ISSN 2712-8008
Volume / Том 25 №2 2025
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622+553.982+537.8: 001.895
Article / Статья

# Electromagnetic technologies in oil production: effective solutions and commercialization opportunities

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# Электромагнитные технологии при добыче нефти: эффективные решения и возможности коммерциализации

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Received / Получена: 08.11.2024. Accepted / Принята: 05.12.2024. Published / Опубликована: 01.04.2025

*Keywords:*
oil producing industry, enhanced oil recovery methods, thermal influence, high frequency electromagnetic heating, oil production profitability, energy balance, hydraulic fracturing.

The Russian Federation, as a country that is one of the largest centers of oil production, is currently increasingly puzzled by the threats of reducing its volumes. Despite the achieved level of the industry infrastructure development, serious problems arise with the development of new explored (primarily in oil source rocks and reservoirs of viscous oil) and the pre-processing of residual reserves, since most wells in them do not reach flow rates close to profitable. This is primarily due to the long-term intensive depletion of easily recoverable (active) oil in all explored areas. The increase in the share of unconventional oil in the total balance of its reserves, which is especially important for the "old" production regions, inevitably makes it necessary to search for and commercially introduce new ways of extracting it. Meanwhile, the geopolitical problems that have arisen in recent years in relation to the Russian Federation, actualize the issues of its technological sovereignty in this area of knowledge.

Among the many methods of increasing oil recovery and inflow intensification, the method of influencing the bottom-hole formation zone with a high-frequency electromagnetic field is distinguished, which, despite many years of research, is still considered experimental in the Russian Federation and is limited to evaluating the production and technical characteristics of use. At the same time, financial and economic indicators are overlooked, the identification of which will make it possible to justify the relative low cost and high profitability of the innovative methods.

The subject of the research is technological developments in the field of exposure of oil-containing rocks to a source of electromagnetic radiation. The purpose of the study is to determine the degree of technical and technological readiness of oil field development methods based on the use of electromagnetic field energy, in terms of the effectiveness of technology implementation and the possibility of commercialization of developments.

The main research methods are the analysis of scientific literature and a review of available patents, systematization and generalization of specialized data, methods of economic analysis.

The paper reveals the prospects of electromagnetic technologies and the degree of development of this topic in the scientific community of the Russian Federation and foreign countries: the process of electromagnetic influence on the bottom-hole zone, its thermohydrodynamic effects, directions of industrial use in the petroleum branch are described, the key problems of the technology's market positioning and limitations of its commercialization opportunities are outlined. In addition, an analysis of the effectiveness of electromagnetic treatment in comparison with other types of impact on the reservoir is presented, and additional effects and increased effectiveness of electromagnetic effects when combined with other types with the formation of combined methods are determined. Based on the calculation of the energy balance, the economic efficiency of technology implementation has been established.

The results of the work can be used in the analysis of prospects for the completion of deposits with oil reserves, the extraction of which by other methods besides electromagnetic heating (or combined with it) is economically unprofitable.

*Ключевые слова:*
нефтедобывающая отрасль, методы увеличения нефтеотдачи, тепловое воздействие, высокочастотный электромагнитный нагрев, рентабельность добычи нефти, энергетический баланс, гидроразрыв пласта.

Российская Федерация как страна, являющаяся одним из крупнейших центров добычи нефти, в настоящее время все чаще озадачивается вопросом угроз снижения объемов нефти. Несмотря на развитость отраслевой инфраструктуры, серьезные проблемы возникают с разработкой новых разведанных (в первую очередь, в нефтематеринских породах и коллекторах вязкой нефти) и довыработкой остаточных запасов, поскольку в них большинство скважин не выходят на уровни дебита, близкие к рентабельным. Это связано, в первую очередь, с многолетним интенсивным исчерпанием легкоизвлекаемой (активной) нефти на всех разведанных площадях. Увеличение доли трудноизвлекаемой нефти в общем балансе ее запасов, что особенно актуально для «старых» регионов добычи, неизбежно делает необходимым поиск и промышленное внедрение новых способов ее извлечения. Между тем геополитические проблемы, возникшие в последние годы в отношении Российской Федерации, актуализируют вопросы ее технологического суверенитета и в этой области знания.

Среди множества методов увеличения нефтеотдачи и интенсификации притока выделяется метод воздействия на призабойную зону пласта высокочастотным электромагнитным полем, который, несмотря на многолетние исследования, до сих пор считается в России экспериментальным и ограничивается оценкой производственно-технических характеристик использования. При этом упускаются из виду финансово-экономические показатели, выявление которых позволит обосновать относительную малозатратность и высокую рентабельность инновационного метода.

Предметом исследования выступают технологические разработки в области воздействия на нефтесодержащие породы источником электромагнитного излучения. Целью является определение степени технико-технологической готовности методов разработки нефтяных месторождений, основанных на использовании электромагнитной энергии, с точки зрения эффективности внедрения технологии и возможности коммерциализации разработок.

Основными методами исследования выступают анализ научной литературы и обзор имеющихся патентов, систематизация и обобщение специализированных данных, методы экономической аналитики.

В работе выявлены коммерческая перспективность электромагнитных технологий и степень разработанности данной тематики в научной среде России и зарубежных стран; описан процесс электромагнитного воздействия на призабойную зону, его термогидродинамические эффекты, направления промышленного использования в нефтедобывающей отрасли, обозначены ключевые проблемы рыночного позиционирования технологии и ограничения возможностей ее коммерциализации. Кроме того, представлен анализ результативности электромагнитной обработки в сравнении с другими видами воздействия на пласт, а также определены дополнительные эффекты и усиление эффективности электромагнитного воздействия при их сочетании с образованием комбинированных методов. На основе расчета энергетического баланса установлена экономическая эффективность внедрения технологии, рассмотрены вопрос разработанности расчетного неизотермического модуля и возможность его включения в состав коммерческих симуляторов.

Результаты работы могут применяться в анализе перспектив довыработки месторождений с запасами нефти, извлечение которых другими методами, помимо электромагнитного нагрева (или комбинированных с ним), являются экономически нерентабельными.

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Please cite this article in English as:
Rabtsevich A.A., Kovaleva L.A., Davletbaev A.Ia. Electromagnetic technologies in oil production: effective solutions and commercialization opportunities. *Perm Journal of Petroleum and Mining Engineering*, 2025, vol.25, no.2, pp. 123-135. DOI: 10.15593/2712-8008/2025.2.9

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Рабцевич, А.А. Электромагнитные технологии при добыче нефти: эффективные решения и возможности коммерциализации / А.А. Рабцевич, Л.А. Ковалёва, А.Я. Давлетбаев // Недропользование. – 2025. – Т.25, №2. – С. 123–135. DOI: 10.15593/2712-8008/2025.2.9

## Introduction

Depletion of fields with traditional oil reserves actualizes the problem of transition to new production technologies whichcan provide acceptable profitability in the development of deposits with abnormal oil characteristics – highly viscous, heavy, paraffinic and others, which, in turn, requires reorientation of research efforts to the relevant areas of scientific knowledge [1]. It is known that electromagnetic (EM) radiation through the energy of waves propagating in an oil-saturated reservoir is converted to heat by means of intermolecular friction and, due to one or another value of dielectric losses, determines the volumetric nature of heating fluids in a porous medium with a small temperature gradient, reducing their viscosity, and also leads to a change in the state of aggregation of liquid and solid hydrocarbons [2]. In case of high-viscosity oil or rock with low permeability treatment high frequency (RF) EM action provides a thermoelastic effect of increasing pressure in the reservoir thickness, which makes it possible to influence the reservoir areas outside the limited bottomhole zone [3, p. 27]. Heating also increases reservoir pressure through the release of associated gases dissolved in oil and the evaporation of light fractions.

Special feature of ultra-high frequency (UHF) EM attack is that the dielectric losses in water are substantially greater than those in pure oil. This contributes to the effective application of the given technology in production from flooded fields, transportation of crude oil, etc. [4] Besides, the non-thermal effects of EM treatment include a decrease in surface tension at the interface “oil-ware” and “oil-rock” phases which rises the displacement coefficient as a result of additional washing of film and capillary-retained oil [5].

In spite of the fact that the results of thermal influence on the reservoir practically do not depend on its reservoir properties, within the framework of interaction "field – substance", besides heating by EM-radiation itself, the "non-thermal" effect of the field, determined by its intensity and frequency, as well as by electrophysical characteristics of the rock, is manifested, causing such effects as desorption of surface-active components of oil, change of surface tension of polar liquids, effective viscosity of mutually soluble hydrocarbons and other aspects of rheology [6, p. 30]. On the basis of experimental data of the real field it is defined that at influence of EM-radiation on asphaltene formations "there is a change of their orientation in the direction of field action and their rearrangement with formation of larger accumulations, what leads to additional desorption of asphalt-resinous substances" [7, p. 13–16] [7, p. 13–16]. Dispersion effects at EM-influence are manifested to a greater extent for deep-lying hydrocarbons in carbonate reservoirs [8, p. 14–16]. In general, when applying the technology for carbonate rocks, the depth of occurrence can be 1.5 times greater (up to 3 km) than for terrigenous rocks [9].

## Directions and problems of application of electromagnetic effect

There are various directions of application of EM-impact in the oil and gas industry, first of all, directly in the production of hydrocarbon raw materials. A typical way of realising such effect consists in the presence of an appropriate EM-wave generator installed on the surface near the wellhead or at depth near the bottomhole, and a transmitter that provides EM-wave propagation through the open bottomhole (uncased part of the well or radio-transparent fibreglass casing) into the productive formation, with a wide range of modifications available in the technical embodiment [10].

Thus, a number of authors has proposed to install an emitter in the base of submersible electric motor of the electric configural pump operating at the frequency resonant for the bottomhole zone of reservoir which is determined in the process of systematic testing of its optimal values. First of all, this method makes it possible to revive idle wells, protect equipment and drainage zone from deposits, improve the quality and rheological properties of oil [11].

Another approach is to place in neighbouring wells, one of which is a producing well, EM-emitters operating at resonant frequencies coinciding with the natural frequency of vibrations of hydrocarbon fluid molecules and directed counter to each other. This method allows to intensify oil production from the selected area, to increase the oil recovery factor (up to 60 %), as well as to move hydrocarbon fluid to the producing well in a forced controlled mode (caused by additional pressure gradients), for example, from traps not covered by drainage, vertically and horizontally [12]. These applications relate to low-yielding, under-saturated and intermittent reservoirs.

The next direction of application of EM-effect in oil and gas industry is cleaning of bottomhole formation zone, well and field equipment from harmful deposits. This application is caused by destruction of asphalt-resin-paraffin deposits (ARPD), reduction of the crystallisation onset temperature of paraffin and other fusible substances as a result of temperature increase and, last but not least, improvement of hydrophilicity of working surfaces due to formation of sticky globules from associated water.

For each diameter of the production string acting as a coaxial section, taking into account the difference of the loss coefficient in sediments and clean oil, the optimal frequencies of the microwave range (5–18 GHz) are determined by calculation-analytical and experimental methods, which allows both eliminating and preventing the formation of ARPD on the well surface [13, p. 15–18]. Researchers offer designs of EM-apparatuses applicable in real fields and capable of preventing paraffin deposits during one year. The most optimal field strength for such devices is more than 700 Ersted [14, p. 34–37].

Absorption coefficients of EM waves in the well and reflections from the reservoir confirm the energy efficiency of paraffin plug elimination demonstrated by the moving radiation source. In addition, the selection of optimal parameters for the application of this technology due to the nonlinear dependence of absorption on temperature makes it possible to implement heating with a given depth of penetration in the mode of a “reverse” heat wave acting on the plug from the remote end simultaneously with the displacement of melt products by heavy liquid, which further increases the efficiency of the approach: time and energy costs for removing deposits are reduced [15, p. 7].

An original approach to preventing ASPD was proposed by Inventor Industries Ltd. (UK) when using the Enercat dewaxer: the turbulent oil flow sets quartz crystals in motion, generating EM waves of the required frequency. These waves preserve the micellar structure of paraffins and asphaltenes in the flow of extracted oil [16]. A number of authors also propose using EM radiation to inhibit corrosion processes in downhole equipment, in particular, installations with submersible electric pumps, during oil production in difficult conditions [17].

There are also other ways of using EM forces in oil production, for example, a borehole electromagnetic pulse vibration source has been proposed, based on an impact unit of an original design has been proposed. It provides technical implementation of the vibration wave method of increasing oil recovery in the development of hydrocarbon deposits [18, p. 20–21].

Thus, despite the availability of a wide range of technical solutions of EM-effect and positive effects (selective and volumetric heating, independent of thermal conductivity of oil-saturated formation rock and other treated materials, its high speed and efficiency of conversion into thermal energy, controlled geometry of temperature fields, safety of casing strings, due to the absence of electrochemical effects, etc.), in some cases, the wrong choice of mode and duration [19] of exposure of EM-radiation has an inverse effect on characteristics of hydrocarbon liquids – it can slightly deteriorate their rheological properties, which is especially relevant for oil of different composition [20].

Thus, at oil dehydration convective flows arising in the process of irradiation can contribute to inhomogeneous heating of the surface of water globules, which leads to local rupture of the armouring shell and formation of fine dispersed phase, i.e. even more stable emulsification of oil both at the bottomhole and in the pay zone. Therefore, it is important to select the optimal power range of heat sources, at which the release and settling of dispersed phase occurs [21, p. 17].

The heating temperature in a moving flow reaches its maximum value at a distance equal to the depth of EM-field penetration into the dielectric, so the problem becomes the consideration of mutual coupling of radiators in the presence of their complex in the operating installation. In addition, a significant variation of electrophysical parameters of hydrocarbon-containing fluids uncontrolled in the conditions of field complexes requires matching of the generator with the load, which is insensitive to such variation.

The use of metal well structures, in particular steel tubing as a coaxial line in real production conditions inevitably encounters a significantly different from the calculated absorption index and accelerated attenuation of EM waves due to the presence of rust and roughness on the walls, distortion of the obtained measurement results, growth of parasitic capacitance and corresponding energy losses [22, p. 16–21].

Unaccounted and untargeted losses of EM-energy, including due to water cut of products [23], as well as a number of problems presented above entail a significant reduction in the profitability of the technology compared to the designed one, but even so, according to the calculated data, the energy balance ratio for vertical wells is 6:1, and for horizontal wells – 10:1 [24, p. 15–18]. Some researchers point out that the energy balance, understood as the ratio of energy obtained as a result of additional oil production to the energy consumed for the operation of the EM-emitter, in ideal conditions can be brought to 40:1 [25].

The economic effect can also be expressed in the extension of the inter-repair period of wells operation in difficult production conditions from 1–2 months to 6–9 months, their repair can be carried out at simultaneous operation of wells (without killing them) at a certain modification of the technological scheme of the radiating EM unit [26, p. 8].

## Electromagnetic technology comparisonwith other modes of exposure and the possibility of their combination

To understand the potential for the introduction of EM technology into the oil industry, it is necessary to compare its economic efficiency with other methods of influencing formations and fluids [27]. First of all, it is necessary to compare it with a heating method similar in energy principle, for example, induction.

Since the key difference in the nature of heating under EM exposure from induction is that in the first case, volumetric heating occurs over a large depth of wave penetration, while in the second case, heating occurs in the near-wall layer, respectively, a much more significant temperature difference in the thickness of the liquid and an uneven distribution of its velocity over the flow cross-section are formed, an experimentally confirmed difference in the structure of the convective flow arises. High-frequency exposure leads to a three- or more vortex flow structure, and induction exposure leads to poorly developed heat and mass transfer of hydrocarbon-containing liquid [28, p. 9–12].

In addition to the lower efficiency of induction heating compared to that considered in this article, its implementation requires the use of complex design installations, selected individually for each technological process, conductive pipes, the thickness of their walls, materials of their manufacture with different electrophysical properties, operating temperature, fluid velocity, flow nature and other production parameters [29, p. 11–12]. In addition, it is necessary to establish clear operating modes of the equipment, regulated by an automatic control system, which determines significant costs for the maintenance and repair of industrial installations, in particular, maintaining the optimal frequency of the inductor current [30, p. 21–22]. The use of induction heating in melting paraffin plugs is also not without its drawbacks: heating the metal adjacent to the deposits does not lead to heating of the entire plug due to the low thermal conductivity of paraffin. Thus, the energy costs of this method significantly exceed EM heating [21, p. 38].

Also it has been obtained experimental data comparing the key method considered in the article with electrical heating of hydrocarbon liquid [32], including for the purposes of its degassing. It was found that the rate of gas release during electrical heating is significantly lower than during EM exposure, and in addition, in the first case there is a temperature lag before the start of the gas release process. During degassing, the tangent of the dielectric loss angle in oil increases, which enhances the effectiveness of the EM effect, while the dielectric constant is practically unchanged [33, p. 14]. Electrostatic heating is also dangerous due to the possibility of breakdown when the threshold voltage is reached, especially for produced oil with high water cut [34].

The feasibility of EM destruction of produced water-oil emulsions and dehydration of oil which is characterized by acceptable separation quality with low energy costs for the formation of temperature fields is experimentally confirmed under operating conditions of field complexes [35]. This method allows to triple the time to achieve the established values of the mass fraction of water; it is 6.6 times more cost-effective compared to steam treatment using standard steam generators [36, p. 13–14]. It has been proposed a functional diagram of the process and the corresponding list of environmentally friendly devices (electrodynamic processing chamber) which make it possible to eliminate a significant share of expensive equipment (heating furnaces, settling tanks, water treatment plants) and, in general, simplify and automate the greater part of the production line [37, p. 18].

In compliance with optimal parameters of selection of frequency, radiation power and emitter dimensions, EM action also reduces oil viscosity faster and more than its direct heating [20], which is dangerous due to deposition of heavy hydrocarbons on heating surface, as well as short service life (burnout) of heating elements. Since the oil contains a large number of polar components (asphalt-resinous compounds), its rheological structure changes during production using an EM field [38], a ponderomotive force arises, therefore, the start time of filtration of high-viscosity oil is reduced by at least half compared to conventional heating of the bottomhole zone.

In addition, thermomechanical, thermoelectric and other derivatives of the force action of the field destroy the adsorption layer of oil on the walls of capillaries, which slows down the adsorption process and improves the filtration capabilities of the rock [39].

Proper selection of parameters for EM heating of oil reservoir, bituminous deposits and water-oil-saturated sands [40], taking into account their electrophysical parameters and features of convective heat transfer makes it more technically feasible, controlled (inertialess) and highly competitive even in comparison with in-situ combustion [15, p. 21–28], pulse pressure, steam gravity drainage, formation of an oil rim (dilution with light fractions) and other innovative technologies having significant limitations in application and many times higher energy consumption [41]. Energy savings also increase due to higher efficiency compared to other methods [42].

Meanwhile, despite a number of competitive advantages of using EM technology in the oil production industry, in real field conditions its application has a number of rather serious limitations that are critical from the economic point of view. First of all, problems arise when taking into account the distances between injection and production wells, which in the case of saturation of the reservoir with oil with very high viscosity are not overlapped by the EM field; such situations are characterised by the absence of filtration flow, ineffective energy expenditure. Such problems are solved, as a rule, by combining the technology in question with other methods of stimulation, forming combined methods.

One of the most developed methods is simultaneous EM-treatment with solvent injection into the bottomhole formation zone, which, allowing for the amount of displacing agent, cycle duration, heat loss estimation and other parameters, makes it possible to significantly increase the drainage radius and heat coverage of the formation, thus overcoming stagnant zones between wells. Evaluation of energy efficiency of the presented method for the purpose of oil production intensification shows its directly proportional relationship depending on viscosity values – the higher the viscosity of formation oil, the more effective this combined approach is in comparison with other methods in specific conditions of the developed field [43, p. 14–19].

The influence of the EM field combined with the injection of a mixing agent on multicomponent hydrocarbon systems causes the phenomenon of electrothermodiffusion – thermodiffusive mass transfer of EM origin, which is particularly effective in the development of high-viscosity oil deposits [44, p. 3–5]. The researchers propose to strengthen the presented method by pumping the solvent through the inner pipe of the injection well (acting as a coaxial line), which is heated due to the presence of the final electrical conductivity of metals, which, in turn, leads to the entry of the agent into the formation already in hot form. This approach, depending on the electro-, physical and chemical properties of the oil-saturated formation, allows increasing the energy balance in equivalent units above the value of 6 to 1 [44, p. 20–24]. At certain technical modification and cyclic influence the presented method is also suitable for extraction of extra-viscous oil and even bitumen [45].

For oil with low viscosity at conventional heating with solvent, as a rule, filtration flow moves with higher speed than at EM heating. This is explained by the fact that the lightest fractions are involved in the formation of the displacement front, while high-frequency impact causes desorption of polar components (primarily asphalt-resin compounds) from the rock surface, which increases viscosity and filtration resistance. As a result, the oil displacement factor in the second case is 35–40 % higher, which, of course, affects the development profitability [46, p. 6–7].

In addition, the above phenomenon allows this combined method to be used effectively for low-permeable reservoirs; in [46, p. 13] it is shown that to achieve the same result, the permeability value of the filter rock is directly proportional to the required EM emitter power. On the basis of experimental studies of high-viscosity oil filtration it is also stated that EM-impact is especially effective for carbonate-saturated reservoirs: at the same parameters (duration and power of radiation, pressure gradient, etc.) the volume flow rate of oil is 5–6 times higher than for terrigenous ones. The concentration of the auxiliary agent is also of great importance – in the case of using, for example, hydrochloric acid (as an electrolyte), its optimum ratio with water is caused by the maximum dielectric energy losses in the solution [47, p. 16–17]. The combination of chemical and EM effects also allows using combined approaches to remove harmful refractory deposits on pumping equipment, in the wellbore and bottomhole zone [13, p. 15–18].

Not only solvents, but also magnetic fluids (conductive and polarizable molecular magnetoactive solution or colloidal solution of ferromagnetic particles of nanofraction) can act as auxiliary agents (working fluids), regulating the depth of propagation and enhancing the effect of the EM field in terms of overcoming the critical pressure gradient, increasing the oil mobility coefficient (up to 9 times), increasing the displacement coefficient [48, p. 11–14], which are reflected in the effective indicators of field development of oil recovery (up to 38 % of conventional flooding), cumulative oil production (up to 85 %) and the oil recovery coefficient (up to 35 %) [48, p. 20].

Carbon filler (gas coal) introduced into high-viscosity oil as part of a suspension (to obtain a low freezing point) in antifreeze or hydrocarbon liquid is also used as a working agent in EM treatment. For unstable (high value of instability index for asphaltenes) heavy oil, the conventional method of dielectric heating is more effective, while for stable oil, a hybrid scheme of action is more effective: the specified filler in combination with a complex of distributed low-power emitters [49, p. 21–23]. Yttrium iron garnet [50], aluminum [51] and zinc [52] oxides (including in different concentrations [53]), iron [54] and copper [55], nickel [56], bismuth ferrite [57], barium titanate [58] and other metal compounds with oxygen [59] can also be used in this capacity.

One of the most effective ways to enhance the EM effect is its combination with the injection of carbon dioxide and nitrogen, which thin high-viscosity oil. [60].

Acoustic (ultrasonic) impact on hydrocarbon liquids is recognized as less effective than EM [61]. However, their combined use (electromagnetic-acoustic heating) [62, p. 3] with the correct selection of frequency and power of the fields mutually enhances the positive effects: this combination allows, while simultaneously selecting fluid, to expand the drainage radius, to freely introduce and use various reinforcing agents in the formation [63, p. 18].

The introduction of certain substances into hydrocarbon-containing liquids during their extraction has a special development prospect. For a long time, this method has been actively used in the petrochemical and oil refining industries, for example, to improve the efficiency of energy transfer in endothermic heterogeneous catalytic processes. In this case, the transformation of EM energy by the substance of an industrial catalyst (metal or oxide) into heat energy required to carry out the reaction is used. The introduction of such a catalytic reactor leads to a simplification of the process flow diagram due to the absence of water as a heat carrier; the efficiency of endothermic heterogeneous reactions occurring under EM radiation is twice as high as the efficiency of a traditional reactor [64, p. 12–20].

A combination of electromagnetic, acoustic, thermal and hydrodynamic methods of action within a single technological space is proposed by the developers of the YARUS pilot plant. It is designed for pulse-wave destruction of high-viscosity oil and natural bitumen directly at the production site. According to the authors, the reactor allows producing semi-synthetic and synthetic oil in one stage without preliminary preparation of the raw material and without a water recycling system by changing the phase In application of the system of emitters used to create EM fields combined methods can be composed by themselves. One of them is the use of waves of different frequencies – depending on energy-efficient ranges for specific conditions. In particular, it is proposed to use radiation of optical (absorbed by the surface layer of the armouring shell) and UHF (deeply penetrating into the emulsion thickness) ranges for destruction of oil-water emulsion in reservoir conditions at the displacement front and in the bottomhole zone of the formation [66, p. 4–5].

Researchers also found that the combined action of high-frequency and low-frequency EM fields allows accelerating the dynamics of emulsion separation three times faster than a separate high-frequency and 12 times faster than a separate low-frequency action [67, p. 17]. In addition to the emerging ponderomotive forces, this method causes inhomogeneity of the emerging thermal field and a shift in water concentration, contributing to the formation of two stratification fronts and accelerated destruction of emulsions.

The original approach of combination of separate impact by electric and magnetic fields is realised in the design of electromagnetic dehydrator in which the electric field is created by a system of electrodes, and the pulsating magnetic field crossed with it – by a single-phase winding, as a result of which the frequency of droplet collisions increases, and this leads to their accelerated merging and sedimentation. This approach allows eliminating the disadvantages of the methods used separately, provides by inducing eddy currents high productivity of the electric field without reaching a critical value of the intensity, leading to the destruction of water droplets or breakdown of the emulsion along their chain [68].

It is known that particularly stable emulsions are observed in sludges, which are harmful wastes of the oil industry, accumulated in specialised sludge pits [69]. The researchers proposed a technological unit including a quarter-wave resonator allows their utilisation on an industrial scale by means of EM-energy. Its operation leads to the destruction of the armouring shell, produces dielectrophoresis and provides electrocoagulation, that is, it implements all the mechanisms of electrophysical separation of a multicomponent heterogeneous medium into separate phases [70, p. 13–17].

The efficiency of the process of recycling highly stable water-oil emulsions and oil sludge compounds can be increased both by the interaction of high-frequency and ultra-high-frequency fields and by introducing a demulsifier using the method of compounding them with crude (unprepared) or commercial oil [71, p. 5–7]. This approach allows achieving “an increase in the productivity of plant by 2.5–3 times and a decrease in the content of chloride salts by 2.2 times in comparison with the basic technology with the same amounts of residual water and mechanical impurities” [71, p. 31–36], and significantly reduces the cost of production process.

A significant proportion of non-hydrocarbon impurities in oil sludge as a multi-component raw material require the use of approaches on the selective isolation of target products through their sequential heating. EM effect has the ability to control volumetric heating, which allows for step-by-step fractional processing (electromagnetic pyrolysis), adaptable to a wide range of chemical compositions of hydrocarbon-containing waste. At the same time, dielectrics (metal oxide catalysts of various compositions) specially introduced and contained in sludge act as thermal transformers and catalysts for their destruction, allowing for the separation of up to 2/3 of the mass fraction of the hydrocarbon part contained in the waste in terms of target products (ethene, aromatic and other fractions) [72, p. 16–20].

### Development of electromagnetic technologies: foreign and domestic experience

Despite the significant development at theoretical and applied level, the availability of ready-made technical solutions, as well as a number of pilot tests in the domestic oil industry mass application of well treatment with a high-frequency EM field has not received any serious development. By contrast, in foreign practice, the introduction of this method on an industrial scale is increasingly developing, which is confirmed by the dynamics of the the patent landscape growth, the subsequent transfer of technology and its commercialization: over the period of 1991–2024 in the world there is an annual patenting growth in the technology under consideration and related topics. The largest share of patents in this area is held by companies affiliated with the largest oil-producing corporations, mainly from the United States: Halliburton Energy Services (7 % от всего количества патентов), ExxonMobil Upstream Research Company (4.7 %), Schlumberger Technology Corporation (4.1 %), Harris Corporation (2.3 %), Saudi Arabian Oil Company (1.5 %), Baker Hughes Incorporated (1.2 %), Schlumberger Canada Limited (1.1 %).

In foreign jurisdictions, the most significant patents with the maximal subsequent citation over the past decade include:

– JP-2016525177-A – Electromagnetically assisted ceramic materials for heavy oil recovery and on-site steam generation (Saudi Arabia, 2013) [73];

– US-9739126-B2 – Effective solvent extraction system incorporating electromagnetic heating (USA, 2014) [74];

– US-10626711-B1 – Method of producing hydrocarbon resources using an upper RF heating well and a lower producer/injection well and associated apparatus (Norway, 2018) [75];

– US-10954765-B2 – Hydrocarbon resource heating system including internal fluidic choke and related methods (Norway, 2019) [76];

– US-11729870-B2 – Multilateral open transmission lines for electromagnetic heating and method of use (Canada, 2020) [77];

– US-11920448-B2 – Apparatus and methods for electromagnetic heating of hydrocarbon formations (Canada, 2022) [78].

The most relevant Russian patents in this area are the following:

– “RU-2720338-C1 – Method of Developing Deposits of Heavy Oil, Oil Sands and Bitumen” (Ufa, 2020) [79];

– “RU-2704159-C1 – Method of Developing Hydrocarbon Deposits” (Volgograd, 2019) [80];

– “RU-2648411-C1 – Method for Increasing Oil Recovery Factor in Hard-to-Recover and Depleted Fields” (Volgograd, 2018) [81].

It is worth noting that, as a rule, the copyright holders of these patents remain their developers – small innovative enterprises, universities or public organizations.

Thus, the application of EM heating in global oil production practice is becoming increasingly relevant; critical issues have also been identified, overcoming which is of decisive importance for the development of this technology and further realization of its potential in oil production industry. It has been identified the main economic factors of expediency of EM technology introduction in comparison with alternative methods. The most important factors are the availability and acceptable cost of energy sources for creating a field and heating the formation. However, for some countries, the key factors are regulatory requirements for the environmental friendliness of production, according to which this technology has an absolute advantage [82].

Among foreign countries, Canada is the country in which the methods of EM-action on the reservoir and downhole zone have been most developed over the last decade. First of all, this is the project ESEIEH (Enhanced Solvent Extraction Incorporating Electromagnetic Heating), where the injection agent is propane or butane. Initially, a key problem of this approach was that using EM heating to temperatures equal to, for example, those achieved by steam drainage was not energy efficient, the range of EM heating applications being limited to the downhole zone and dependent on the amount of energy consumed. In addition, to take advantage of the controllability of the EM irradiation process (compared to other thermal methods) it is required accurate computerized models to select a set of possible combinations of frequencies, capacity levels, auxiliary agents (if any) and well designs which allow the most cost-effective option for a particular well to be calculated. In the end, only the totality of the ordered data makes it possible to realise economic models of the way to manage production with maximum profit [83].

According to other foreign works, high-frequency EM heating, in comparison with its low-frequency version, steam drainage and direct heating, is more energy efficient even taking into account additional losses of EM energy in power transmission lines [84]. Some studies indicate a threefold or more increase in flow rate after EM treatment of wells in oil fields [85]. EM treatment is also recommended to precede steam drainage when developing bituminous sands [86] or reservoirs with ultra-low permeability [87].

Based on the available technical and technological solutions, it is possible to calculate the energy balance data when using EM well treatment. From the economic point of view calculation of the balance for a certain (annual) period of time, taking into account the time of a single treatment and the differences in well types (table) is of the greatest interest.

Based on the table presented, it can be argued that the processing time of wells, especially vertical ones, has virtually no effect on the balance coefficient during subsequent production over a fairly long period of time. However, a shorter period of operation of the EM installation allows for the successive treatment of a larger number of wells, and this will lead to the achievement of more significant production volumes in the field as a whole. Besides, a comparative analysis of the use of EM impact on high-viscosity oil formations by vertical and horizontal wells, taking into account the technical features

Energy balance of wells EM treatment

| Plant operation time, days | Additional production per year, tonnes | Obtained energy equivalent, J | Plant power consumption, J | Balance coefficient |
|---|---|---|---|---|
| | | Vertical well | | |
| 30 | 286 | $13.1 \cdot 10^{12}$ | $2.1 \cdot 10^{12}$ | 6.39: 1 |
| 60 | 585 | $27.0 \cdot 10^{12}$ | $4.2 \cdot 10^{12}$ | 6.51: 1 |
| 90 | 856 | $39.4 \cdot 10^{12}$ | $6.2 \cdot 10^{12}$ | 6.35: 1 |
| | | Horizontal well | | |
| 10 | 115 | $5.28 \cdot 10^{12}$ | $0.366 \cdot 10^{12}$ | 14.4: 1 |
| 15 | 156 | $7.21 \cdot 10^{12}$ | $0.55 \cdot 10^{12}$ | 13.1: 1 |
| 25 | 233 | $10.7 \cdot 10^{12}$ | $0.917 \cdot 10^{12}$ | 11.7: 1 |

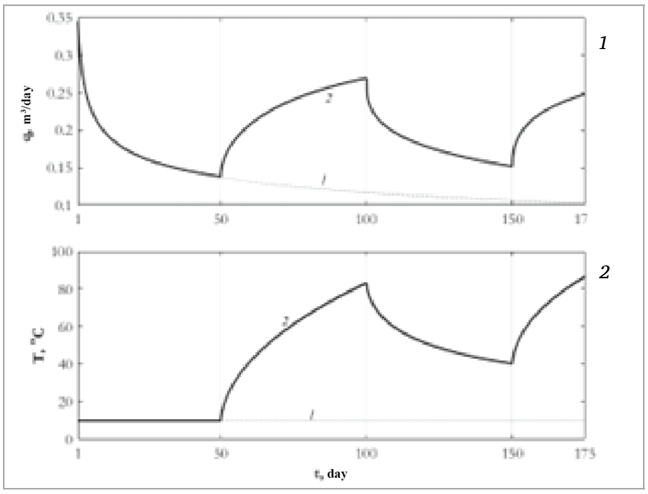

Fig. Dynamics of oil flow and temperature changes in a well with hydraulic fracturing under EM stimulation

of their arrangement, shows an approximately twice as large effect from the horizontal placement of the radiation source. On average, taking into account variable costs, operating expenses of the unit and other components of the cost of produced oil, the payback period of HF EM equipment is about 1.5 years.

Special attention should be paid to determining the economic efficiency of super-viscous oil production from low-permeable deep reservoirs, since such formations will inevitably become the objects of development as traditional oil reserves are depleted [88]. Traditional production technologies (flooding, hydraulic fracturing, steam injection, etc.) are not currently effective at such sites [89], but their combination with EM heating can lead to an acceptable level of profitability [90].

Let us consider a variant of numerical modelling of multistage technology of heavy oil production in a well with hydraulic fracturing and stage-by-stage high-frequency EM-influence [91]. At the first stage the "cold" production is carried out, at the second stage it continues with the EM-wave generator switched on, at the third stage the production of heated oil is carried out without influence – until the well flow rate decreases to the initial value; then the stages are repeated, starting from the second stage (figure).

The given figure demonstrates a significant increase in oil flow with increasing temperature at EM-action 2 in the near-wellbore region compared to "cold" production 1 after hydraulic fracturing. Economic analysis of the technology of staged thermal stimulation of a well in a low-permeability reservoir with ultra-viscous oil with pre-fracturing has shown that the EM unit in this variant of use pays off in 16 years. "Cold" production without additional heating from such a fractured reservoir is not cost-effective. This approach can be further developed in various ways: its combination with injection of a mixing agent [92] or construction of a horizontal well with multistage hydraulic fracturing [93], which will reduce the payback period by increasing the volume of fluid flow to the well.

The development of the non-isothermal computational module and the possibility of its inclusion in commercial simulators also deserve special attention. Numerical models on the issue under consideration have received in recent decades a significant scientific substantiation [94], software products which allow you to identify the dependence of reservoir characteristics, saturating fluid and other parameters on temperature have been developed. Thus, a number of works by domestic scientists consider the following problems:

1. The problem of numerical calculation of the dependence of the temperature field of viscoplastic oil on pressure and time in the problem of non-isothermal filtration, taking into account the reduction of calculation time through the use of non-uniform meshes, which allowed developing algorithms and a set of computer programmes, as well as obtaining the results of computational experiment applicable in practice [95, p. 5].
2. The issue of implementation of computational algorithms and development of a software package for numerical integration of equations of non-isothermal multicomponent filtration with phase transitions and chemical reactions. The peculiarity of the presented programmes is the consideration of permeability and porosity growth caused by thermal effect on the formation. The author points out that the existing commercial simulators do not allow to take this aspect into account, while the original approach and the corresponding development make it possible to perform comprehensive modelling (compared to Schlumberger Eclipse) and evaluate the efficiency of thermal EORs in high-viscosity oil fields [96, p. 5].
3. The issue of constructing a physical and mathematical model of non-isothermal filtration of a two-phase liquid in fractured-porous media taking into account the parameters and location of extended single and discrete fractures, operating temperature during production, non-stationarity of well operating modes, identification of the combined influence of the listed factors on the filtration process, as well as comparison of the calculation results of the developed model and

commercial simulators (with tNavigator the difference did not exceed 2 %) [97, p. 3–7].

4. The issue of designing a hydrodynamic model of the process of thermal barochemical impact of heat-generating agents (mixtures) on the wellbore zone of an oil reservoir, taking into account the dynamics of the phase state of a multicomponent hydrocarbon system, as well as the creation of a corresponding software package that allows identifying the formation of pressure fields and volumetric heating, determining the degree of cleaning of the well zone from solid paraffin deposits and their involvement in the filtration process, calculating the radius of action of the method, state the expediency of the impact and evaluate the effect of well treatments through the increase of the intensity and volume of oil production from a heated formation [98, p. 4–5]. Verification of the calculation results was carried out by the author in a hydrodynamic simulator Schlumberger Eclipse [98, p. 17–18].

5. The issue of using numerical three-dimensional calculations in the formation of a new averaged non-isothermal model for two-phase filtration, which can be used in geological and hydrodynamic modeling of optimal field development under conditions of hot and cold flooding of a multilayer oil reservoir. Verification of the calculation results and the operation of the software package was carried out by the author in the Tempest hydrodynamic simulator [99, p. 4–10].

6. The issue of determining the flow lines of non-isothermal non-linear filtration of a multiphase multicomponent fluid during the development of fields with hard-to-recover reserves, which allows using the software package developed by the author to determine the efficiency of using thermal methods to oil recovery growth during the development of high-viscosity heavy oil fields [100, p. 14].

Modeling of the field development process using EM technology takes place in individual software packages, for example, Tempest [41, p. 14]. However, it can be concluded that the simulators used by Russian companies do not have the corresponding capbilities of analysis. Therefore, it seems premature to talk about the operation of a full-fledged calculation non-isothermal module as part of domestic commercial simulators at this stage.

## Conclusion

Thus, further prospects for increasing production in the Russian Federation are associated, first of all, with the development of hard-to-recover reserves, in particular, from high-viscosity oil reservoirs. The method of the bottomhole formation zone stimulation with a high-frequency EM field, taking into account the specific energy consumption in comparison with other thermal methods, is economically viable and allows in the near future to transfer large reserves of high-viscosity oil explored in the country into the category of recoverable ones [101]. For regions historically specializing in oil production and refining, the method is also promising for fields with a late stage of development [102]. It is also worth noting that in the process of widespread implementation of EM technology in the domestic oil production industry, equipment mass-produced in Russia can be used, which in the current geopolitical situation is an important factor in its support and scaling.

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Funding. The article was prepared at the expense of the grant of the Russian Scientific Foundation No. 22-11-20042.

Conflict of interest. The authors declare no conflict of interest.

The authors' contribution is equivalent.