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Review article

Alternative Methods of thermal Oil Recovery: A Review

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ABSTRACT

Oil production from fields with hard-to-recover reserves always remains a challenge for the oil and gas industry, mainly due to one special factor – the high viscosity of oil, which implies low mobility of oil in a porous medium. Over time, traditional methods of increasing oil recovery become less effective due to a decrease in readily available oil reserves and the complexity of geological conditions for field development. In this regard, the need to use innovative methods to increase oil recovery is becoming more urgent. In recent decades, research in this area has shown significant progress, various methods have been introduced to reduce the viscosity of oil. One of the most effective and actively developing approaches in this area is thermal methods of enhanced oil recovery. They are based on the injection of thermal energy into the reservoir in order to reduce the viscosity of oil and, consequently, increase mobility, which in turn will greatly facilitate the displacement of oil from the rock to the surface.

Despite certain successes achieved in the use of various methods of increasing oil recovery in the production of heavy oil, the problem of finding alternative methods remains relevant.

This article presents the review of alternative methods of enhanced oil recovery, including principle of operation of electromagnetic heating of the reservoir, the influence and effectiveness of radio waves and microwave frequencies on the reservoir and the properties of oil, ultrasonic exposure, advantages and disadvantages of alternative methods, comparing them with traditional methods, analyzing the productivity of fields where alternative methods of enhanced oil recovery were used.

Keywords: *oil reservoir; thermal methods of enhanced oil recovery; electromagnetic heating; ultrasonic exposure; microwave radiation; radio waves; heavy oil.*

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Научный обзор

Альтернативные методы теплового повышения нефтеотдачи: обзор

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АННОТАЦИЯ

Добыча нефти из месторождений с трудноизвлекаемыми запасами всегда остается вызовом для нефтегазовой отрасли в основном из-за одного особого фактора – высокой вязкости нефти, что подразумевает низкую мобильность нефти в пористой среде. С течением времени традиционные методы повышения нефтеотдачи становятся менее эффективными из-за уменьшения запасов легкодоступной нефти и усложнения геологических условий разработки месторождений. В связи с этим применение инновационных методов повышения нефтеотдачи становится более актуальной задачей. В последние десятилетия исследования в этой области показали значительный прогресс, внедрялись различные методы для снижения вязкости нефти. Одним из наиболее эффективных и активно развивающихся подходов в этой области являются термические методы повышения нефтеотдачи. Они основаны на закачке тепловой энергии в пласт с целью снижения вязкости нефти и, следовательно, повышения мобильности, что, в свою очередь, значительно облегчит вытеснение нефти из породы на поверхность.

Несмотря на определенные успехи, достигнутые в использовании различных способов повышения нефтеотдачи при добыче тяжелой нефти, проблема поиска альтернативных методов остается актуальной.

В данной статье представлен обзор альтернативных методов повышения нефтеотдачи, к которым относятся принцип действия электромагнитного нагревания пласта, влияние и эффективность радиоволн и микроволновых частот на пласт и свойства нефти, ультразвуковое воздействие, преимущества и недостатки альтернативных методов, сравнение их с традиционными методами, анализ производительности месторождений, на которых использовались альтернативные методы повышения нефтеотдачи.

Ключевые слова: *нефтяной пласт, тепловые методы повышения нефтеотдачи, электромагнитное нагревание, ультразвуковое воздействие, микроволновое излучение, радиоволны, тяжелая нефть.*

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Ғылыми шолу

Мұнай өндіруді жылумен арттырудың балама әдістері: шолу

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АННОТАЦИЯ

Өндірілуі қиын қорлары бар кен орындарынан мұнай өндіру әрқашан мұнай-газ саласы үшін қиындық болып қала береді, негізінен бір ерекше факторға байланысты – мұнайдың жоғары тұтқырлығы, бұл кеуекті ортада мұнайдың төмен қозғалғыштығын білдіреді. Уақыт өте келе мұнай өндіруді арттырудың дәстүрлі әдістері оңай қол жетімді мұнай қорларының азаюына және кен орындарын игерудің геологиялық жағдайларының күрделенуіне байланысты тиімсіз болып келеді. Осыған байланысты мұнай өндіруді арттырудың инновациялық әдістерін қолдану қажеттілігі өзекті бола түсуде. Соңғы онжылдықтарда осы саладағы зерттеулер айтарлықтай прогреске қол жеткізді, мұнайдың тұтқырлығын төмендетудің әртүрлі әдістері енгізілді. Бұл саладағы ең тиімді және белсенді дамып келе жатқан тәсілдердің бірі - мұнай өндіруді арттырудың термиялық әдістері. Олар мұнайдың тұтқырлығын төмендету және осылайша ұтқырлықты арттыру мақсатында жылу энергиясын қабатқа айдауға негізделген, бұл өз кезегінде мұнайды тау жыныстарынан жер бетіне шығаруды айтарлықтай жеңілдетеді.

Ауыр мұнай өндіруде мұнай өндіруді арттырудың әртүрлі әдістерін қолдануда қол жеткізілген белгілі бір жетістіктерге қарамастан, балама әдістерді іздеу мәселесі өзекті болып қала береді.

Бұл мақалада мұнайды электромагниттік жылытудың әсер ету принципі, радиотолқындар мен микротолқынды жиіліктердің қабатқа және мұнай қасиеттеріне әсері мен тиімділігі, ультрадыбыстық әсер ету, балама әдістердің артықшылықтары мен кемшіліктері, оларды дәстүрлі әдістермен салыстыру, мұнай өндіруді арттырудың балама әдістері қолданылған кен орындарының өнімділігін талдау кіретін мұнай өндіруді арттырудың балама әдістеріне шолу жасалады.

Негізгі сөздер: *мұнай қабаты, мұнай өндіруді арттырудың термиялық әдістері, электромагниттік қыздыру, ультрадыбыстық әсер, микротолқынды сәулелену, радиотолқындар, ауыр мұнай.*

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Introduction

Heavy oil is characterized by its high viscosity and density, rendering it unsuitable for extraction using conventional techniques due to its unique physical features. However, the depletion of light oil reserves and the rising global energy demand have led to a heightened interest in heavy oil reserves [1]. Given the depletion of conventional and readily accessible reserves, heavy oil is emerging as a crucial resource in addressing the global energy demands. Nevertheless, the acquisition, manipulation, and conveyance of viscous petroleum need the utilization of specialist methodologies and advancements. Several studies have been undertaken to elucidate the impact of these approaches on the global growth in oil output.

Thermal approaches rely on the provision of heat to the reservoir. The primary factor contributing to the enhanced oil recovery is the reduction in oil viscosity, which subsequently leads to an elevation in the mobility coefficient [2]. The reservoir can receive heat through two methods: steam or water injection, or the initiation of a combustion front within the reservoir. Thermal methods are widely employed in the extraction of heavy oil, with steam-based techniques being the primary procedures utilized. These include cyclic steam stimulation (CSS), steam flooding (SF), and gravity drainage by steam (SAGD), alongside in-situ combustion (ISC) and hot water flooding [3]. Nonetheless, a diverse range of techniques exists, encompassing joint injection of steam, solvents, and other gases. Currently, thermal approaches for enhancing oil recovery, alongside flooding techniques, are widely regarded as the sole alternative being adopted on an industrial scale [4].

The study investigated alternative approaches to boost oil recovery by addressing the reduction of oil viscosity, augmentation of its mobility, and facilitation of its extraction to the surface. Currently, a diverse array of methodologies exists, with certain approaches demonstrating successful validation, while others exhibit inherent limitations. The existing techniques encompass induction heating and microwave irradiation with the purpose of decreasing oil viscosity, as well as electric heating and radiofrequency heating. Among the several approaches currently accessible, radio wave and microwave methods have been extensively studied and have already been implemented in the USA.

The exploration and production of oil and gas fields encounter various obstacles, one of which is to the imperative of maintaining a consistent flow rate from the well. The flow rate is influenced by various factors, including the hydrodynamic properties of the formation, the extent of the drained area, and the effectiveness of the well-formation connection [5]. The efficacy of the connection between the well and the formation is frequently compromised as a result of the early and subsequent stages of opening, rendering numerous wells inefficient [6]. As the production process advances, it is common for the permeability levels and hydraulic conductivity of the bottomhole formation zone to see a decline [7].

A decrease in temperature results in a rise in the viscosity of oil, leading to a decrease in its mobility and exacerbating the productivity of the well. Hence, inquiries regarding the most efficient functioning of the field and the formulation of approaches to sustain a consistent flow rate are now being investigated [8].

The exploration of alternate approaches for enhancing oil recovery has led to the consideration of electromagnetic (EM) heating techniques employing radio frequencies or microwaves for heavy hydrocarbon resources. This subject has been examined by multiple scholars, such as Abernathy in 1976 [9], Kasevich [10], Islam in 1991 [11], Ferry in 2001 [12], Sahni in 2001 [13], Fanchi in 1990 [14], Das in 2008 [15], Carrizales in 2008 [16], Ovalles in 2002 [17], and others. The authors conducted a study to analyze the impact of a radio frequency (RF) / microwave (MW) signal on the reservoir, specifically examining its ability to enhance the extraction process of heavy crude oil by reducing its viscosity through considerable heating. One primary limitation of this approach is the insufficient dielectric properties exhibited by porous medium, which hinders the attainment of a substantial temperature rise within a tolerable timeframe, hence resulting in elevated energy consumption. The essay provides a comprehensive analysis of this particular procedure. Various methods of heating the formation, including as microwaves, radio waves, induction heating, and electric heating, are also taken into consideration. The article provides a comparative analysis of these strategies and offers concise descriptions for each.

Thermal Enhanced Oil Recovery Methods

In the context of any thermal enhanced oil recovery (EOR) technique, heat is produced either at the surface or within the reservoir. The thermal EOR methods, such as hot water and steam injection techniques, are widely utilised in many applications due to their high level of dependability [18]. Furthermore, the utilisation of various injection and production well orientations in steam injection techniques enhances their efficacy in the retrieval of low API gravity crude oils encompassing a wide variety of viscosities [19]. For example, in various EOR techniques such as steam flooding, CSS, and SAGD, steam is utilised as the injected fluid. However, the distinct well configurations employed in each process enhance their effectiveness in extracting heavy oil, extra-heavy oil, and bitumen, respectively [20]. Nevertheless, the utilisation of steam in industrial processes presents significant environmental problems due to the substantial amount of fresh water required for injection and the subsequent heating of water to produce steam through fuel combustion, resulting in the emission of greenhouse gases (GHG). Solvent-steam procedures have been suggested as a means to reduce the environmental impacts associated with steam injection methods [21, 22]. Solvent-steam processes have a reduced steam consumption in comparison to steam processes in isolation.

In addition, the introduction of solvents into a steam stream is anticipated to enhance oil output by further reducing viscosity through the miscibility of solvents with oil. Nevertheless, it should be noted that not all oil fractions exhibit miscibility with every type of solvent. The fraction of asphaltenes in crude oils is notably intractable in commonly employed solvents such as CO_2, CH_4, and conventional alkanes. Moreover, the solvents that may dissolve asphaltenes, namely aromatics, are mostly recognised for their hazardous properties. Therefore, the careful choice of solvent of utmost importance in ensuring the efficacy of solvent-steam processes [23].

In addition to conventional steam injection techniques, in-situ heat production systems have demonstrated potential for the extraction of highly viscous oils. The approaches under consideration are specifically ISC and electrical and electromagnetic stimulation technologies. The implementation of the Improved Oil Recovery (IOR) technique known as the ISC process has demonstrated the potential to produce oil displacement rates of up to 95%. Due to the inherent challenges associated with controlling the propagation of the combustion front, the successful implementation of ISC in its entirety has been limited to a select number of field applications [24]. The primary factor contributing to the limited efficacy of ISC is primarily attributed to the intricate dynamics of combustion, oxidation, and cracking reactions, as well as the markedly diverse characteristics of oil reservoirs [25].

Alternative Methods of thermal Oil Recovery

The current technologies for enhanced oil recovery are associated with several restrictions, such as elevated expenses, increased greenhouse gas emissions, and operational intricacies [26]. In order to address the aforementioned economic, environmental, and technological limitations, extensive research is currently being conducted to explore alternate methodologies.

An additional technique that can be used in conjunction with or as an alternative to conventional EOR methods is known as Electrical-based EOR. Therefore, by employing various electrical techniques such as sound waves, RF waves, inductive heating, DC heating, etc., it is possible to extract oil from reservoirs at a much reduced expense and with improved efficiency as compared to the standard methods of enhanced oil recovery discussed earlier. The primary objective of the EOR method is to enhance the oil's mobility by reducing its viscosity, hence facilitating its movement towards the producing well [27]. The aforementioned phenomenon occurs due to the introduction of electrical energy into the reservoir, which can result in two outcomes: an increase in the temperature of the oil or the generation of vibrations within the hydrocarbon molecules.

The categorization of electric heating methods can be based on the frequency at which electrical current is utilised, resulting in three primary classifications. Ohmic or resistive heating is most effectively achieved through the utilisation of low-frequency electric current, whereas high-frequency electric current is commonly employed for microwave heating techniques. In contrast, it has been observed that inductive heating can employ a variety of low- and medium-frequency electric currents, with the specific choice depending on the level of energy accessibility [28].

Radiofrequency/microwave radiation

RF/MW heating refers to a thermal process wherein the dielectric constituents of a substance experience an increase in temperature. The rotation of molecules, particularly those with polar characteristics, is induced by the impact of an electromagnetic field on the substance. Polar molecules exhibit a propensity to align themselves with electromagnetic fields, hence engendering intermolecular interactions that give rise to the production of heat energy.

One of the primary objectives of the proposed methodology is the exploration for substances that had the ability to engage in beneficial interactions with RF/MW radiation. The examination of the high-frequency/microwave techniques employed in the technological process of ceramic material processing for heating applications has yielded valuable insights. Indeed, throughout this particular process, the RF energy that is received undergoes a conversion into thermal energy within the substance, resulting in a subsequent elevation in temperature. Sutton's article demonstrates the capability of radio frequency / microwave radiation to induce high temperatures in ceramics, above the threshold of 1400°C,

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while also facilitating the removal of water from the material [29].

The utilization of silicon carbide (SiC) as a heat exchanger in the suggested approach is justified by its notable thermal conductivity, which facilitates the efficient transfer of heat into the reservoir. In isolation, SiC is capable of addressing a portion of the issue due to its limited power penetration depth, which amounts to a few centimeters (specifically 10 cm at a frequency of 2.45 GHz) [30]. Furthermore, it has been observed that the temperature increase can surpass 1000°C when thermal emission is taken into account [31]. In order to mitigate any potential adverse consequences arising from the elevated temperature within the reservoir, it is advisable to incorporate SiC in conjunction with an additional substance possessing enough transparency to RF and MW radiation. Leiser observed that the proportion of microwave-absorbing material to materials that are transparent to microwaves has the ability to self-regulate the heating process and, furthermore, enhance the extent of energy penetration [32]. Aluminum oxide (Al_2O_3) is a material that exhibits transparency in the RF/MW range, possessing the following noteworthy attributes: remarkable dielectric properties spanning a wide frequency spectrum; demonstrates commendable resistance to potent acids and alkalis when subjected to elevated temperatures; exhibits favorable thermal conductivity; possesses high levels of strength and rigidity.

At a frequency of 2.45 GHz, the power exhibits a penetration depth of around 10 meters. In the current phase, it has been shown that the inclusion of a composite material comprising SiC and Al_2O_3 can enhance the depth of energy penetration while concurrently generating elevated temperatures. This is attributed to the material's capacity to convert electromagnetic energy into thermal energy.

The study conducted by Peraser et al. [33] utilized numerical simulations to compare the effectiveness of RF and MW technologies, operating within the frequency range of 140 to 2450 MHz and with input power ranging from 10 to 100 kW, with CSS in the context of a heavy oil field located in Alaska. The findings of the study indicated that RF and MW technologies outperformed CSS in this particular scenario [33]. The researchers demonstrated that the effectiveness of steam injection in heavy oil reservoirs in Alaska is constrained by the poor permeability of the geological formation. However, it was observed that the formation has the potential to absorb radio frequency heating (RFH) and microwave heating (MWH) energy. As a result, the permeability of the formation is not as crucial in the context of MWH and RFH. Furthermore, the authors proposed the potential feasibility of restricting the use of MWH and RFH to certain regions of interest. This targeted approach could enhance the management of these technologies, thereby rendering both HF and MW potentially viable options for the extraction of heavy oil reserves in Alaska.

Figure 1. Temperature (°F) profile after 1 year of EM heating

Figure 2. Viscosity (Pa*s, 1Pa*s = 1000 cp) Profile After 1 Year of EM Heating

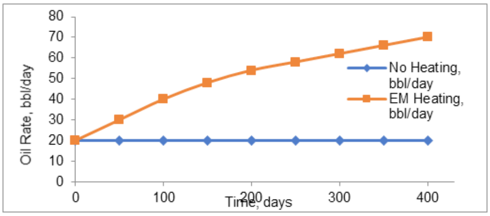

Figure 3. Oil Production Rate After 1 Year

According to their research findings, following a year of EM heating, the temperature in the vicinity of the borehole experiences a rise of 120°F in comparison to the starting temperature of the reservoir. This increase corresponds to a 76% augmentation in the reservoir temperature. The temperature observed at a distance of 10 meters from the wellbore exhibits a significant jump to 141°F, indicating a notable 17% increase in reservoir temperature, as depicted in Fig. 1.

As the temperature in the vicinity of the borehole rises, there is a corresponding drop in the viscosity of the fluids in contact. The oil's viscosity undergoes a reduction from an initial value of 3062 centipoise (equivalent to 3.062 Pascal-seconds) to 98.9 centipoise (0.0989 Pascal-seconds), resulting in a decrease in viscosity of 97%. Fig. 2 illustrates the observed reduction in the viscosity of oil.

Fig. 3 depicts the production profile of the reservoir subsequent to one year of EM heating, along with a comparative analysis of production outcomes with and without the implementation of EM heating. The initial production level, in the absence of any heating, is recorded at 19 barrels per day. However, after

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implementing continuous electromagnetic heating, the output significantly rises to 71 barrels per day by the conclusion of the first year. This represents a notable increase of 273% in productivity.

According to the findings of Peraser et al. [33], the utilization of electromagnetic heating at moderate power levels in the megawatt range might result in a significant enhancement in heavy oil extraction rates, with an increase of up to 200% seen [33]. Nevertheless, despite the outstanding potential for heavy oil resources in Alaska, no pilot sites were established subsequent to this study.

The impact of microwave heating on the bottom-hole zone of a well is contingent upon the absorption of electromagnetic energy within the hydrocarbon-saturated rock. Ultrahigh frequency oscillations (UHF) refer to oscillations characterized by a frequency (f) above 300 MHz or a wavelength (λ) shorter than 1 m. The current electromagnetic impact technique enables microwave fields to penetrate to a significant depth vertically along the bottom of the well. The interaction between matter at the atomic and molecular scale influences the behavior of electrons, resulting in the conversion of microwave energy into thermal energy. Microwave energy is a highly convenient heat source that possesses undeniable advantages over alternative sources across several applications. When subjected to heat, it exhibits no pollution and does not produce any combustion byproducts [34]. Furthermore, the efficient conversion of microwave energy into heat enables the attainment of exceptionally rapid heating rates, without subjecting the material to detrimental thermo-mechanical strains [35].

Low frequency heating

The electric heater, operating at a frequency of 60 Hz, is a technique in which the electrical conductor functions as the primary heat source [36]. The passage of electric current is restricted to the conductor, resulting in ohmic heating. This implies that the conductor serves as the primary origin of thermal energy. In practical terms, it is possible for this to function as a heated pipe, such as when it is subjected to steam or hot water, without being discharged into the reservoir. Consequently, the efficacy of the heating process is contingent upon the quality of thermal contact established between the heater and the reservoir, in addition to the thermal conductivity exhibited by the reservoir. An increase in the thermal conductivity of the reservoir leads to a corresponding increase in the temperature difference between the heater source and the distant drain point.

In order to maintain a constant thermal power provided to the reservoir, it is necessary to ensure a constant temperature difference between the source and receiver sites. One benefit is the potential to utilize direct energy derived from the grid in a downward direction. Devices with power outputs in the region of several hundred kilowatts are technically conceivable, considering the necessary power density. One drawback of this approach is the constrained drilling area, which is a consequence of its reliance on heat conductivity. Furthermore, the heaters serve the purpose of generating the elevated temperatures necessary for the operation of the temperature difference mechanisms. The elevated temperature can give rise to thermal contact issues as a result of surface drying in close proximity to the heater.

Ultrasonic exposure

The impact of ultrasound on viscosity reduction in superheavy oil was investigated by Wang et al. [37]. The initial viscosity of the superheavy oil was measured to be 1250 MPa*s. The wave frequency range examined was found to be between 18 kHz and 25 kHz, while the output power ranged from 100 W to 1000 W. The use of ultrasound at frequencies of 18, 20, and 25 kHz resulted in a decrease in the viscosity of oil to 480, 890, and 920 MPa*s, respectively. However, it should be noted that the duration of radiation had an impact on these alterations. The findings of their study additionally demonstrated that ultrasonic radiation-induced cavitation has the capability to fragment sizable, weighty molecules of superheavy oil into lighter hydrocarbon compounds. Furthermore, it has been determined that the primary influential factors in decreasing the viscosity of heavy oil are the ultrasonic frequency, power level, and duration of radiation.

Hamidi et al. conducted research that yielded comparable findings, wherein they extensively examined the impact of ultrasound on both the pressure drop and viscosity alteration of the oleic phase within a porous medium [38]. The researchers conducted experiments to investigate the impact of ultrasonic frequencies and power on different types of oil. Their findings indicate that heat generation, cavitation, and viscosity reduction are the primary factors to be considered when employing ultrasound techniques to maximize oil recovery. Based on the findings of Palayev's research [39], it is possible to derive the following conclusions: the application of ultrasonic waves to oil exhibits a more pronounced reduction in viscosity compared to thermal heating alone or a combination of heating and ultrasonic treatment.

The present study examines the utilization of ultrasonic technologies in the oil fields of Kazakhstan. a limited number of scholarly publications and articles discuss the utilization of ultrasonic technologies in many domains, as indicated by publicly accessible research.

In the study conducted by Ershov M.A. and Mullakaev M.S. [40], the authors employed the ultrasonic approach in conjunction with the use of chemical reagents to achieve a reduction in oil viscosity. Laboratory experiments were conducted using oils with the qualities outlined in Table 1.

The reagents included in the studies included xylene, toluene, butyl acetate, hexane, and gas condensate. The most significant decrease in oil viscosity can be attained through the synergistic impact of ultrasonic treatment and the utilization of chemical reagents at:

In the case of the Eastern Zhetybai field, the application of an intensity of 12 W/cm^2 for a duration of 1 minute, along with the addition of 2% xylene, resulted in a significant reduction of dynamic viscosity by 44%. Similarly, the introduction of 2% butyl acetate led to a viscosity reduction of 38%. For the Aschisay oil, subjecting it to the same intensity for a shorter duration of 15 seconds, combined with the addition of 2% butyl acetate, resulted in a viscosity reduction of 42%. Furthermore, the introduction of 2% toluene led to a viscosity reduction of 35%. It is worth noting that the application of ultrasonic treatment on the oil of the Kyrykmyltyk field exhibited lower efficiency compared to the other oils under investigation.

The conditions in which ultrasonic exposure can be used in field conditions. Mullakaev et al. established a set of fundamental criteria that outline the necessary correspondence between the key parameters of reservoir oil, geological and physical features of the well, and the utilization of ultrasonic exposure equipment and technology [41]. The reservoir conditions encompass certain parameters, such as a permeability over 0.25 microns, a porosity exceeding 20%, a rock composition primarily consisting of sandstone, and a temperature range of 10–135°C at the lowermost point. Additionally, the pressure at the bottom of the reservoir ranges from 40–400 atm. The reservoir fluid conditions should align with a dynamic viscosity of less than 25 MPa*s under reservoir conditions, while the temperature at which paraffin crystallization initiates should be lower than both the bottom-hole and reservoir temperatures.

To get an optimal resolution for the problem of enhancing oil fluidity and decreasing viscosity, an analysis was performed on an experiment conducted under controlled laboratory settings, with a frequency of 42.8 kHz. In the course of this experiment, the oil sample, whose properties are outlined in Table 2, was subjected to ultrasonic irradiation using a magnetostrictive transducer.

The phenomenon of lowering the viscosity of oil by the application of ultrasonic therapy can be attributed to the occurrence of cavitation processes during this treatment. These processes entail the localized concentration of acoustic field energy in the form of cavitation bubbles, which are of relatively modest magnitude. The emergence of high energy densities is a consequence of the collapse of these bubbles [42]. Moreover, in the process of cavitation, there is a disruption of elongated and complex hydrocarbon molecules, accompanied by the liberation of thermal energy, commonly referred to as exothermy.

Table 1. Group composition of the studied oil samples

Oil field	Dynamic viscosity, at 20°C, MPa*s	Content, % by mass		
		paraffin	resins	asphaltenes
Eatern Zhetybai	575	28,3	19,3	3,8
Kyrykmyltyk	8159	15,5	25,9	6,6
Aschisay	360	18,9	15,2	4

Table 2. Key indicators

Parameter	Value
Oil viscosity, at 20°C	853 kg/m^3
Kinematic viscosity	1,348*10^{-5} m^2/s
Water content	0,06%

Table 3. Results of the experiment

Parameter	Results after 30 s	Results after 45 s	Results after 60 s
Temperature, °C	25	30	32
Kinematic viscosity, 10^{-5} m^2/s	1,147	1,078	1,008

This study provides empirical evidence supporting the efficacy of ultrasonic treatment in altering the viscosity of oil. During the conducted studies, the oil was subjected to heating. The specimen was subjected to ultrasound at a frequency of 42.8 kHz, with an acoustic output of 1000 watts for durations of 30 seconds, 45 seconds, and 1 minute.

During the experimental procedure, a specific volume of oil was introduced into a tank. Subsequently, an ultrasonic emitter waveguide was immersed into the tank, initiating the process of ultrasonic therapy on the oil. Following the completion of the processing procedure, the temperature of the oil was assessed and subsequently transferred into a receptacle of a viscometer for the purpose of viscosity measurement. Subsequently, the experiment was replicated using a fresh volume of oil sample, along with a modified length of ultrasonic treatment. Table 3 displays the outcomes of an experimental investigation pertaining to the alteration of oil viscosity by the use of ultrasound. The experiment was conducted on oil samples with a temperature of 20°C,

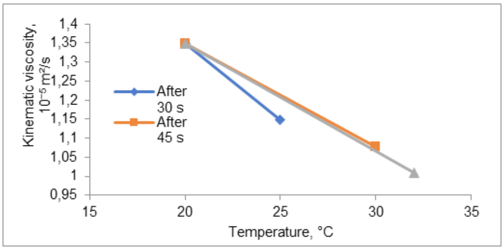

Figure 4. Results of the experiment

and the ultrasonic treatment durations were set at 30 seconds, 45 seconds, and 1 minute.

Graphs illustrating the variations in oil viscosity are generated based on the acquired data. The graphs depicted in Fig. 4 are presented.

The viscosity of oil is reduced by 14.91% after being exposed to ultrasonic waves for 30 seconds. This reduction increases to 20.03% when the exposure time is extended to 45 seconds. Finally, a 25.22% drop in viscosity is observed when the oil is exposed to ultrasound for 1 minute.

Therefore, the use of ultrasonic waves to oil exhibits a notable efficacy in decreasing viscosity. The utilization of this feature is applicable in the transfer of viscous fluids through oil pipelines, contingent upon the economic viability of incorporating ultrasonic equipment.

Conclusion

The findings from multiple research investigating the effects of alternate approaches on the structural and mechanical properties of oil systems exhibit significant inconsistencies. Nevertheless, it may be argued that the aforementioned approaches to manipulating oil result in the disruption of intermolecular connections, hence enhancing its viscosity-temperature characteristics and facilitating their viable application in industrial settings. Based on the analysis of the reviewed literature, it can be inferred that the efficacy of ultrasound as a standalone approach for influencing the bottom-hole zone may be limited in these particular circumstances. However, when employed in conjunction with chemical, thermal, and hydrodynamic techniques, the utilization of ultrasound shows considerable promise [43]. The aforementioned substance can be classified as a very effective supplementary catalyst that facilitates the reduction of viscosity in heavy oils, hence leading to a subsequent enhancement in oil recovery.

This article demonstrates the efficacy of electromagnetic heating as a viable technique for extracting heavy oil reserves. The empirical findings indicate that the implementation of electromagnetic heating techniques yields a substantial enhancement in oil extraction rates, surpassing a 200% rise. The primary issue encountered in all the proposed electromagnetic heating (EMH) methods is the inadequate dielectric and thermal properties exhibited by the reservoir rock. These properties hinder the efficient heating of the collector, hence limiting the extent to which its temperature may be raised within a reasonable timeframe and with a reasonable consumption of power and energy.

In recent times, there has been a resurgence of interest in the application of ultrasound for improved oil recovery. This renewed attention is primarily driven by its significant potential for augmenting production levels, its cost-effectiveness, minimal energy requirements, versatile applicability, capacity to selectively target certain zones, and absence of environmental damage. The technology is predicated on the principle of inductive heating. The electrical power can be modulated within a spectrum spanning from 0% to 100%, hence enabling operation with variable temperature and/or pressure. The objective is to raise the temperature of the entire volume to a level that allows for effective movement, taking into consideration the viscosity of the bitumen, which is anticipated to be less than 150°C. The utilization of an advanced electromagnetic processing technique, specifically employing ultrasonic stimulation on wells characterized by high oil viscosity levels and significant disparities in viscosity between the generated and injected fluids, is advised for the purpose of stimulating the bottom-hole zone [44].

The development of oil production in contemporary Kazakhstan is seen as a crucial aspect in the establishment of a sustainable economy for the Republic. The rise in production rates has resulted in a decline in the quantity of oil fields characterized by high-flow rates. The low values of reservoir oil fluidity in existing fields can be attributed to the observed increase in this parameter. Therefore, it is imperative to address the challenges associated with the exploration of economically viable methods for mitigating viscosity in natural environments. The next factors delineate the primary elements that render electromagnetic heating systems the optimal selection: the reduction of water consumption is among the added advantages of this approach; the applicability of this technique extends beyond heterogeneous and low-permeability layers; depth and lithology do not impose limitations on the implementation of this method; this technique can be employed in scenarios where low-power productive zones necessitate the extraction of thermal energy to non-oil-bearing adjacent layers [45].

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ДОПОЛНИТЕЛЬНО

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Вклад авторов. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующий образом: Каиргельдина Л.К. – сбор и обработка материалов, анализ полученных данных, литературный обзор, визуализация данных, написание текста статьи; Сарсенбекұлы Б. – постановка задачи, концептуализация и дизайн исследования, администрирование проекта, курирование данных, визуализация и структурирование материала.

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