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Article

Physical Basis for Creating Energy and Resource-Saving Rheo-Technology in Oil Production

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Abstract: In a previous paper we presented the results of our investigations on the application of externally imposed temperature fields for the improvement of the non-Newtonian properties of raw oil in the well and also on the possible use of electric and magnetic fields in the water flooding process of the oil layer. In this article, some additional results are presented with regards to the application of external pressure fields to the same purpose, with the goal of increasing the well output and improve the efficiency of gaslift wells and oil pipelines. The possibility of regulating the gas-liquid system saturation pressure is discussed as well, to expand the opportunity of varying the well operating regime.

Keywords: rheo-technology; oil recovery; pressure treatment; non-Newtonian oils; electronic paramagnetic resonance (EPR)

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1. Introduction

The wide range of technological systems applied in oil-and-gas production and also recovered non-Newtonian oils are characterized by non-equilibrium properties, which differ in their complicated rheophysical parameters and existence of “memory” [1–6]. Over recent years, investigations on the regulation of rheophysical properties of these hereditary systems by physical fields have been undertaken under the leadership of the principal author [5,7–12].

The application of externally imposed physical fields such as magnetic, electric, pressure and temperature fields during the investigations testified to the possibility regulation of the systems' properties and revealed the common mechanism of all physical field effects, allowing us to extend the possibility of their application in different oil recovery processes. As a result of these physical fields effects, systems temporarily experienced changes in their rheological properties (decrease of viscosity and shear stress) and acquired the Newtonian properties with a subsequent return to their initial non-Newtonian properties. The results of the investigations also proved the availability of the "memory" of these systems which predetermined the necessity of applying repeated or cyclic physical fields on the investigated systems.

It is clear, that at the same time, new power and resource-saving technology possibilities are raised, which can be combined under the general name rheo-technology. One of the methods to enhance the technological efficiency of recovery and transportation of non-Newtonian oils is the regulation of the rheological properties of these oils [8,10,12–18]. As the main mechanism for the regulation of rheological properties of the non-Newtonian oils, the authors offer the application of externally imposed magnetic, electric, pressure and temperature fields.

2. Application of Pressure Fields

2.1. Theory of pressure treatment

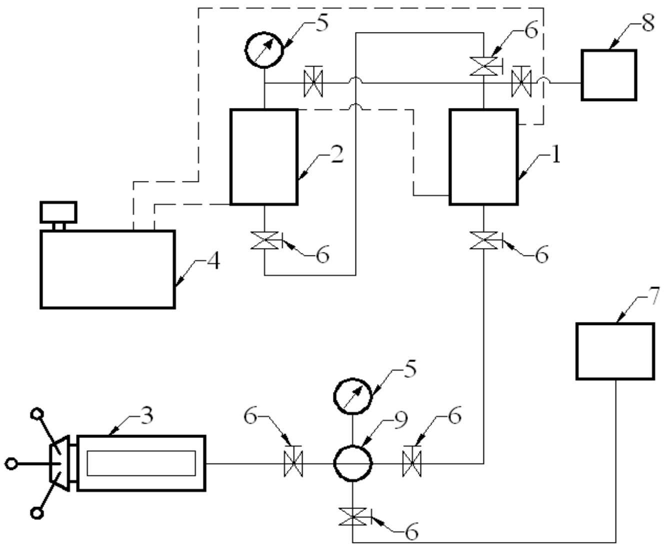
It was established by numerous investigations that, as a result of pressure treatment, non-Newtonian oils and systems adopt Newtonian liquid properties [5,11,15,19,20]. Some has argued that [21,22] when oils containing high-molecular compounds are treated, a destruction of the paraffin structure takes place, which results in the change of the system properties (decrease of viscosity), which is then gradually returns to the initial state as the structural "grid" of paraffins is restored.

Resins and asphaltenes play the role of "clamping modules" in the structural processes of paraffin "grid". Apart from the aforesaid, there is quite significant play in the restructuring mechanism and, probably, the defining role belongs to the electrokinetic effects, which occur in the process due to weak electric fields similar to those appearing during the heat or magnetic treatment of the systems [10]. To check the aforesaid assumption on the pressure treatment mechanism, investigations on the oil samples before and after the pressure treatment were performed using the electronic paramagnetic resonance (EPR) effect, as described in Section 2.3. In turn, oils with Newtonian properties lead to an increase of the well's oil output and the decrease of the priming pressure during pipeline transportation of these oils.

2.2. Experimental setup

Pressure treatment was performed according to the scheme shown in Figure 1.

Figure 1. Schematic experimental setup for pressure treatment. Item 1: high pressure liquid container; 2: high pressure bomb (PVT: Pressure, Volume and Temperature); 3: measuring press; 4: thermostat; 5: standard pressure gauge; 6: valve; 7: container for compressing liquid; 8: vacuum pump; 9: manifold.



The investigated sample of oil with a high content of heavy hydrocarbon fractions was placed into the PVT bomb (item 2) and high pressure container (1). Then, with the aim of eliminating the influence of gas and air in the pressure treatment process, the oil was carefully evacuated with a vacuum pump (item 8). The temperature was kept at the same level by the thermostat (4). Excess pressure was created in the PVT bomb (2) by the pump (3) by compressing a liquid which is separated from the investigated oil in the PVT bomb by the PVT bomb's piston, at that point, pressure loading was applied (for the minimum amount of time) to attain the required pressure value Po. Then, having reached pressure Po, valve (6) was closed to isolate the container and the standard pressure gauge (5) showed a pressure fall down to some stabilized value. Following this, the next system pressure loading was undertaken to reach the required pressure Po, once again there was a consequent pressure fall to a stabilized value, this was greater than the previous stabilized pressure value after the first test. The test was repeated through several pressure cycles until the full pressure treatment of the system was maintained, i.e. no further pressure fall was recorded and the pressure remained at the required value Po (see Figure 2).

This process of full pressure treatment of the system took from 48 to 72 hours. In this case, to save time, repeated system pressure loadings up to the required value Po were done without waiting for the pressure to stabilize. After a certain number of cycles, no further pressure fall was recorded and the pressure was stable (see Figure 3). The system was then considered to be pressure treated [12,15].

It should be noted that the system can be pressure-treated by unloading the system. In this case the pressure treatment procedure will be as per the scheme mentioned above, but in the reverse order, i.e., by reducing the system pressure in each cycle until there is no further pressure increase in the system and the pressure is stable.

Figure 2. Pressure changes as a result of full pressure treatment of oil from the Mishovdag field (Azerbaijan).

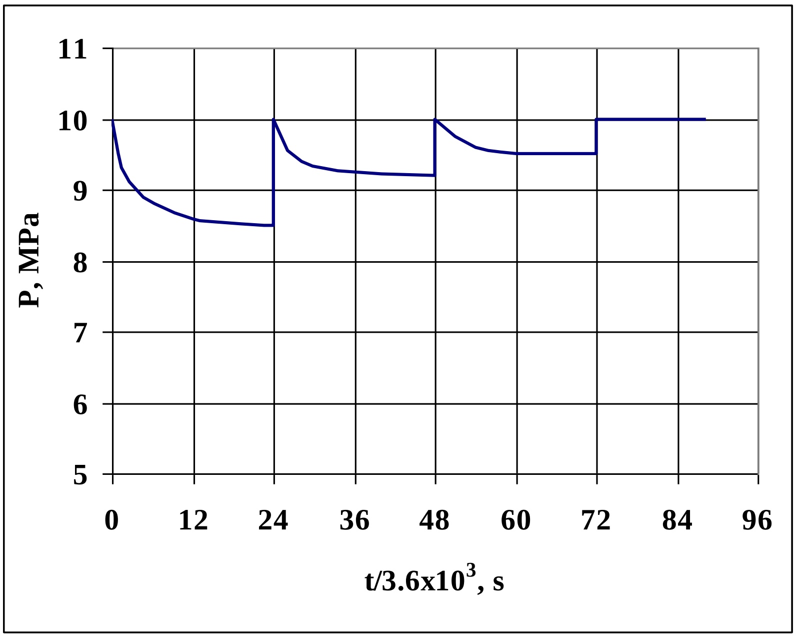
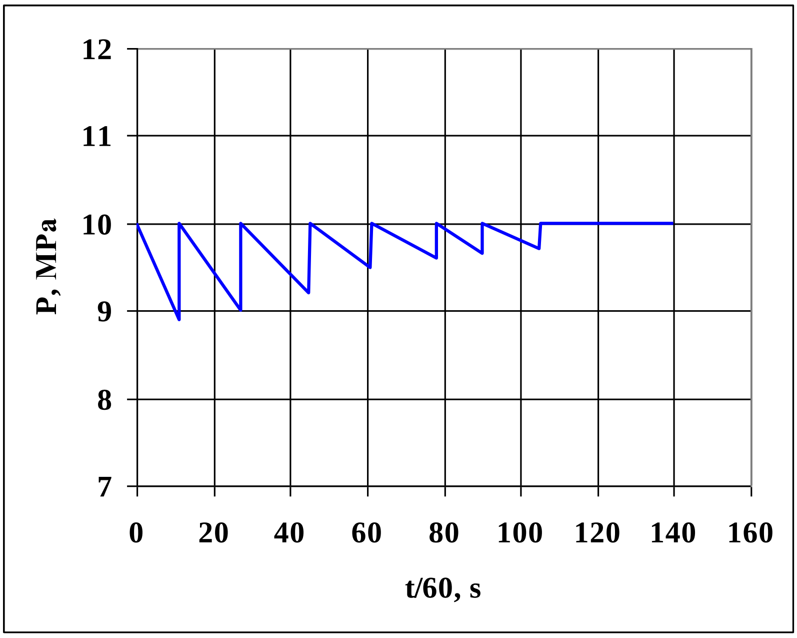
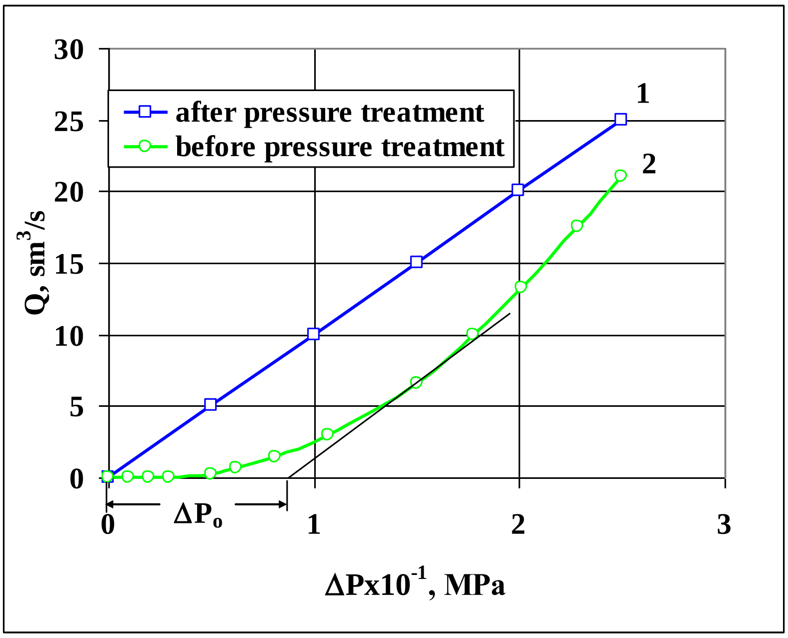


Figure 3. Pressure changes after consecutive pressurizing of oil from the Mishovdag field (Azerbaijan).



Following this, an experiment was performed on flowing the investigated oil (before and after pressure treatment) through a capillary (diameter D = 0.004 m, length L = 0.6 m) under pressure. The experiment was performed according to the ASTM (American Society of Testing Materials) test procedure. Differential pressure (ΔP) was created by means of valve at the end of the capillary (pressure at the beginning of capillary was kept the same). At the certain ΔP the appropriate values of Q were measured and graphs plotted to display the dependence of Q on ΔP during the flowing of oil before and after the pressure treatment (see Figure 4). As can be seen from the graph, oil after the pressure treatment behaves as a Newtonian liquid (curve 1).

Figure 4. Relation between Q and ΔP for oil before and after pressure treatment.



At balance of differential pressure forces and friction forces:

$$\Delta P_o \pi r^2 = \tau_o 2\pi r \ell \quad (1)$$

Whence:

$$\tau_o = \Delta P_o r/2\ell \text{ — initial shear stress} \quad (2)$$

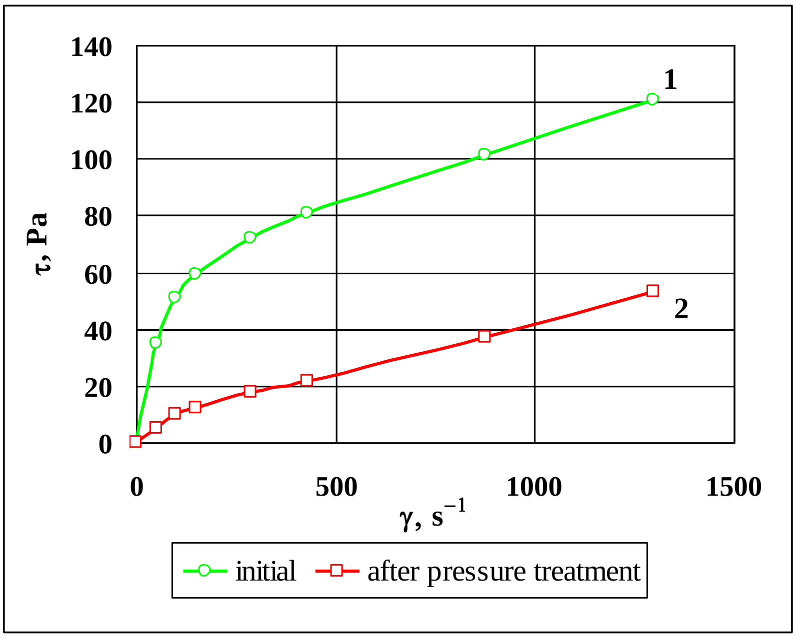
where ΔP_o = initial differential pressure, $\Delta P_o/\ell$ = initial pressure gradient, r = radius of capillary, ℓ = length of capillary.

It should be noted that the same test results were achieved when taking a sample of oil from the Shavol oilfield (Hungary), as the physical/chemical properties of this oil are the same as oil taken from the Mishovdag oilfield.

To evaluate the variation of oil properties after pressure treatment, the oil's rheograms (see curve 2, Figure 5) were taken on a RHEOTEST "HAAKE RV-11" instrument. The investigated oil was placed in the appropriate tank of the device. The temperature was kept at 353 K. A Z41 cylindrical measuring system was used according to DIN53018 (DIN—Deutsche Industry Norm). According to the velocity gradient values γ (preset by device) we got values of τ — shear stress. Then rheograms were plotted to display the dependence of τ on γ. To set the system "memory" reaction to the effect, the roto-viscometric measurements were performed on the tested samples over a 24 hour period. The results have shown that the improved rheological properties of oil were retained for a long period (up to 30 days) after pressure treatment (see Figure 6). At the same time, the influence of the oil sample's storage temperature on maintaining the improved rheological properties could be seen (see Figure 7).

It should also be noted that the same test results (as shown on Figures 5–7) were achieved when performing the roto-viscometric measurements for the non-Newtonian oil of Azerbaijan oilfield (Mishovdag) after its pressure treatment.

Figure 5. Roto-viscometric measurements for the oils of the Shavol oilfield (Hungary).

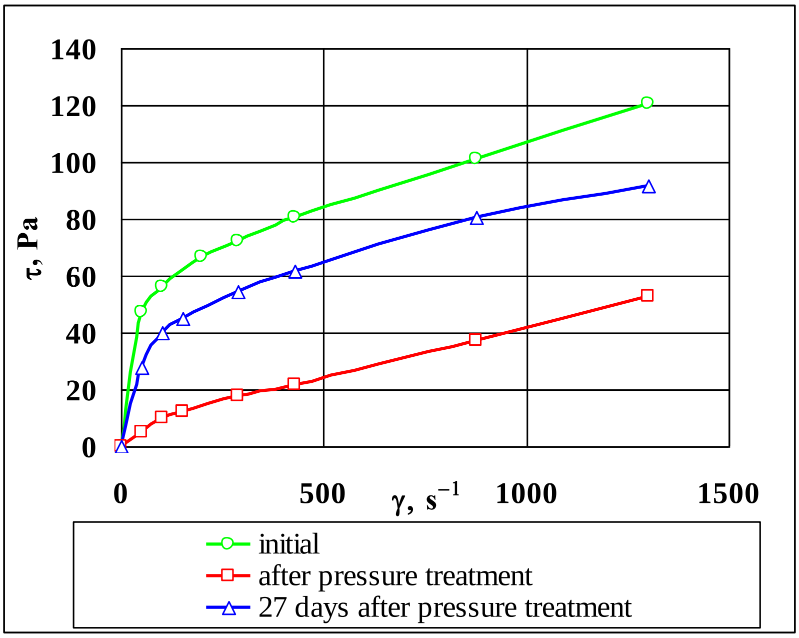


With regard to practical application, hereafter we give just a few examples of pressure treatment application to show how the procedure can be applied in practice. The procedure was applied on active oilfields of Azerbaijan (Shirvan, Balakhani, Binagadi, Narimanov) and Russia (Samootlor) having their wells operating in varying modes and pipeline networks.

Even through producing wells and pipeline flows are quite different applications, the author's main idea is to show the possibility of regulation of oils' rheological properties. These oils are lifted from the bottom to the surface in the case of producing wells and transported by pipeline in the case of pipeline flows. For both cases there is need for quite high differential pressure (energy consumption of layer in the first case and injection pump in the second case) to provide the movement of non-Newtonian oil in the well as well as in the pipeline. Thus, the benefit of our methodology in these two cases is the acquisition of Newtonian properties for non-Newtonian oils and hence provision of flowing for these oils at lowest differential pressure (less consumption of natural and artificial energy).

A deep well pump operating procedure is considered. The pump operating procedure is referred to as the mechanized operating procedure, i.e., when the reservoir energy is not enough to drive the oil from the well to surface. Here, there is a static level of oil in the well which exerts pressure to the oil in the bottomhole zone. By turning on the pump the oil is pumped from the borehole to the surface, thus the pressure to the oil in the bottomhole zone is decreased. The pump is then stopped, allowing the oil in the borehole to reach its static level (the pressure to the oil in the bottomhole increases). The cycle is maintained, repeatedly switching the pump on and off.

Figure 6. Roto-viscometric measurements of the "memory" reaction to pressure treatment for the Shavol oilfield (Hungary).



This method of pressure treatment is similar to that mentioned above in the experiment (see Figure 3) and in such a way the pressure treatment of oil in the bottomhole zone can be undertaken. Significant increases of well production have been observed using this procedure on many wells of Shirvan oilfield (Azerbaijan).

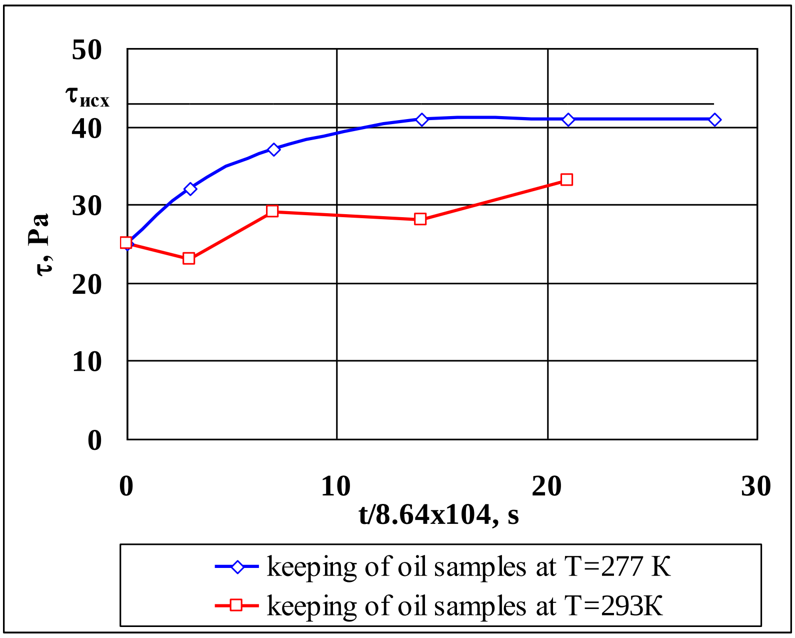
The procedure was also applied to some blowers (flowing well operations) of the Narimanov oilfield (Azerbaijan) and the Samootlor oilfield (Russia) and in this case the pump on/off operation was replaced by opening and closing the valve on the well head.

In the next example gas-lift well operations are considered where pressure in the supply network is insufficient to start gaslift in the well. Gas is pumped into the well for a period of time and then stopped. This cycle is repeated successively, allowing the system loading and unloading to be as described in the experiment above. After a period of time the gas-liquid mixture in the well becomes pressure treated leading to a change of its rheological characteristics, thus enabling it to rise to the surface.

Thus, by means of pressure treatment of the gas-liquid mixture some wells of the Narimanov and Binagadi oilfields (Azerbaijan) were put into operation at the initial pressure in the supply network (which, prior to the treatment was not sufficient to put the well into operation). This type of pressure treatment can be applied on gaslift wells not only for their start up, but also for increasing the efficiency of working gaslift wells.

Similarly, by turning the pump on and off it is possible to pressure-treat non-Newtonian oils transported by pipeline. Oil in this case develops more favorable properties (Newtonian) for its further efficient transportation. This also can be applied for pipeline start up. This procedure was successfully applied on inner-filed pipelines of mentioned oilfields. It should be noted that during the application of pressure treatment on some of the wells of the above mentioned oilfields, the wells output was increased by 25%–30%.

Figure 7. Dynamics of shearing stresses for the oils of the Shavol oilfield (Hungary) at different storage temperature after pressure treatment (γ = 145.5 s^{-1}).



2.3. Mechanism of pressure treatment

The pressure treatment experiment indicates that hydrodynamics are not directly responsible for the pressure treatment mechanism. To establish the processes taking place in oils during pressure treatment, oil samples were examined before and after heat treatment using electronic paramagnetic resonance (EPR) [11].

The investigation results using the radio spectroscopic method are illustrated in Figure 8 and they are indicative of the change of concentrations of paramagnetic centres (CPC) after pressure treatment. In all of the experiments it was evident that the system returned to its initial state after a period of time. This “return” process depends upon the duration of electrokinetic effects, i.e., leveling of CPC, which are matched with the variation of rheological properties of non-Newtonian oils. Variation of the EPR signal after pressure treatment may be explained as being based on the free-radical nature of paramagnetism, at the expense of the destruction of polynuclear structures of high-molecular compounds with the formation of non-paired spins, which is indicated by the growth of the EPR spectrum intensity.

3. Application of Electric and Magnetic Fields

3.1. Theory of electric and magnetic treatment and experimental setup

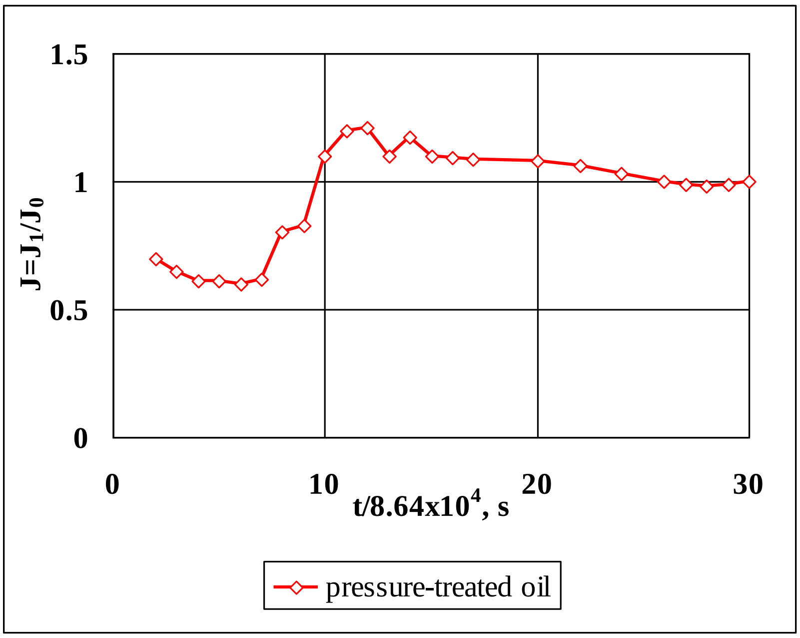
In preceding years there has been some convincing evidence of the benefits of the application of physical-magnetic and electric fields on thermodynamic properties of liquid systems in processes of oil recovery, cleaning of propellant and oils, and decontaminating sewage [9,23,24]. Investigations show that the effects of magnetic and electric fields have a common nature. During the application of external fields, nonpolar components are aligned along lines of force. The system, therefore, is no longer electro-neutral and reacts to this effect.

Theoretical and practical investigations on electrical treatment are based on modern theory of stability and coagulation of disperse system Deryagin-Landau-Verwey-Overbeek (DLVO theory), which considers aggregative stability as the result of the balance of Van der Waals forces and electrostatic repulsion forces [25,26].

During the electrical treatment of disperse systems some interesting effects are observed such as electrophoresis, which occurs in the presence of double electric layer (DEL) polarization; formation of interaction forces between particles and field, which usually appear in nonpolar medium and fields of high intensity; structure formation in nonpolar and polar mediums, etc. [27].

One of the important thermodynamic parameters of oil is saturation pressure Pn. The precise value of saturation pressure Pn and the possibility of its regulation are important in the view of the establishment of optimum production condition of a well. Herewith, investigation results of electric field effect on multiphase reservoir system are submitted.

Figure 8. Variation of the EPR signal intensity for pressure-treated oil (T = 353 K) of the Shavol oilfield. (J_1: intensity of EPR signal after pressure treatment; J_0: intensity of EPR signal before pressure treatment).

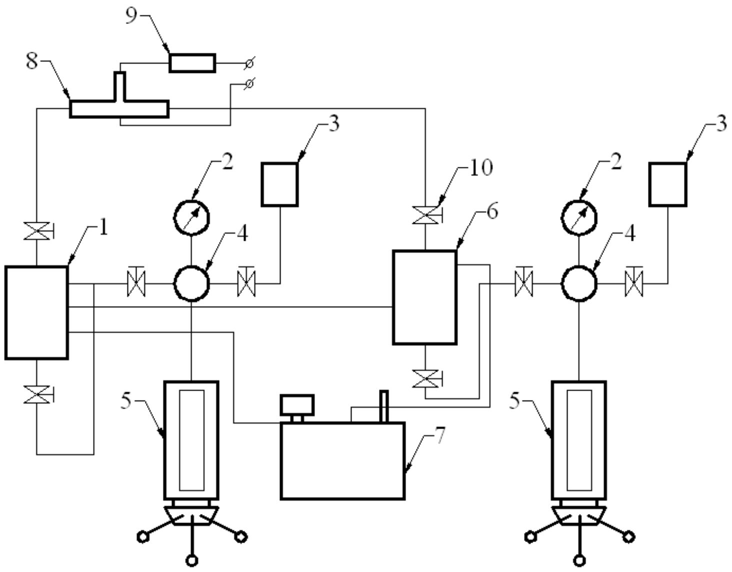


Experiments on the treatment of gas-liquid systems with electric fields have been undertaken according to the method illustrated in Figure 9 below. In the first series the recombined sample was the mixture of water and natural gas. During the treatment of this mixture with electrostatic field with intensity of 3,000 V/m, the decrease of system saturation pressure from Pno = 11.1 MPa to Pn1 = 9.5 MPa (ΔP = 1.6 MPa) was noted.

Repeated determination of saturation pressure for system of “water + gas” showed the return of the saturation pressure back to its initial value at the end of the second day following the switching off of the electric field.

As the output of producing wells, generally, is watered, then the next series of experiments were done with recombined samples of "oil + water + natural gas". A recombined sample was formed from the following: high viscosity oil from the Shirvan oilfield (Azerbaijan), water (10%) and natural gas from the Zirya field (Azerbaijan) with gas factor G = 30 m^3/m^3. The initial average value of the system saturation pressure was Pno = 7.0 MPa at temperature of experiment 315 K. This recombined sample has undertaken treatment with electrostatic field. The intensity of this field in different series of experiments was 3,000, 6,000 and 12,000 V/m, respectively. For each level of intensity there were 3–4 series of experiments. The results of the experiments showed the following: during the electric treatment with an intensity of 3,000 V/m, the system saturation pressure dropped 0.65 MPa; an electric treatment having an intensity of 6,000 V/m led to an average decrease of the system saturation pressure of 1 MPa; at an intensity of 9,000 V/m the pressure drop was 0.6 MPa, and at 12,000 V/m the recorded decrease was 0.3 MPa.

Figure 9. Schematic experimental setup for liquid-gas system treatment with electric field. Item 1: PVT bomb; 2: standard pressure gauge; 3: container for compressing liquid; 4: manifold; 5: measuring press; 6: PVT bomb; 7: thermostat; 8: electrotreatment unit; 9: rheostat, 10: valve.



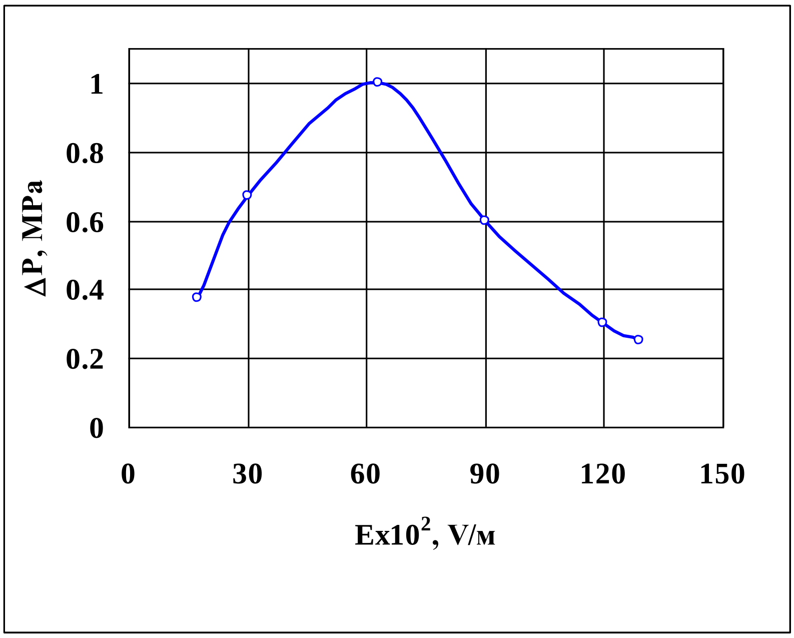
Thus, for this kind of gas-water-oil system at an investigated intensity range of 3,000–12,000 V/m the most optimum recorded value, regarding electric treatment, was with an electric field intensity of 6,000 V/m (see Figure 10)

It should be noted here that system saturation pressure decrease were also achieved during magnetic treatment of the system. In this case, in the scheme illustrated in Figure 9 the electrotreatment unit was replaced by a magnetic treatment unit.

The initial average value of system saturation pressure was Pno = 4.0 MPa at temperature of experiment 315 K. A recombined sample underwent the treatment with a magnetic field. The intensity of this field in different series of experiments was 1,300, 1,900 and 2,600 Oersted. For each level of intensity there were 3–4 series of experiments.

The results of experiments showed that during magnetic treatment with the intensity of 1,300 Oersted, system saturation pressure dropped by 0.3 MPa, an intensity of 1,900 Oersted led to an average decrease of system saturation pressure of 0.6 MPa, and at an intensity of 2,600 Oersted the pressure drop was 1.0 MPa.

Figure 10. Dependence of saturation pressure Pn changes on electric field intensity E while electrotreatment of "oil + gas + water" system.



Thus, for this kind of gas-water-oil system at investigated intensity range of 1,300–2,600 Oersted the most optimum, with respect to magnetic treatment, was the intensity of magnetic field—2,600 Oersted.

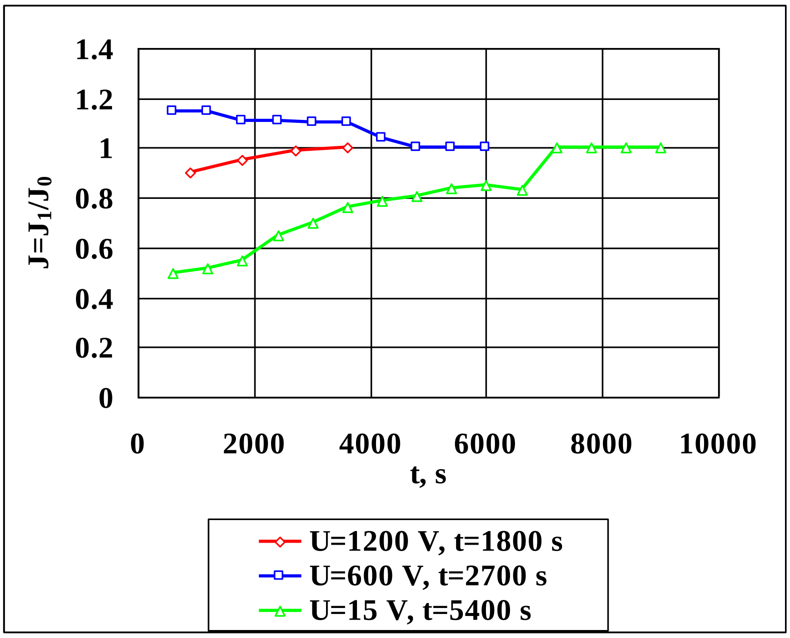
3.2. Mechanism of electric and magnetic treatment

The results obtained above determined the next stage of investigations, which was to investigate the methods of diagnosis of the system condition after electrotreatment, namely, the possibility of determining the "response" of a treated liquid to an external action. It is possible to study the restructuring process in liquids by methods of radiospectrometry. One of these methods is electronic paramagnetic resonance (EPR) [27]. The EPR spectrum is characterized by the intensity of the absorption lines, width and shape of lines, value of g-factor, and hyperfine structure (HS). The EPR signal of samples was recorded on a РЭ-1301 radiospectrometer, consisting of a microwave oscillator (SHF—superhigh frequency), strong electromagnet, detector section and recording device.

Investigated samples of oil with a high content of heavy hydrocarbon fractions were exposed to electric fields with intensities of 1,200, 600 and 15 V. As shown in Figure 11, a variation of the EPR signal is observed, indicating the definite system "response" to the treatment. The analysis of results shows that, as in the case of heat and pressure treatment of heterogeneous systems, there is variation of paramagnetic properties, characterized by concentrations of paramagnetic centres (CPC).

System "response" on electrotreatment can be linked with the behavior of internal diffusive processes connected with imbalances of Van der Waals forces, and forces of electrostatic repulsion by dispersed particles.

Figure 11. Variation of EPR signal intensity after treatment with electric fields of different intensity. (J_1: intensity of EPR signal after treatment; J_0: intensity of EPR signal before treatment).



4. Conclusions

The application of physical fields in oil recovery processes (thus creating different electrokinetic, molecular and thermodynamic effects) allows us, depending on geotechnological conditions, to select the optimum effect methods and further develop effective power and resource-saving technology.

Why this technology is attractive? The communality of the approach while increasing the efficiency of technological processes when lifting the raw oil from vertical, horizontal or directional wells and also when transporting this oil using pipelines (which often have complicated profiles) allows us to combine all these processes into one technological process.

Considering *a priori* that producing wells and pipeline flows are essentially different applications, there is still some commonality to be found between these two processes, this being that the production and transportation of non-Newtonian oils is taken at a high differential pressure, but the same processes for Newtonian oils is taken at a considerably lower differential pressure. This allows us to reveal that the advantage lies in the ability to acquire Newtonian properties for non-Newtonian oils over a period of time by subjecting them to the specified treatment.

Thus, performing cyclic impulse changes of pressure in the system (pressure treatment) which does not require any special equipment and additional cost, we managed to demonstrate the possibility of start up and putting into operation gaslift wells and pipelines at low priming pressures.

Along with this, the possibility of pressure treatment of non-Newtonian oil in the bottomhole by using the changes in hydrostatic pressure of oil column in the well (this was achieved by turning the well pump on and off) lead to the condition whereupon non-Newtonian oil in the bottomhole temporary acquired Newtonian properties. Consequently, at the same differential pressure, a 25%–30% increase of well output was observed

Our establishment of the communality of the mechanism of all physical fields effects—generation of electrokinetic processes—allows us to regulate the moment of gas liberation from the oil in the bottomhole by the electric and magnetic treatment of gas-liquid system. This technology does not require any particular expenses and does not change the technological process itself.

The examples of practical applications mentioned in this paper should serve to attract the attention of field specialists and researchers and to show availability and possibility of increasing the efficiency of technological processes by the regulation of rheological properties of non-Newtonian oils. This can also serve as stimulus for the widening of practical application of this technology, taking into account specific field conditions.

Thus, these investigations allow us to create the basis for energy and resource-saving rheotechnology. It is clear that provision of increasing efficiency of technological process is economically attractive and it can be demonstrated without difficulties by oil industry economists.

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