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Review

Improving the Efficiency of Oil and Gas Wells Complicated by the Formation of Asphalt–Resin–Paraffin Deposits

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Abstract: A number of difficulties may be encountered in the final stages of oil field exploitation, including the formation of asphalt–resin–paraffin deposits (ARPDs). It is expedient to use complex technologies to remove the already formed deposits and prevent the formation of ARPDs. This paper focuses on the complex technology of oil field exploitation. This technology combines both the removal of organic deposits and the prevention of the formation of these deposits in the well bottomhole formation zone (BHFZ) system. The calculations for determining the process parameters of selling the ARPD inhibitor solution into the BHFZ are presented in this article. This complex technology includes the process of ARPD removal by flushing the well and the subsequent injection of the developed ARPD solvent into the BHFZ. In addition, the technology is complemented by a method of preventing the formation of these deposits. This method consists of squeezing the ARPD inhibitor and then pumping it by the selling fluid from five to ten times of the volume. This article contains a detailed calculation of the methodology and provides the diagrams for the solvent and inhibitor injection.

Keywords: asphalt–resin–paraffin deposits; complex technology; inhibitor; ARPD solvent; bottomhole formation zone; methods for removing ARPDs; methods for preventing the formation of ARPDs; Romashkinskoye field

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1. Introduction

The oil field exploitation process can be roughly divided into four stages. Stage 1 is the period of oil production enhancement while also consisting of the bringing-in of wells and field development. Stage 2 is characterized by sustained maximum oil extraction. It is the period that characterizes the exploitation of the field by the level of oil production and the rate of withdrawal from the initial recoverable reserves. Stage 3 is characterized by a drastic decline in the oil production and a significant growth in the well production water cut. This stage is often referred to as the late stage of development. Stage 4 is referred to as the final stage of oil field development. It is characterized by a relatively slow, gradual decline of oil production and a high water cut of well production. As of the current date, most oil fields are under the late stage of development. This stage is associated with a number of challenges during the production and operation of reservoir fluids. The deterioration of temperature and pressure conditions, increased water cut (over 80%), weighting of oil, and low oil production rates are typical for this stage. In addition, asphalt–resin–paraffin deposits are formed in the downhole equipment and in the bottomhole formation zone [1–8]. In this article, the bottomhole formation zone means a layer area adjacent to the wellbore where the filtration properties of a pay zone have changed.

The measures for controlling the asphalt–resin–paraffin deposits (ARPDs) have been implemented since the 1960s [1,2]. Since then, multiple scientific studies aimed at the removal and preventing the formation of organic deposits in the well-formation system have been carried out. However, according to these studies, the methods for removing and preventing the formation of ARPDs were substantially considered as separate methods. Now, a few studies describing the complex technology for removing and preventing the formation of ARPDs for the entire well-formation system have been performed. It is necessary to know the composition of the oil and deposits, the geological structure of the formation, the reservoir properties of the rock, and its lithological composition.

The aim of this work is to develop a complex technology of exploitation. This technology includes the removal of organic deposits formed in the well bottomhole formation zone (BHFZ) system. It can be achieved by flushing the well and pumping the developed solvent into the BHFZ, and by injecting the ARPD inhibitor into the BHFZ to prevent the formation of these deposits in the well BHFZ system.

These methods can be applied separately, but the maximum effect can be achieved by implementing the operations in a sequential order: (1) flushing the downhole equipment with subsequent treatment of the BHFZ with an ARPD solvent; (2) injecting the ARPD inhibitor into the BHFZ.

The evidence from practice dealing with ARPDs shows two main areas of focus: (1) the removal of the already formed deposits; (2) the prevention of the formation of deposits.

2. Literature Review

The methods for removing ARPDs include: thermal (steam injection, flushing with hot oil or water as a coolant, the use of electric furnaces, induction heaters, etc.), mechanical (the use of scraping tools, scratchalizers mounted on rods), and chemical (the use of organic solvents or detergents to remove ARPDs) [1–9].

The most widely used methods for removing ARPDs are chemical methods, namely the use of organic ARPD solvents (individual organic solvents, natural-type solvents, oil refinery and petrochemical products and waste, organic solvents with surfactant additives [10], water-based removers, etc.) [11–16]. The chemical methods of removing asphalt–resin–paraffin deposits are based on the various reagents used [17–21]. There are methods to remove organic deposits by mixing crude oil with a paraffinic solvent followed by decantation and gravity separation using a vacuum filtration [22,23]. The application of unique condensate feedstocks has resulted in natural multicomponent hydrocarbon solvents for ARPD removal [24].

The deposition of paraffin can lead to a suspending production of hydrocarbons. One particular article [25] presents a new and cost-effective technology for removing paraffin deposits from downhole equipment using inexpensive and environmentally friendly agents. These agents are able to generate heat and pressure under certain conditions.

The chemical removal of ARPDs using hydrocarbon solvents can improve the oil production process, increase the life cycle of the downhole equipment, and accelerate the dissolution and dispersion of organic deposits [26,27]. Solvents based on aromatic and saturated hydrocarbons, gas condensates with various modifying additives, have proven to be highly effective in removing ARPD [28,29].

The composition, structure, and properties of these deposits must be considered when choosing the most efficient method for removing ARPDs [12,14,30–33]. The composition of organic sediments is determined by their origin, the composition of the oil, and the mechanism of their formation. Nonetheless, the existence of multiple methods for removing ARPDs fails to completely solve the problem of the formation of ARPDs in downhole equipment.

Industrial experience shows that paraffin deposits are formed by two mechanisms: the process of growth directly on the surface of the pipe, and the accumulation of paraffin crystals in the oil, which eventually attach to each other and to the metal [1–3,12,26,27]. Therefore, specialists of the oil industry are looking for ways to prevent the formation of organic deposits.

The main methods for preventing (preventive measures) the formation of ARPDs include: (1) the use of protective coatings (coating of pipes with epoxy resins, finely crushed glass, Bakelite varnish, resins, the use of glass-reinforced plastic rods); (2) physical methods (vibrational, ultrasonic methods, exposure to magnetic, electric, and electromagnetic fields); (3) chemical methods (the use of wetting agents, modifiers, depressors, and dispersants) [34–36]. Modifiers and dispersants with completely different molecular structures and mechanisms of action can be effective in the fight against asphalt–resin–paraffin deposits due to their high efficiency and cost-effectiveness [37]. However, the use of modifiers requires protecting them from the cold to prevent freezing. Modifiers suitable for year-round use were created. They could become a good alternative to such methods as hot oiling and hot watering [38]. The modifier can be incorporated into paraffin crystals during the nucleation process and change the growth and characteristics of the crystal surface. At the same time, it forces them to assemble again into micelle-like aggregates. Subsequently, smaller crystals of paraffin are formed, which remain stable in the oil. The modifier also helps to reduce the tendency of paraffin crystals to form a three-dimensional grid. This reduces the pour point and viscosity of the oil [39,40].

There is evidence that the term "modifier" is interchangeable with a depressant that reduces the pour point. However, the exact mechanism of how the crystal modifier functions is still ambiguous and requires further study. Some researchers have put forward the theory that the modifier reduces the solidification temperature due to the formation of obstructing needle-shaped crystals (spheroliths). Examples of paraffin crystal modifiers are polyalkyl methacrylate, polymeric fatty ester, methacrylic acid ester, and crystalline-amorphous copolymers and crystalline amorphous copolymers, such as polyethylene butene and polyethylene–polyethylene propylene. It has been reported that the chemicals described above can help in regulating the rheological properties and the size of the paraffin crystals in medium-distillate crude oils and fuels. [41–43].

To prevent the formation of ARPDs in oil fields, applied is a chemical method for protecting downhole equipment based on the use of dedicated chemicals—ARPD inhibitors [44], which are ionic or non-ionic surfactants. Paraffin inhibition can be achieved in two ways: firstly, by affecting the wettability of metal surfaces through a film-forming action; secondly, by using materials that modify and disperse the paraffin crystals. It is reported in the literature [45] that inhibition is the most promising and cost-effective method of combating paraffin.

The removal of most asphalt-containing substances from the oil significantly improves the process of developing an oil field. It has been proved that, in the presence of asphaltenes in oil at a certain concentration, paraffin is deposited on the walls of well equipment in the form of individual particles that have a slight tendency to stick to each other. The inhibitor, attaching to the asphaltene particles, does not allow the formation of the paraffin crystal nuclei. A great deal of work was done by the French Oil Company [45,46], and they came to the conclusion that inhibitors, such as polyethylene, are effective only when natural polar substances are present in crude oil, and, when these substances are absent, a dispersant may be required.

Ionic surfactants are divided into cationic and anionic ones. Anionic surfactants dissociate in water into ions (a positively charged cation and negatively charged anion). The negatively charged anion has surface activity. The most typical anionic surfactants used in the oil industry are alkyl acryl sulfonates (sulfonols), alkyl sulfonates, alkyl sulfates, etc. [47]. Cationic surfactants also dissociate in water into ions, but, in contrast to anionic surfactants, cations are positively charged ions and have surface activity. Examples of cationic surfactants include: aliphatic amines—salts of hydrochloric acid, imidazoline derivatives, etc. Non-ionic surfactants do not dissociate in water into cations and anions. Oxyethylated alkyl phenols (surfactants of the OP-10 type), oxyethylated fatty alcohols and acids, block copolymers of ethylene and propylene oxides (disolvans, separaols), and amines are used as non-ionic surfactants [48–52].

In [53], chemicals such as polyalkyl methacrylate, Poly(maleic anhydride-alt-1-octadecane), Polyalkyl methacrylate-co-ethylene glycol, and Copolymers of maleic anhydride with concentrations ranging from 100 to 1000 ppm are cited as inhibitors of paraffin deposition. As a solvent in this work, the authors cite n-pentane with a concentration of 5–20% by weight. The results of this study show that n-pentane can reduce the solidification temperature of the deposits.

The continuous addition of polymer inhibitors is considered an effective method of removing deposits. The addition of copolymers, such as polyacrylates, polymethacrylates, or poly(ethylene-co-vinyl acetate) (EVA), allows the inhibition of the precipitation phenomenon. However, this effect is specific, i.e., these copolymers have different characteristics depending on their physico–chemical properties in the solution. In [54], the influence of the EVA vinyl acetate content on the viscosity and pour point of Brazilian crude oil was evaluated. The results showed that, below the temperature at which paraffin crystals begin to form, the copolymer has a strong effect on reducing the viscosity of the oil. Not only the solubility parameter and the vinyl acetate content but also the molecular weight and polydispersity have an important influence on both the behavior of the phase and the decrease in the solidification temperature.

In another work [55], a depressor was used as an inhibitor, which is able to reduce the pour point of oil. A modified copolymer of ethylene and vinyl acetate 10 mol.% (EVA10) was used as a depressor. The studies were carried out by hydrolysis and esterification using systems of paraffin models with different paraffin content. The results of the research allowed us to evaluate the effectiveness of additives in crude oil with different paraffin content.

There are additives that act in a complex way and exhibit both inhibitory and depressive properties [56,57]. For example, the experimental additive K-210 exhibits the best inhibitory and depressive properties in high-paraffin oil [56,58].

Various works describe all kinds of chemicals that can prevent the formation of organic deposits. One of these methods is the method of separating fractions of asphaltenes and paraffin. The determination of the content of asphaltenes and paraffins in oil can play a very important role in eliminating or, at least, alleviating the production problems associated with deposits of paraffin and asphaltenes. Due to the incorrect characteristics of these fractions, serious problems may arise during the development of deposits complicated by ASF [59,60].

Various types of additives are used to prevent the formation of ARPD, such as asphaltene precipitating dispersants [61–66].

ASP dispersants are a group of surfactants that are adsorbed on the surface of the pipe walls and reduce the adhesion of the paraffin. This can be either due to a change in the wettability of the pipe wall, or due to the formation of a thin layer by which the paraffin crystals easily peel off. The paraffin dispersant is also adsorbed on paraffin crystals and forms the crystal lattice structure of paraffin in crude oil. The crystal structure of paraffin later reduces the morphology of the growing crystals and delays the formation of a three-dimensional crystal. This modified spherical crystal from a large plate crystal increases the oil fluidity [67,68]. However, the paraffin dispersant has limited effectiveness if it is not used with an oil flow-improving polymer. It is reported that the paraffin dispersant works extremely well with a polymer flow improver due to its characteristic to prevent the deposition of paraffin and deposition on the surface of the walls of downhole equipment. In the presence of water, surfactants, such as the alkyl sulfonates and ethoxylates of fatty amines, can also act as paraffin dispersants.

The interaction between paraffin particles and hydrophilic groups of the surfactant leads to the dispersion of paraffin particles to smaller sizes. This can lead to the prevention of the agglomeration and deposition of paraffin. These surfactants work best with esters with a longer chain due to the molecular structure factor [66–73].

Inhibitors and dispersants are introduced in a small amount up to 3% [74]. Most dispersants are non-polymeric surfactants used to reduce the size of flocculated asphaltenes [75].

Strong organic acids, such as dodecylbenzene sulphonic acid (DBSA), and other long-chain organic surfactants, such as nonylphenol, are used as dispersants and surfactants and have been studied well [71,72,76]. Strong organic acids, especially DBSA, attack the heteroatomic sites of asphaltene molecules [73–76]. Acids can form a solvation shell around the asphaltene molecules and can also dissolve them.

When selecting an ASP inhibitor, it is necessary to take into account both its inhibitory properties and dispersing ones.

A composition is known for the prevention of asphalt–resin–paraffin deposits [77], containing in % wt.: surfactant–potassium or potassium–sodium salt of carboxymethylate of oxyethylated alkylphenol 25–30, polar electrolyte and acid amide 3–8, waste from the production of butyl alcohols-methanol-aldehyde fraction 1–30, water 32–43, with the content of polar electrolyte 1–4% by weight, and an acid amide of 1–6% by weight. The disadvantage of this composition is the scarcity of some of the components and their high cost. The known composition does not have a sufficient degree of the dispersion of ASP particles.

A composition for the prevention of asphaltene–resin–paraffin deposits is known [78], containing a surfactant, an additive, and an aromatic solvent. As a surfactant, a product of the sequential addition of ethylene and propylene oxides to tall oil fatty alcohol (10–30% by weight) is used, and a polyethylene glycol monoalkyl ether based on primary fatty alcohols ALM-10 or DS-10 or Alcamonum DS-10 (1–3% by weight) is used as an additive, and aliphatic alcohol and/or aromatic hydrocarbons in a ratio of 1:1 (the rest) are used as an aromatic solvent. However, the disadvantage of this composition is the low efficiency of preventing ARPD in producing wells in fields with a high content of high-molecular paraffins, asphaltenes, and resins.

A composition is known for the prevention of asphaltene–resin–paraffin deposits [79], containing in % wt.: block copolymer of ethylene and propylene oxides-20–65; oil-soluble surfactant—1–15; monoalkyl ether of polyethylene glycol based on a compound with a mobile hydrogen atom-3–10; and the solvent for the rest. The disadvantage of the composition is the low efficiency of preventing the formation of ASF in oilfield equipment and the bottomhole zone of the formation. The known composition does not have a sufficient degree of the dispersion of ASP particles.

There is a known inhibitor for preventing the formation of asphalt–tar and paraffin deposits in oilfield equipment [80], containing in % wt.: ethylene copolymer with vinyl acetate-30–70, oxyalkylated alkylphenolaminoformal-degid, and resin for the rest. The disadvantage of the known inhibitor is the low dispersing ability of the composition against ARPD and the insufficient duration of the reagent's action in the winter season.

Despite the variety of chemical compositions to prevent the formation of asphalt–resin–paraffin deposits, the problem remains relevant today. And, in order to solve this problem, it is necessary to approach it comprehensively. First, remove the formed deposits, and then pump in a paraffin deposition inhibitor to prevent the formation of ARPD, which will have both inhibitory and dispersing properties.

The results of laboratory experiments are presented in this article, as well as a calculation methodology for a complex technology to remove and prevent the formation of ARPD. The Volga-Ural region of the Russian Federation (e.g., Romashkinskoye field) was used for the example. This oil field is characterized by a low tarry oil component, dominated by paraffins and asphaltenes [81–83].

According to a service experiment at the Romashkinskoye field, the traditional methods for dealing with ARPDs aimed at removing and preventing the formation of deposits. Mechanical, chemical, physical, and thermal methods and the use of protective coatings in the downhole equipment are used. The optimal and cheap method for dealing with ARPDs in the fields of the Republic of Tatarstan (RT) is a mechanical method using the polymer scratchalizers. The scratchalizers simultaneously perform two functions: removing organic deposits from the tubing walls and centering the sucker rod string in inclined wells in order to protect the tubing walls from abrasion [84,85].

The thermal methods, as well as the combined methods (thermal methods in combination with ARPD solvents), are used along with mechanical methods for removing deposits. It is necessary to substantiate the injection rate, coolant temperature, type of coolant, and the technological scheme of flushing (direct or back flushing) when planning the thermal methods with the use of ARPD solvents. For these purposes, we need to calculate the depth distribution of the coolant temperature in the tubing string and in the annulus [86]. For example, the Public Joint-stock Company Tatneft uses thermal distillate treatment for simultaneously creating thermal and chemical effects on organic deposits. A well is flushed with distillate, heated to 85 °C (for wells equipped with sucker rod pumps), for wells equipped with electrically driven centrifugal pumps, up to 75 °C [85,86]. Additives to the distillate, for example dimethyldioxane (DMD), NBR-1M, etc., are also used. The frequency and efficiency of the distillate treatments depend on the intensity of the formation of the ARPDs, the temperature of the distillate, the water cut of the formation products, the rate of fluid lifting in the tubing string, etc. [87–90].

Among the thermal methods, the hot oil treatment of wells has become widespread. Experimental studies have shown that the heat penetrates at a depth of less than 300 m from the wellhead, while the formation of ARPDs starts at a depth of 900 m and below. As a result, the treatment of wells with hot oil does not always result in the required technical objectives.

The Public Joint-stock Company Tatneft has developed a method of well bottomhole zone treatment [91] where the proposed composition is pumped to the well bottom overlapping the reservoir interval, then the NEKhS-40 RE heater is lowered into the perforation interval. The composition is heated to the temperature of 80–90 °C, which is subsequently squeezed into the depth of the formation. For the BHFZ treatment, a well with an injection capacity of at least 30 m^3/day is selected. This method provides the removing of ARPDs from the walls of tubing and the BHFZ.

According to the regulatory documents, it is necessary to assess the possibility of its use, the volume of the solvent, and its composition depending on the type of deposits prior to applying the method of injecting the ARPD solvent. The approximate radius of the BHFZ and the volume of the solvent are calculated. The radius of the treatment zone is taken from 0.5 to 2.0 m depending on the thickness of the formation. The equipment by which the solvent will be pumped is selected. While pumping, the injected amount, injection pressure, and the pressure on the production casing are monitored. After the solvent is pumped, the well is left to react for 24 h.

The solvents for removing ARPDs from tubing walls are delivered to wells in several ways. According to the first method, the ARPD solvent (5 m^3) is pumped into the annulus of the well and is subsequently displaced with displacement fluid. The treatment of the tubing walls is implemented by pumping a solvent from the annulus. In this case, the well operation is not stopped. According to the second method, the ARPD solvent is also pumped into the annulus but is not displaced with displacement fluid. The removal of the ARPDs is performed when the solvent, falling down to the pump intake along with the flow of formation products, enters the tubing. According to the third method, the ARPD solvent enters the annulus and is subsequently displaced with oil until its complete release through the tubing to the wellhead. The well operation is stopped for 8–10 h for the solvent to react with the organic deposits. According to the fourth method, the solvent is pumped, using hollow rods, into the tubing string until they are completely filled. In this case, the well operation is stopped. According to the fifth method, valves are installed in the tubing at a depth of 600 m, which facilitate filling the tubes without using a pump. The solvent is pumped into the annulus and into the tubing through the valve. The well is left to react for 8–10 h. The reaction products and deposits are flushed out after the resumption of well operation [87,92].

Chemical methods, based on the use of ARPD solvents and inhibitors [93,94], are widely used for dealing with ARPDs in the oil fields of the Republic of Bashkortostan (RB), as well as in the fields of RT. The following inhibitors are used: SNPKh-7941, SNPKh-7963, SNPKh-7920, SNPKh-7843, INPAR, etc. [95–98]. Such ARPD solvents as inter alia, Nefras, SNPKh-7870, hexane fraction, and liquid hydrocarbon wastes are used in the fields of RB. The downhole equipment is flushed by pumping the solvent into the annulus due to its pump-induced circular circulation through the annulus, bypass valve, tubing and wellhead. Other embodiments of solvent injection, for example, the injection of a chemical into the annulus and having it remain therein for up to 12 h, are also used. The ARPDs, together with the solvent and formation products, are flushed out by the flow to the wellhead upon the resumption of well operation. In the fields of RB, ARPD inhibitors can be supplied through the annulus into the BHFZ, thereby preventing the formation of ARPDs in the downhole equipment [99]. ARPD solvents can also be pumped not only into producing wells but also into injection ones, removing organic deposits on the walls of water-injection wells [100–102].

Despite the diversity of methods for dealing with ARPDs and a large number of reagents for removing and preventing the formation of deposits, this problem is still relevant to date. This is due to ARPD inhibitors being injected directly into the well. However, when injecting the ARPD inhibitor onto the bottom of a well, it often enters the formation fluid after the formation of solid paraffin particles has begun [103]. This is due to the fact that the formation of ARPDs can occur before the formation fluid enters the well in the pore space of an oil reservoir. To solve this problem, it is expedient to squeeze the ARPD inhibitor directly into the BHFZ. Research [104] discloses information on the injection of the ARPD inhibitor into the BHFZ, with its subsequent displacement into the formation and bringing it to the surface of a well. This technology is aimed at preventing the formation of ARPDs only in downhole equipment.

Industrial tests performed at the Zhirnovskoye and Romashkinskoye fields did not result in long-term effects. During these tests, the downhole equipment was preliminarily cleaned of deposits, after which the ARPD inhibitor was injected into the BHFZ and displaced with oil; like the previous experience of injecting the ARPD inhibitor in the BHFZ, the technology provides for the removal and prevention of the formation of deposits only in the downhole equipment [50,105].

Many scientific papers are devoted to studying the methods for removing organic deposits in oilfield equipment, and the tasks of removing ARPDs were addressed separately. In spite of that, the complex technologies, including the removal of deposits in downhole equipment, with the subsequent prevention of the formation of ARPDs in the BHFZ, remain poorly studied.

There is a known technology for dealing with saline deposits wherein the inhibitor is injected in the BHFZ [106–109]. The effect of scale inhibitors is based on the adsorption processes. By adsorbing on the centers of the formation of saline deposits, the inhibitors reduce the growth of crystals, change their shape, prevent them from sticking together, and reduce the adhesion to the walls of the downhole equipment. The inhibitor must be adsorbed relatively quickly onto the rock surface and slowly desorbed during the well operation. This principle can also be applied to wax inhibitors. The slower the ARPD inhibitor is flushed out of the reservoir pores, the longer its inhibitory effect lasts.

In order to deal with ARPDs in downhole equipment, it is necessary to use a complex technology aimed at removing the already formed deposits with a solvent, followed by the injection of an ARPD inhibitor into the BHFZ.

The review of the literature in the field of controlling asphalt–resin–paraffin deposits demonstrates that a large amount of diverse scientific papers are devoted to solving this problem. Despite the various technological procedures performed in direct experience, the issues of dealing with ARPDs still remain unsolved. The use of traditional methods does not always ensure the achievement of positive results. When the field is under the late stage of development, it is expedient to use complex technologies aimed at removing the already formed deposits and preventing the formation of ARPDs. In this case, it is necessary to know the composition of the oil and deposits, the geological structure of the formation, the reservoir properties of the rock [110], as well as its lithological composition.

3. Summary and Prospects

The late stage of oil field development is accompanied by the undesired formation of organic (asphalt–resin–paraffin) deposits. In order to increase the overhaul period of wells operation, it is necessary to holistically consider the process of cleaning downhole equipment and the BHFZ from ARPDs.

When substantiating the technology for removing ARPDs from downhole equipment operated by sucker rod deep-well pumping units, the standard methods of flushing equipment with solvents are used [111–114]. We have developed a technological scheme for preventing the formation of deposits by dosing an ARPD inhibitor in the bottomhole zone.

To implement the technological process of flushing a well from ARPDs with a solvent, it is necessary to perform a number of steps:

1. Prepare a solvent for injection into the well. The composition of the used solvent consists of aromatic and aliphatic hydrocarbon solvents, and a nonionic surfactant. It is a depressor-dispersing additive containing a Yalan-E2 emulsifier, a copolymer of ethylene with alpha–olefins having a molecular weight of 500 to 100,000, or polyalkyl acrylate. The solvent has high flushing and dispersing ability with respect to ARPDs; therefore, it can be proposed for removing deposits in oil wells (for flushing downhole equipment from deposits) (Russian patent No. 2632845) [115]. The volume of solvent (V, m^3) required for cleaning the production string and pumping equipment from ARPDs without lifting the downhole equipment (sucker rod pumps) is calculated according to the formula:

$$V = H \cdot V_1 + V_T - V_{rs},\ m^3 \tag{1}$$

   where: H is the pump-setting depth, m; V_1 is the specific annular volume, m^3/m; V_T is the tubing volume, m^3; V_{rs} is the rod string volume, m^3.
2. Stop the down-hole pumping unit. Connect the pumping unit to an annular valve and to a tank truck with a solvent. The solvent can be pumped with or without a packer. When connecting a tank truck with a solvent and a unit to a well annulus, it is necessary to: put the injection line of the pumping unit under pressure of 1.5 times the working pressure permissible for the production string of the well; open the valves, check for circulation; the injection pressure of chemicals should not exceed 8.0 MPa; ensure the tightness of the lines; use the sealing elements made of oil-resistant materials; the minimum feed rate of reagents is 3–4 L/s.
3. Inject the solvent using the cemented aggregate unit through the annulus in a volume equal to the annular volume and the tubing volume to the wellhead. The technological scheme for injection of an ARPD solvent into a well is presented in Figure 1.
4. Leave the well to react for 8–10 h.
5. The processed products are sent to the flow line.

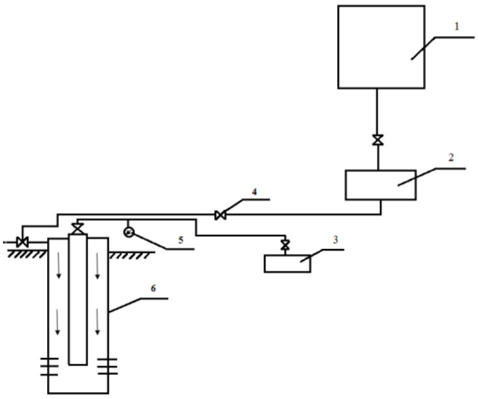

Figure 1. Technological scheme for injection of an ARPD solvent into a well. **1**—a tank truck with an ARPD solvent; **2**—a pumping unit; **3**—a ditch tank; **4**—valves; **5**—a pressure indicator; **6**—a well.

If necessary, it is possible to perform the treatment of the BHFZ with an ARPD solvent; this requires the following calculations:

Radial size of the BHFZ, within which the pressure is less than or equal to the saturation pressure [35]:

$$R_{BHFZ} = R_k^a \cdot r_C^{1-a} \tag{2}$$

where: R_k is the conditional supply contour radius (conventionally taken half of the distance between wells), m:

$$a = \frac{P_{sat} - P_{bot}}{P_{res} - P_{bot}}; \tag{3}$$

P_{sat} is the saturation pressure, MPa;

P_{bot} is the bottomhole pressure, MPa;

P_{res} is the reservoir pressure, MPa;

r_c is the radius of a well, m.

The volume of solvent (V, m^3) injected into the well for the BHFZ treatment:

$$V = \pi \cdot m \cdot h \cdot \left(R_{BHFZ}^2 - r_C^2\right) \tag{4}$$

where:

m is the porosity, unit fractions;

h is the effective thickness of a producing formation, m.

When injecting a solvent into the BHFZ, standard methods and equipment are used for the BHFZ treatment. The technological scheme for injection of a solvent into the BHFZ is similar to the technological scheme for injection of an ARPD inhibitor into the BHFZ, presented in Figure 1.

Laboratory experiments of adsorption–desorption processes for an ARPD inhibitor were carried out, and the detailed description of the methodology and the results obtained is presented in papers [115,116]. Laboratory experiments were carried out on an assembled model of a filtration plant. The ARPD inhibitor (20%) was injected into the core sample with varying amounts of oil pumped after the inhibitor had been injected. The effect of the pumped oil volume on the subsequent desorption of the inhibitor from the core pore walls was investigated. The papers noted the highest rate of increase in the adsorption of the inhibitor IN-1 was observed in the area of low values of its initial concentration in the oil. The reason for this is the high surface tension of the IN-1 inhibitor against the rock. The investigations of the desorption behavior of the inhibitor from the pore walls depending on the different lengths of the bulk model were carried out. The increase in the volume of formation covered by the ARPD inhibitor solution treatment results in a proportional increase in inhibitor removal time. An ARPD inhibitor (20%) was also injected into the core with varying amounts of oil pumped after the inhibitor had been injected. The effect of the volume of pumped oil on the subsequent desorption of the inhibitor from the core pore walls was investigated. According to the results, it is necessary to inject inhibitor into the borehole zone by at least 5 to 10 times of the fluid volume sale. It is necessary to reduce the loss of inhibitor during the initial operation of the well after the treatment has been performed. It is recommended to use oil as the selling fluid.

Based on the results of laboratory studies of the adsorption–desorption processes for an ARPD inhibitor, the technological parameters of the ARPD inhibitor solution displacement into the BHFZ were calculated.

The required data obtained over the course of laboratory studies, relative to the adsorption–desorption processes for an ARPD inhibitor, made it possible to determine the technological parameters of the ARPD inhibitor solution displacement into the BHFZ: volumetric flow rate of fluid (well production rate); coefficient A, accounting for the unevenness of removal of the ARPD inhibitor from the BHFZ, and the required amount of the ARPD inhibitor for injection into the BHFZ. The detailed description of the methodology for determining the aforesaid parameters is presented in papers [116].

The results of laboratory experiments [115,116] made it possible to develop a technology for preventing the formation of ARPDs, which resides in squeezing an ARPD inhibitor followed by its displacement with 5 to 10 times the volume of displacement fluid into the BHFZ, where it is adsorbed and retained onto the rock surface. In the process of fluid filtration through the BHFZ, a gradual desorption process occurs. The inhibitor is released and enters the well with the reservoir fluid, providing conditions for preventing the formation of deposits.

The technology of injection of an ARPD inhibitor solution into the BHFZ, with its subsequent displacement with 5 to 10 times the volume of displacement fluid, includes the following steps:

1. Selection of an ARPD inhibitor and determining its minimum effective concentration required for inhibiting ARPDs in the BHFZ and, accordingly, in downhole equipment. The ARPD inhibitor is pumped (injected) into the formation in the form of a 15–20% solution. Oil is used as a solvent. In order for the ARPD inhibitor to be flushed out by the produced fluid from the BHFZ for a long (120–180 days) time, the ARPD inhibitor solution must not only be injected into the BHFZ but also displaced into the depth of the formation.
2. Calculation of the amount of inhibitor (m_{inh}, kg) for injection into the BHFZ [116].
3. Calculation of the volume of solvent (oil) (V_{oil}, m^3) for preparing a 15–20% ARPD inhibitor solution:

$$V_{oil} = \frac{m_{inh} \cdot 100}{\rho_{inh} \cdot C_{inh}} - \frac{m_{inh}}{\rho_{inh}} = \frac{m_{inh}}{\rho_{inh}} \left(\frac{100}{C_{inh}} - 1 \right), \tag{5}$$

where: C_{inh} is the concentration of an ARPD inhibitor in solution—15–20%; ρ_{inh} is the density of an inhibitor, kg/m^3;

4. Calculation of the volume of displacement fluid (oil) (Vdis, m^3), pumped into the BHFZ after the inhibitor solution:

$$V_{dis} = (5 \ldots 10) \cdot V_{sol} + V_0 + V_1 = (5 \ldots 10) \cdot (V_{oil} + V_{inh}) + \tfrac{\pi \cdot d_T^2 \cdot l}{4} + \pi \cdot r^2 \cdot \left(h_{perf} - h_T \right), \tag{6}$$

where: (5 … 10) is 5 to 10 times the volume of displacement fluid; V_{sol} is the volume of the solution, including the volume of oil (V_{oil}) and the volume of an ARPD inhibitor ($V_{inh} = \frac{m_{inh}}{\rho_{inh}}$); V_{inh} is the volume of an ARPD inhibitor; m is the effective porosity of the producing formation, unit fractions; V_0—is the tubing volume, m^3; V_1 is the volume of the production casing from the tubing shoe to the lower perforations, m^3; d_T is the inner diameter of tubing, m; h_{perf} is the depth of the lower perforations, m; h_T is the tubing running depth, m; l is the tubing length, m.

5. Preparation of a 15–20% inhibitor solution in a boiler or measuring tank of the Cemented aggregate unit;
6. Injection of the ARPD inhibitor solution into the BHFZ by the cemented aggregate unit;
7. Displacement of the ARPD inhibitor solution with oil into the formation (with a closed annulus) by the cemented aggregate unit;
8. Reacting. The well is shut down for 12–24 h and all operations are stopped so that the ARPD inhibitor is adsorbed onto the rock surface;
9. Lifting of technological tubing and lowering of downhole equipment;
10. Starting up the well and bringing it to operating mode.

The technological scheme for preventing the formation of deposits via injection of an ARPD inhibitor in the BHFZ is presented in Figure 2.

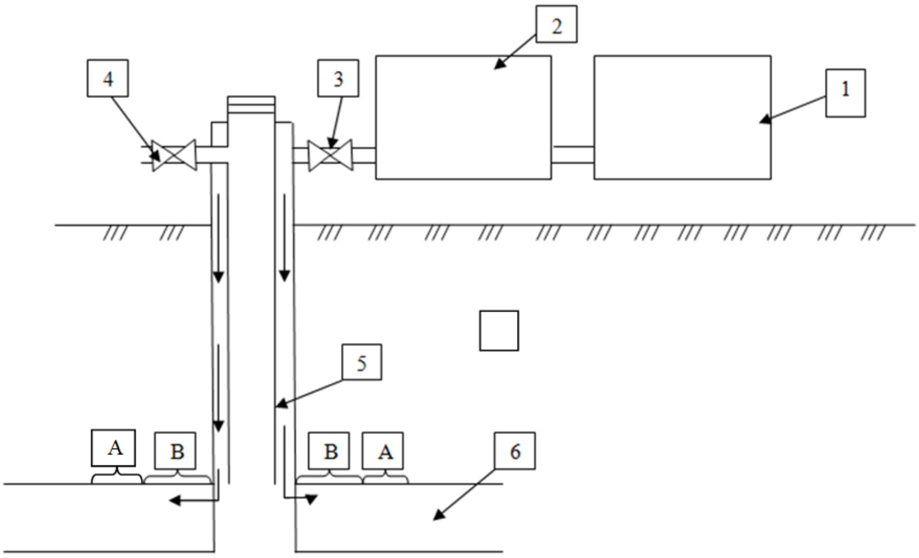

Figure 2. Technological scheme for preventing the formation of deposits via injection of an ARPD inhibitor into the BHFZ. **1**—a tank truck with an ARPD inhibitor solution; **2**—a pumping unit; **3**—an annular valve; **4**—a valve; **5**—a tubing; **6**—a producing formation; **A**—the zone of penetration of the ARPD inhibitor; **B**—the zone of penetration of displacement fluid.

The technology of the injection of an ARPD inhibitor into the BHFZ can be proposed not only for producing but also for injection wells.

The analysis of the existing methods and technologies for removing and preventing the formation of ARPDs has revealed the chemical methods that are most effective and technologically advanced, including the use of solvents and ARPD inhibitors.

The field experience and analysis show that the complex technologies tend to be the most efficient. To control the formation of ARPDs in downhole equipment, it is necessary to use a complex technology aimed at removing the already formed deposits with a solvent, followed by the injection of an ARPD inhibitor into the BHFZ.

The required data obtained during the laboratory experiments is relative to the adsorption–desorption processes of an ARPD inhibitor and made it possible to determine the technological parameters of the ARPD inhibitor solution displacement into the BHFZ. That ensures the further development of a complex technology for removing and preventing the formation of asphalt–resin–paraffin deposits in the well BHFZ system. This complex technology includes the method for removing ARPDs by flushing the well and the subsequent injecting of the developed ARPD solvent into the BHFZ and the method for preventing the formation of these deposits. The preventing method consists of squeezing the ARPD inhibitor, followed by its displacement with five to ten times the volume of displacement fluid into the BHFZ, where it is adsorbed onto the rock surface. In the process of the fluid filtration through the BHFZ, a gradual process of reagent desorption occurs. The inhibitor is released and enters the well with the reservoir fluid, providing conditions for preventing the formation of deposits. These methods can be applied both individually and in combination.

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