations. The most important feature of a nonequilibrium medium is that even a small disturbing force can lead to a disproportionately large effect (trigger effect). It is important to note that the impact should be periodic.

Proceeding from the above-stated information, the developers of plasma-pulse technology came to the following conclusion: in order to excite a complex system at resonance frequencies, it is necessary to have *an ideal, non-linear wide band controlled downhole source of directed periodic elastic oscillations* (*a pump generator*). *Such a source of initiated periodic oscillations will inevitably lead to the self-organization of the system, i.e. ordering of vibrations in the formation, which manifests itself in the form of one or more* (*in the case of a multilayer system*) *quasi-harmonics, and, consequently, the emergence of resonant phenomena* [17].

The downhole source of elastic vibrations in order to cause influence on the bottomhole formation zone and the reservoir as a whole must, on the one hand, have sufficient power to destroy the colmated area, increase the mobility of the well fluid, on the other hand, maintain the integrity of the cement ring.

The high-voltage plasma-pulse generator has these properties, it was developed by us [17, 25]. The use of an *«explosive»* calibrated wire to initiate electrical breakdown in the interelectrode space contributes to the formation of a stable cold low-temperature plasma, regardless of the conductivity of the well fluid and the hydrostatic pressure of the surrounding medium. Plasma is an ionized gas with a high temperature and pressure, which is formed in 50-55 μs due to the instantaneous evaporation of a specially selected calibrated metal conductor. A distinguishing feature of such a plasma is quasineutrality.

The process of plasma formation is accompanied by an elastic pulse with a duration of 50-55 μs with a frequency spectrum from units of hertz to 10.0 kHz, a pulse pressure of more than $2 \cdot 10^3$ MPa and a temperature above 25000 °C.

The mentioned characteristics: the ability to accumulate a large amount of energy and to allocate it with high speed and temperature for a short time, creating oscillations and waves

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with a significant amplitude (the theory of nonlinearity), are inherent in non-linear systems of objects [6, 11, 22, 30, 33].

The expansion of the plasma channel and its subsequent «collapsing» according to the periodic principle exerts a sign-changing load on the bottom-hole formation zone and the formation as a whole. As a result of repeated periodic repetition of repression-depression cycles, shock hydraulic pressure waves propagate along the matrix of the formation and its porous medium and change the porosity and permeability properties of rocks. Under their influence, the perforation intervals are cleared from the colmatizing particles of the rock and the mud residue, its filtrate, and precipitates of salts and asphalt-resin-paraffin formations precipitated in the porous medium. Pressure pulses open the natural cracks in the reservoir and promote the formation of new cracks [16-19, 25].

Numerous geophysical, hydrodynamic studies have shown that with periodic exposure the porosity of the reservoir changes insignificantly and the permeability increases sharply.

In order to obtain additional fluid inflow into the production well or increase the injectivity of the nearfield zone of the injection well, it is necessary to initiate a series of elastic periodic pulses along the entire working interval of perforation which pressure would exceed the plugging factor, and the propagation velocity of these pulses would increase the formation pressure conductivity factor [25].

A specific feature of the proposed well plasma-pulse technology is that it effects not only the near well bore zone, but also the reservoir as a whole, due to the deep penetration of the seismoacoustic wave into it and the creation of resonant processes in the formation.

The necessary number of periodic pulses of «pumping» depends on the mining-geological, porosity and permeability and other features of the reservoir, as well as the properties of the formation fluids and is calculated using a special method. Impulses initiated at equal intervals of time with a certain pressure at the initial stage create a shock wave that in the elastic medium causes elastic oscillations in the entire gas-liquid pore system.

The operating range (effective distance) of the plasma-impulse influence on the reservoir under certain geological conditions can be up to 1800 m. Therefore, the wells located at the developed formation often perceive this effect. Due to cleaning of collector pores, creation of new cracks and better washability of oil, the movability of the formation fluid increases, water cut is reduced and the production rate of the product extracted from the treated and observed wells is increased.

It is obvious, the parametric resonance of the formation, the synchronization of the dynamic system, as a result of which the light phase replaces the heavy one, can explain the decrease in water cut after the impact, since periodic fluctuations of the formation fluid occur.

During the motion of liquid droplets due to the inhomogeneity of the capillaries, their different curvature, a difference in the surface tension forces arises, the so-called capillary resistance. As research has shown, elastic waves can help to reduce capillary resistance. The effect of an elastic wave on a drop can on average be characterized by a vibrational force that, in the case of waves of certain characteristics that depend on the geometric dimensions of the droplets and capillaries, and also on the physical properties of the capillary liquid and the capillary walls, can be directed against the capillary resistance vector, which leads to its decrease [13].

When considering the flow of a viscous compressible fluid along the capillary along which the bending waves propagate, it was possible to establish that for certain sizes of capillaries the waves can provide a significant acceleration of the flow of the liquid. Moreover, this effect is especially significant for narrow pores which diameter is of the order of 1-10 μm. Even with wave amplitudes on the surface of pores not exceeding a fraction of a percent of its diameter, the effect of flow acceleration can reach five or more orders [13].

In order to achieve a similar effect by increasing the static pressure gradient along the pore, it would take more than 10^5 times to increase it, which is almost unrealizable. This fact allows us to

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consider waves as one of the most effective mechanisms for accelerating flows in capillaries and porous media. Understanding this effect makes it possible to use it to accelerate the flow of fluid in the near well bore zones in injection and production wells in order to intensify the flow of fluid into the well or to increase the injectivity and to change the injectivity profile. This effect, which has been discovered in theory, is one of the scientific principles on which the idea of using waves in the oil industry is based. Experiments and our practice of industrial application are confirmed by the research of Russian scientists. It is assumed that these effects are related to the existence of «micro-embryos» – the smallest gas bubbles or drops of condensate, which co-operative action manifests itself when reaching the transition pressure [13].

Laboratory and simulation studies (A.V.Maksiutin, Saint-Petersburg Mining University, 2008) of plasma-pulse action on heavy and highly viscous oil and porous media with heavy and highly viscous oil deposits in Tatarstan (Romashkinskoye deposit, carbonate reservoir, oil density 0.84 g/cm^3, viscosity 40 mPa·s) and the Republic of Komi (Usinskoe deposit, carbonate reservoir, oil density 0.87 g/cm^3, viscosity 703 mPa·s) confirmed the prospectivity of the technology [14] and showed following:

1) a decrease in the intensity of viscosity, thixotropic viscoelastic properties of high-viscosity oils is achieved due to the dispersive effect of the initiated elastic waves on the main structure-forming components of oil – asphaltenes;

2) periodic plasma pulses have a hydrophobic effect on the porous environment of the reservoir rocks, which contributes to the reduction of capillary pressures and the improvement of the porosity and permeability characteristics of the productive reservoir [13, 14];

3) new perspectives are opening up in increasing recoverable reserves of heavy and highly viscous oil deposits with hard-to-recover reserves in the complex use of plasma-pulse technology with temperature and physicochemical effects of aqueous solutions of alkali and acidic compounds;

4) a one-time plasma-pulse processing of samples and formations leads to a rearrangement of the structure of the oil, which persists for a long time (95 days or more, the samples of the oil from Usinskoe deposit retained a lower viscosity after the plasma-impulse action - PIA for more than two years) [14].

A noticeable effect is observed when applying PIA in injection wells in order to increase the injectivity and leveling of its profile. A focused elastic periodic pulse directed into the formation clears the channels in the near well bore zone of the formation, destroys the layer of the colmatant with abnormally superfluous surface energy, which makes it possible to improve the injection well injectivity in the irradiated part of the formation or interlayers. And since the depth of the impact on the reservoir is hundreds of meters or more, the effect of injection is perceived by neighboring production wells. In addition, previously missed unwashed interlayers are put into operation. Practice has shown that the treatment of injection wells by this method makes it possible to significantly increase the coverage of the development site by waterflooding and to slow down the rate of decline in hydrocarbon production [16].

It should be noted that in order to level the injectivity profile or to redistribute the injected fluid through the interlayers, it is not necessary to conduct isolation and drainage activities using various surface-active materials. The achieved effect makes it possible to include in the work previously unwashed zones, to increase flooding coverage, thereby increasing the oil recovery factor (ORF), and this task is solved without any additional capital expenditures.

We have been successfully applying the plasma-pulse technology in various geological-technical conditions, in deposits with terrigenous and carbonate reservoirs and heavy oils in Russia (Ural-Volga, Timan-Pechora, Western Siberia) (see the table) and abroad (China, Kuwait, Kazakhstan, Uzbekistan, Czech Republic, USA), which is confirmed by geological-physical studies before and after the application of the technology.

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The examples of processing productive oil reservoirs in Russia using the technology of plasma-pulse impact

Deposit	Well number	Well type	Collector type	Density, g/cm^3	Viscosity, mPa·s	Well operation parameters, t/day		Growth, %
						before impact	after impact	
Sovetskoe	631	Producing	Terrigenous	0.772	1.6	11	16	45
Pervomaiskoe	856	"	"	0.753	0.9	27	41	52
Ardalinskoe	5	"	Carbonaceous	0.845	1.52	45	62	38
Dyususchevskoe	7	"	"	0.845	1.52	2	11	450
Zapadno-Sikhoreiskoe	70	"	"	0.845	1.52	85	165	94
Ardalinskoe	8	"	"	0.845	1.52	25	32	28
Oshkotynskoe	44	"	"	0.845	1.52	22	30	36
Raevskoe	6	Injection	Terrigenous	Formation water	1.015	11	70	536
Zapadno-Noyabrskoe	185	"	"	Same	1.015	28	75	167
Sutorminskoe	8741	"	"	"	1.015	70	140	100
Sutorminskoe	1475	"	"	"	1.015	50	94	88
Muravlenkovskoe	2087	"	"	"	1.015	275	700	154
Sredne-Irkutskoe	235	"	"	"	1.015	110	259	135
Romanovskoe	1079	"	"	"	1.015	100	190	90
Lomovoe	616	"	"	"	1.015	19	116	511
Severo-Vakhskoe	1046	"	"	"	1.015	0	90	–

The work begun at the Saint-Petersburg Mining University, R&DE of EFA n.a. D.Efremov, CJSC «ROST», OJSC SPC «GeoMIR», OJSC «Georezonans» is being successfully developed by NOVAS Energy Services, «NOVAS Sk» (resident of the Skolkovo State Fund). A large group of companies, with the support of investors and the Skolkovo Foundation (the General Director – Candidate of Economic Sciences, N.P.Ageev, the Director for Strategic Development of NOVAS Energy Services, P.G.Ageev, scientific consultant on PIA technology – professor of the Saint-Petersburg Mining University, Doctor of Engineering, A.A.Molchanov), is conducting mass production and piloting of plasma-pulse technology in Russia and abroad [1, 16-19, 25-27, 34]. The equipment based in plasma-pulse technology has been successfully used to impact more than 400 oil wells with various geological and technical conditions, the results of the works are widely covered in the press and are available on the website www.NOVAS-Energy.ru and «NOVAS Sk» (http://sk.ru/net/1110227/). The technology is protected by Russian and US patents.

The experience of using the plasma-pulse equipment shows that even in wells with hard-to-recover hydrocarbon reserves, reservoirs with a porosity of 2-3 % and a permeability of (1.5-3) 10^{-12} m^2, one can obtain a multi-month effect of increasing the production rate of wells and reduce the water content in the producing fluid. The aftereffect lasts from 6 to 24 months, sometimes even more, depending on the properties of the reservoir and the stage of reservoir development.

On the basis of fundamental scientific research of outstanding scientists of the Academy of Sciences of the USSR and the Russian Academy of Sciences, academicians A.S.Alekseev, I.I.Blekhman, R.F.Ganiev, A.N.Dmitrievsky, Ya.B.Zeldovich, L.D.Landau, V.E.Nakoryakova, A.K.Chetverushkin and other authors of plasma-impulse technology it is proposed to use the underwater electrical explosion of conductors (UEEC) as a powerful source of hydraulic pulses, in which the process of a conducting channel formation is a series of phase transformations of metal under exposure to pulsed current and then taking samples of hydro-medium for checking the explosion products [3, 6-8, 10, 21, 26, 27, 34]. A typical process of initiating a discharge is the breakdown of the interelectrode gap in a liquid under the action of an electrical voltage that arises between the electrodes when a charged capacitor is connected to them through an initiating conductor [25]. In the formation of the explosion channel, the discharge current instantaneously reaches tens and hundreds of kiloamperes, a low-temperature plasma is formed with a temperature at the initial stage up to $2.5 \cdot 10^4$ °C. With intensive energy release, the rate of channel expansion is comparable with the speed of sound in the liquid and even exceeds it. In such cases, the compression wave propagating in the liquid turns into a shock wave in the immediate vicinity of the channel or is im-

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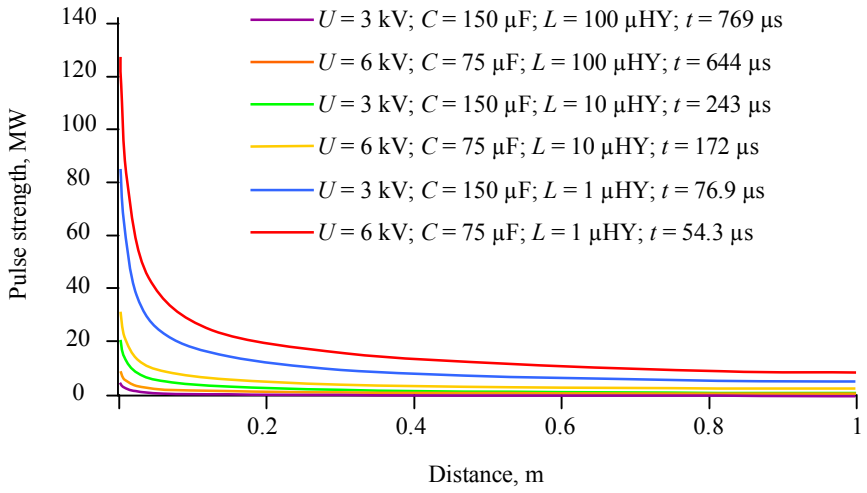
mediately radiated as a shock wave. During the discharge process during the passage of current, the temperature of the plasma changes insignificantly, reducing only after the end of the discharge. Plasma heating causes a pressure increase in the channel. Under the influence of increased pressure, the channel expands. The pressure in the channel during the discharge passes through a maximum at the initial stage, despite the increase in its volume the pressure in the channel increases and falls to the end of the discharge. At the maximum point, the pressure reaches $2 \cdot 10^3$ MPa with a moderate energy density in the channel [10, 21, 27].

The plasma density during the discharge varies insignificantly and is maintained at a level of 10^{20} particles per 1 cm^3. This happens because the decrease in the density of the plasma due to the expansion of the channel is compensated by the arrival of new particles as a result of the evaporation of water from the walls of the channel. The expansion of the channel continues after the end of the energy release, first under the influence of pressure increased in comparison with the hydrostatic pressure, and then due to the inertia of the flowing fluid flow. At the post-discharge stage, the channel becomes a gas bubble. Expansion of the bubble occurs until the kinetic energy of the diverging flow goes completely into the potential energy of the bubble, the pressure in which is less than the hydrostatic pressure. Then, under the action of hydrostatic pressure, the fluid moves back, the potential energy again turns into the kinetic one of the converging flow. When the cavity collapses, the gas pressure increases sharply. Under the action of this pressure, the liquid is thrown back and the process is repeated in the form of subsequent damping pulses [10, 21, 27].

The energy released in the discharge channel is used mainly for the work done by the channel upon expansion (about 50 %) and on heating of matter in the discharge channel. The work done by the channel is divided into energy of compression waves (up to 20 %) and pulsation energy (up to 30 %) [21, 27]. According to data [3], the energy of the shock wave is 62.8 %, the thermal radiation consumes 6.2% and the formation of the gas bubble – 31%. As a rule, theoretical calculations of activated processes are extremely complicated and most often supplemented by physical experiments [10, 11, 21, 27].

The question of the efficiency of energy conversion during PIA arises with the need to select the optimal discharge mode of the *LC*-circuit, at which a maximum of mechanical action is provided [22]. The shock wave parameters can serve as a measure of such impact. Most studies show that high efficiency is observed when the discharge proceeds in a regime close to critical when all the energy stored in the capacitors is discharged during one positive half-wave of the discharge current. A discharge close to the critical one ($\eta < 1$) ensures the fastest transfer of the stored energy to the discharge channel and the greatest acoustic efficiency. In the agreed mode, the rise time is $0.8\sqrt{LC}$. Proceeding from this, the period of intensive energy release should not exceed 40 μs, the inductance of the discharging circuit is $3\text{-}4 \cdot 10^{-6}$ HY, the capacity of power capacitors is 80-120 μF. The maximum pressure in the channel $P_a^m \cong 0.17(p_0 C U_0^2 / L l_{\text{d.g}})^{1/2}$ depends on the properties of the conductor, the rate of energy supply and the hydro-dynamic characteristics of the productive reservoir (p_0 is the hydrostatic pressure in the well, C is the conductor capacitance, U_0 is the charge voltage of the capacitors, L is the inductance of the discharge circuit, $l_{\text{d.g}}$ is the length of the discharge gap, m). At a well depth of 3 km, the pressure will be 325 MPa at $C = 170$ μF, $U_0 = 6$ kW and $L = 1$ μHY.

Voltage and capacitance are the main factors determining the length (voltage) and diameter (capacity) of the spark channel. With increasing voltage, the pulse energy ($W = CU^2/2$) and the steepness of the current pulse front increase sharply. An increase in the inductance of the discharge circuit leads to a sharp increase in the pulse duration and a change in the slope of the front. Therefore, an insufficient decrease in inductance leads to an increase in the mechanical efficiency of the discharge. An increase in the resistance of the discharge circuit reduces the energy of the pulse and the amplitude of the current, causes an increase in the pulse duration, and sharply affects the slope of the front, making it more gently-sloping, which ultimately reduces the efficiency coefficient.



The dependence of the shock wave power on the distance (from 0.01 to 1 m) with a plasma-pulse action of the equipment with different condenser capacitance, voltages and inductance of the discharge circuit

The length of the initiating conductor $l_{opt} = 1.35 \cdot 10^{-3} U_0 \sqrt[4]{LC}$. Its diameter is

$$d_{opt} = \left(\frac{W_0}{\sqrt{LC} h^*} \right)^{1/4},$$

where $h^* = \rho_c \sigma_{co} (\lambda_c + \gamma_c)$; ρ_c – conductor resistance; σ_{co} – conductor metal density; λ_c, γ_c – energy expenditure during melting and evaporation of the conductor metal.

The radiation power of the shock wave (see the figure) is determined by the formula [21]

$$P = \frac{2 \cdot 10^2}{\sqrt{r}} \left(\frac{C U_0^2}{L} \right)^{5/16} \omega^{7/16},$$

where r – position of the shock wave front with respect to the initial position of the initiating conductor; ω – resonance frequency.

It is known that acoustic and electromagnetic fields (the so-called electro-osmosis) contribute to the acceleration of physical and chemical processes [5, 27, 34]. When plasma-pulse action due to an electric discharge in the hydrosphere, the powerful pulsed elastic «shock waves» (with an energy of the order of $2 \cdot 10^8$-10^{10} MPa) are formed, which increase the mobility of the well fluid in the formation in the mode of the resonant state by «dominant» frequencies [3, 7, 8, 11, 23, 24].

Conclusions

1. The oil deposit is a multifactorial dynamic dissipative system and possess and demonstrates all the properties of nonlinear self-organizing systems.

2. For ordering of physical and chemical processes in the formation in the parametric resonance mode, it is sufficient to periodically apply pressure to the reservoir with wide band pressure pulses of an independent nonlinear source.

3. An independent well source is a plasma-pulse generator with an energy of about one kilojoule and a frequency spectrum from a few hertz to 10.0 kHz with an elastic pulse repetition period of 1-2 pulses per minute.

4. Application of the plasma-pulse action on the productive reservoir by the developed equipment provides the following:

– an increase in the oil and gas flow rate and injectivity of injection wells by a factor of 2-6, and an improvement in the «oil-water» ratio of the produced fluid;

– an increase in recoverable oil reserves without significant capital investment for any water cut of wells (more than 75 %), the impact is generally made on oil reservoir and previously unaffected zones and interlayers, resulting in an increase in the production rate of wells located at the same productive reservoir;

– an increase in the injectivity of injection wells with a decrease in injection pressure and, as a result, an increase in the flow rate of observed wells, a decrease in the rate of fall in the flow rate of hydrocarbons, and hence, increase of ORF;

– ecological cleanliness, simplicity and safety of operation;

– minimum consumption of material resources, the recoupment of costs for a complex of works on the application of the PIA does not exceed 3 months depending on the mode of operation;

– minor time input for processing the well (8-10 hours), after which it is put back into operation;

– guaranteed increase in production rate for liquid and oil, the duration of the effect of exposure is 6 to 24 months and more.

5. Even greater prospects are opened with the use of complex technology for the treatment of reservoirs with hard-to-recover hydrocarbon reserves, including with highly viscous oils, injection of reagents, and also in slot-type unloading of the working interval of horizontal wells with the simultaneous application of plasma-pulse technology without the application of hydraulic fracturing of layer during the extraction of methane from coal seams in the operating mines.

REFERENCES

1. Ageev P.G. Efficiency is confirmed. *Nefteservis*. 2009. N 4 (8), p. 44-48 (in Russian).

2. Bogomol'nyi E.I. Intensification of extraction of high-viscosity paraffinic oils from carbonate reservoirs of the Udmurtia deposits. Izhevsk: Institut komp'yuternykh tekhnologii, 2003, p. 272 (in Russian).

3. Bunttsen R. The application of exploding wires in the study of the power of underwater explosions. Elektricheskii vzryv provodnikov: Per. s angl. Moscow: Mir, 1965, p. 225-238 (in Russian).

4. Vibrations in technology. Spravochnik: In 6 vol. Vol. 2. Oscillations of nonlinear mechanic systems. Ed. by I.I.Blekhman. Moscow: Mashinostroenie, 1979, p. 351 (in Russian).

5. Gershtanskii O.S., Sherstnev N.M., Krylov D.A., Ugoleva A.V., Kurbanbaev M.I., Elemanov B.D. Influence of physical fields on technological processes of oil production. Moscow: OJSC VNIIOENG, 2001, p. 236 (in Russian).

6. Gulyi G.A. Scientific foundations of discharge-impulse technologies. Kiev: Naukova dumka, 1990, p. 203 (in Russian).

7. Zel'dovich Ya.B. The theory of shock waves and introduction to gas dynamics. Moscow-Leningrad: Izd-vo AN SSSR, 1946, p. 187 (in Russian).

8. Zel'dovich Ya.B., Raizer Yu.P. Physics of shock waves and high-temperature hydrodynamic phenomena. Moscow: Nauka, 1966, p. 688 (in Russian).

9. Ibragimov L.Kh., Mishchenko I.T., Cheloyants D.K. Oil production intensification. Moscow: Nauka, 2000, p. 414 (in Russian).

10. Kortkhondzhiya V.P., Mdivnishvili M.O., Saralidze Z.K. On the nature of the impulse pressure produced by the explosion of a wire in water. *Zhurnal tekhnicheskoi fiziki*. 2006. Vol. 76. Iss. 11, p. 43-46 (in Russian).

11. Krivitskii E.V. Dynamics of electric explosion in a fluid. Kiev: Naukova dumka, 1966, p. 206 (in Russian).

12. Kuznetsov O.L., Simkin E.M. Transformation and interaction of geophysical fields in the lithosphere. Moscow: Nedra, 1990, p. 269 (in Russian).

13. Landau L.D., Livshits E.M. Theoretical physics: In 10 vol. Vol. 6. Hydrodynamics. 3-e izd., pererab. Moscow: Nauka, 1986, p. 736 (in Russian).

14. Maksyutin A.V. Experimental studies of the rheological properties of high-viscosity oils under elastic wave action. *Avtomatizatsiya, telemekhanizatsiya i svyaz' v neftyanoi promyshlennosti*. 2009. N 5, p. 4-8 (in Russian).

15. Mirzadzhanzade A.Kh., Khasanov R.N., Bakhtizin R.N. Simulation of oil production processes. Nonlinearity, unevenness, heterogeneity. Moscow-Izhevsk: Institut komp'yuternykh tekhnologii, 2004, p. 308 (in Russian).

16. Molchanov A.A., Ageev P.G. New efficient technology for accelerated development of oil wells when putting them into operation. *Oil & Gas Eurasia*. 2009. 7/8, p. 74-77 (in Russian).

17. Molchanov A.A., Ageev P.G. Plasma-pulse impact on the oil reservoir as a multifactorial dynamic dissipative system. *Karotazhnik*. Tver': AIS, 2011. Iss. 2 (200), p. 94-106 (in Russian).

18. Molchanov A.A., Ageev P.G. Plasma-pulse impact on the productive reservoirs. *Oil & Gas Journal*. 2008. N 9 (22), p. 42-45 (in Russian).

19. Molchanov A.A. Advanced technology providing additional extraction of oil and gas. Toplivno-energeticheskie resursy Rossii i drugikh stran SNG: Mezhdunarodnyi simpozium 24-26 aprelya 1995 g. (dop. k osn. tomu). Saint-Petersburg Mining Institute. St. Petersburg, 1995, p. 25-29 (in Russian).

20. Nakoryakov V.E., Pokusaev B.G., Shreiber I.R. Wave dynamics of gas and vapor-liquid medium. Moscow: Energoatomizdat, 1990, p. 248 (in Russian).
21. Naugol'nykh K.A., Roi N.A. Electric charges in water (hydrodynamic description). Moscow: Nauka, 1971, p. 155 (in Russian).
22. Nonlinear mechanics. Moscow: Nauchnyi tsentr nelineinoi volnovoi mekhaniki i tekhnologii RAN, 2007, p. 155 (in Russian).
23. Nikolaevskii V.N. Mechanism of vibroexposure to oil recovery and dominant frequencies. *DAN*. 1989. Vol. 307. N 11, p. 570-575 (in Russian).
24. Nikolaevskii V.N. Geomechanics and fluid dynamics with applications to the problems of gas and oil reservoirs. Moscow: Nedra, 1996, p. 448 (in Russian).
25. Molchanov A.A., Ageev P.G., Bol'shakov E.P., Yatsenko B.P. Patent 2373386 RF, C/01.07.2008. A method for influencing the near well bore zone and oil-saturated reservoirs (variants) and a device for its implementation. Publ. 20.11.2009 (in Russian).
26. Dmitriev D.I., Molchanov A.A., Sidora V.V. Patent 2244106 RF, MPK E21V43/16. Oil production intensification method. Prioritet 10.01.2005 g.; patentoobladatel' Sankt-Peterburgskii gornyi institut im. G.V.Plekhanova. Publ. 10.01.2005 (in Russian).
27. Pashchenko A.F., Ageev P.G. Plasma-pulse technology for improvement of oil recovery: assessment of mechanical impact parameters. *Nauka i tekhnika v gazovoi promyshlennosti*. 2015. N 3 (63), p. 1-8 (in Russian).
28. Dyblenko V.P., Kamalov R.N., Sharifullin R.Ya., Tufanov I.A. Increase in productivity and well recovery with application of vibration-wave action. Moscow: OLL «Nedra-Biznestsentr», 2000, p. 381 (in Russian).
29. Rogachev M.K., Strizhnev K.V. Fighting the complications during oil production. Moscow: Nedra, 2006, p. 295 (in Russian).
30. Ryskin N.M., Trubetskov D.I. Nonlinear waves. Moscow: Nauka, 2013, p. 306 (in Russian).
31. Seismic acoustics of porous and fractured geological environments: In 3 vol. Ed. by O.L.Kuznetsov. Moscow: Informatsionnyi tsentr VNIIgeosistem, 2004, p. 998 (in Russian).
32. Simkin E.M., Lopukhov G.P. Vibro-wave and vibroseismological methods of producing impact on oil reservoirs. Obzor inf. Ser. «Neftepromyslovoe delo». Moscow: VNIIOENG, 1989. Iss. 15, p. 15-22 (in Russian).
33. Yutkin L.A. Electrohydraulic effect and its application in industry. Leningrad: Mashinostroenie, 1986, p. 253 (in Russian).
34. USA Patent N 9181788 B2 Plasma source for generating nonlinear wide band, periodic, directed, elastic oscillations and system and method for stimulating wells, deposits and boreholes using the plasma source. The Positive decision dated 10.10.2015.

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