ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

ҚАЙЫРЫМДЫЛЫҚ ҚОРЫ
HALYK
CHARITY FOUNDATION

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ
«ХАЛЫҚ» ЖҚ

Х А Б А Р Л А Р Ы

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ
КАЗАХСТАН»
ЧФ «Халық»

N E W S

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF
KAZAKHSTAN
«Halyk» Private Foundation

SERIES
OF GEOLOGY AND TECHNICAL SCIENCES

2 (464)

MARCH – APRIL 2024

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

ЧФ «ХАЛЫҚ»

В 2016 году для развития и улучшения качества жизни казахстанцев был создан частный Благотворительный фонд «Халык». За годы своей деятельности на реализацию благотворительных проектов в областях образования и науки, социальной защиты, культуры, здравоохранения и спорта, Фонд выделил более 45 миллиардов тенге.

Особое внимание Благотворительный фонд «Халык» уделяет образовательным программам, считая это направление одним из ключевых в своей деятельности. Оказывая поддержку отечественному образованию, Фонд вносит свой посильный вклад в развитие качественного образования в Казахстане. Тем самым способствуя росту числа людей, способных менять жизнь в стране к лучшему – профессионалов в различных сферах, потенциальных лидеров и «великих умов». Одной из значимых инициатив фонда «Халык» в образовательной сфере стал проект Ozgeris powered by Halyk Fund – первый в стране бизнес-инкубатор для учащихся 9-11 классов, который помогает развивать необходимые в современном мире предпринимательские навыки. Так, на содействие малому бизнесу школьников было выделено более 200 грантов. Для поддержки талантливых и мотивированных детей Фонд неоднократно выделял гранты на обучение в Международной школе «Мирас» и в Astana IT University, а также помог казахстанским школьникам принять участие в престижном конкурсе «USTEM Robotics» в США. Авторские работы в рамках проекта «Тәлімгер», которому Фонд оказал поддержку, легли в основу учебной программы, учебников и учебно-методических книг по предмету «Основы предпринимательства и бизнеса», преподаваемого в 10-11 классах казахстанских школ и колледжей.

Помимо помощи школьникам, учащимся колледжей и студентам Фонд считает важным внести свой вклад в повышение квалификации педагогов, совершенствование их знаний и навыков, поскольку именно они являются проводниками знаний будущих поколений казахстанцев. При поддержке Фонда «Халык» в южной столице был организован ежегодный городской конкурс педагогов «Almaty Digital Ustaz.

Важной инициативой стал реализуемый проект по обучению основам финансовой грамотности преподавателей из восьми областей Казахстана, что должно оказать существенное влияние на воспитание финансовой грамотности и предпринимательского мышления у нового поколения граждан страны.

Необходимую помощь Фонд «Халык» оказывает и тем, кто особенно остро в ней нуждается. В рамках социальной защиты населения активно проводится работа по поддержке детей, оставшихся без родителей, детей и взрослых из социально уязвимых слоев населения, людей с ограниченными возможностями, а также обеспечению нуждающихся социальным жильем, строительству социально важных объектов, таких как детские сады, детские площадки и физкультурно-оздоровительные комплексы.

В копилку добрых дел Фонда «Халык» можно добавить оказание помощи детскому спорту, куда относится поддержка в развитии детского футбола и карате в нашей стране. Жизненно важную помощь Благотворительный фонд «Халык» оказал нашим соотечественникам во время недавней пандемии COVID-19. Тогда, в разгар тяжелой борьбы с коронавирусной инфекцией Фонд выделил свыше 11 миллиардов тенге на приобретение необходимого медицинского оборудования и дорогостоящих медицинских препаратов, автомобилей скорой медицинской помощи и средств защиты, адресную материальную помощь социально уязвимым слоям населения и денежные выплаты медицинским работникам.

В 2023 году наряду с другими проектами, нацеленными на повышение благосостояния казахстанских граждан Фонд решил уделить особое внимание науке, поскольку она является частью общественной культуры, а уровень ее развития определяет уровень развития государства.

Поддержка Фондом выпуска журналов Национальной Академии наук Республики Казахстан, которые входят в международные фонды Scopus и Wos и в которых публикуются статьи отечественных ученых, докторантов и магистрантов, а также научных сотрудников высших учебных заведений и научно-исследовательских институтов нашей страны является не менее значимым вкладом Фонда в развитие казахстанского общества.

С уважением,
Благотворительный Фонд «Халык»!

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, мұнай және газды өңдеудің химиялық технологиялары, мұнай химиясы, металдарды алу және олардың қосындыларының технологиясы.*

Мерзімділігі: жылына 6 рет.

Тиражы: 300 дана.

Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, химические технологии переработки нефти и газа, нефтехимия, технологии извлечения металлов и их соеденений.*

Периодичность: 6 раз в год.

Тираж: 300 экземпляров.

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19
http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.

Thematic scope: *geology, chemical technologies for oil and gas processing, petrochemistry, technologies for extracting metals and their connections.*

Periodicity: 6 times a year.

Circulation: 300 copies.

Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19

http://www.geolog-technical.kz/index.php/en/

NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 2. Number 464 (2024), 169–182
https://doi.org/10.32014/2024.2518-170X.401

UDC 55.08

© S.R. Rasulov[1*], H.G. Hasanov[2], A.N. Zeynalov[2], 2024
[1]Azerbaijan State Oil and Industry University, Baku, Azerbaijan;
[2]Saipem Contracting Netherlands BV Azerbaijan Branch, Baku, Azerbaijan.
Email: rasulovsakit@gmail.com

A NEW APPROACH TO EXTRACTING HARD-TO-RECOVER OIL RESERVES

Rasulov S.R. — Doctor of Technical Sciences, Professor, Head of Department, Azerbaijan State Oil and Industry University, Azerbaijan, Baku, AZ1010, Azadlig Ave
E-mail: rasulovsakit@gmail.com, https://orcid.org/0000-0002-1548-3143;
Hasanov H.G. — Doctor of Physical and Mathematical Sciences, Saipem Contracting Netherlands BV Azerbaijan Branch, Manager, Azerbaijan, Baku, AZ1083, Salyan Highway
https://orcid.org/0009-0002-9874-7489;
Zeynalov A.N. — PhD in Technical Sciences, Saipem Contracting Netherlands BV Azerbaijan Branch, Manager, Engineer, Azerbaijan, Baku, AZ1083, Salyan Highway
E-mail: anar.zeynalov13@hotmail.com, https://orcid.org/0000-0002-4872-7255.

Abstract. The paper notes that the use of pulsed, optoacoustic waves in order to excite the residual oil for its cleaning of both the bottom hole and the bottom zone of the oil-bearing formation of contamination by solids, is the most effective. A pulsed, optoacoustic wave is an acoustic wave generated by the interaction of powerful laser radiation with a thin layer of a highly absorbing medium. Practically the advantage of this wave is that it can reach values up to $10^8 \div 10^9$ Pa and the parameters of the laser radiation are controllable. In order to improve the efficiency of the vibro-wave treatment of an oil reservoir, a pulsed optoacoustic wave is suggested, taking into account the Knudsen effect. It is noted that the acoustic impact on the oil reservoir in combination with the heating of the bottom hole formation zone, in order to increase the oil recovery is ineffective. The low efficiency of the latter method of formation stimulation in practice is caused by incorrect formulation of physical and mathematical models, namely, not taking into account the emerging Knudsen effect, which significantly affects the process under study. The theoretical calculations performed have shown that in the case of bottom hole cooling (when the oil temperature at the bottom hole and the wellhead differ little from each other) a pulsed, optoacoustic wave with minimum energy loss reaches the bottom hole. Refinement of physical and mathematical models established that pulse, optoacoustic impact on the oil reservoir, in combination with bottom hole cooling, is more effective in comparison with other methods.

Keywords: optoacoustic wave, bottom hole cooling, Knudsen effect, oil deposit, well productivity improvement

© С.Р. Расулов[1*], Х.Г. Гасанов[2], А.Н. Зейналов[2], 2024
[1] Әзірбайжан мемлекеттік мұнай және өнеркәсіп университеті, Баку, Әзірбайжан;
[2] Saipem Contracting Netherlands BV Azerbaijan Branch, Баку, Әзірбайжан.
Email: rasulovsakit@gmail.com

ҚИЫН АЛЫНАТЫН МҰНАЙ ҚОРЛАРЫН ӨНДІРУГЕ АРНАЛҒАН ЖАҢА ТӘСІЛДЕР

Расулов С. Р. — техника ғылымдарының докторы, профессор, кафедра меңгерушісі. Әзірбайжан мемлекеттік мұнай және өнеркәсіп университеті, Әзірбайжан, Баку, AZ1010, Азадлиг даңғылы
E-mail: rasulovsakit@gmail.com, https://orcid.org/0000-0002-1548-3143;
Хасанов Х. Г. — физика-математика ғылымдарының докторы, Saipem Contracting Netherlands BV Әзірбайжан филиалы, менеджер, Әзірбайжан, Баку, AZ1083, Салян тас жолы
https://orcid.org/0009-0002-9874-7489;
Зейналов А. Н. — техника ғылымдарының кандидаты, Saipem Contracting Netherlands BV Әзірбайжан филиалы, менеджер, инженер, Әзірбайжан, Баку, AZ1083, Салян тасжолы
E-mail: anar.zeynalov13@hotmail.com, https://orcid.org/0000-0002-4872-7255.

Аннотация. Мақалада мұнай бар қабаттың төменгі және төменгі саңылау аймағын қатты бөлшектермен ластанудан тазарту үшін қалдық мұнайды қоздыру үшін импульстік, оптоакустикалық толқынды қолдану ең тиімді екендігі атап өтілген. Импульстік оптоакустикалық толқын - күшті лазерлік сәулелену жоғары сіңіретін ортаның жұқа қабатымен әрекеттескенде пайда болатын акустикалық толқын. Іс жүзінде бұл толқынның артықшылығы оның $10^8 \div 10^9$ Па дейінгі мәндерге жетуі және лазерлік сәулеленудің параметрлері бақылануы болып табылады. Мұнай қабатында діріл толқынының әсерлерін пайдалану тиімділігін арттыру үшін Кнудсен эффектісін ескере отырып импульстік оптоакустикалық толқынды қолдану ұсынылады. Мұнай қабатынан мұнай берілуін арттыру мақсатында қабат түбінің ұңғыма аймағын жылытумен ұштастыра отырып, мұнай қабатына акустикалық әсер тиімді еместігі атап өтілген. Тәжірибеде қалыптасуға әсер етудің соңғы әдісінің тиімділігінің төмендігі физикалық-математикалық модельдің дұрыс тұжырымдалмауымен, атап айтқанда зерттелетін процеске айтарлықтай әсер ететін пайда болған Кнудсен эффектісін есепке алмауымен байланысты. Теориялық есептеулер ұңғыма түбін салқындатқанда (түбіндегі мұнай температурасы мен ұңғыма сағасының бір-бірінен айырмашылығы шамалы болған кезде) импульсті, оптоакустикалық толқын ұңғыма түбіне аз энергия шығынымен жететінін көрсетті. Физика-математикалық модельдерді нақтылай отырып, мұнай қабатына импульстік, оптоакустикалық әсер ету, төменгі саңылау аймағын салқындатумен бірге басқа әдістермен салыстырғанда тиімдірек екендігі анықталды.

Түйін сөздер: оптоакустикалық толқын, ұңғыманы салқындату, мұнайдың Кнудсен эффектісі, ұңғыма өнімділігін арттыру

© С.Р. Расулов[1*], Х.Г. Гасанов[2], А.Н. Зейналов[2], 2024
[1]Азербайджанский государственный университет нефти и промышленности, Баку, Азербайджан;
[2]Saipem Contracting Netherlands BV Azerbaijan Branch, Баку, Азербайджан.
E-mail: rasulovsakit@gmail.com

НОВЫЙ ПОДХОД К ДОБЫЧЕ ТРУДНОИЗВЛЕКАЕМЫХ ЗАПАСОВ НЕФТИ

Расулов С. Р. — доктор технических наук, профессор, заведующий кафедрой, Азербайдханский государственный университет нефти и промышленности, AZ1010, прос. Азадлыг, Баку, Азербайджан
E-mail: rasulovsakit@gmail.com, https://orcid.org/0000-0002-1548-3143;
Гасанов Х. Г. — доктор физико-математических наук, Saipem Contracting Netherlands BV Azerbaijan Branch, менеджер, AZ1083, Салянское шоссе, Баку, Азербайджан
https://orcid.org/0009-0002-9874-7489;
Зейналов А. Н. — кандидат технических наук, Saipem Contracting Netherlands BV Azerbaijan Branch, менеджер, инженер, AZ1083, Салянское шоссе, Баку, Азербайджан
E-mail: anar.zeynalov13@hotmail.com, https://orcid.org/0000-0002-4872-7255.

Аннотация. В статье отмечается, что применение импульсной, оптоакустической волны, с целью возбуждения остаточной нефти для её очищения как забоя, так и призабойной зоны нефтеносного пласта от загрязнений твёрдыми частицами, является наиболее эффективным. Импульсная, оптоакустическая волна — это акустическая волна, возникающая при взаимодействии мощного лазерного излучения с тонким слоем сильнопоглощающей среды. Практически преимущество этой волны состоит в том, что она может достигать значений вплоть до $10^8 \div 10^9$ Па, и параметры лазерного излучения управляемы. С целью повышения эффективности применения виброволновых воздействий на нефтяной пласт предлагается применить импульсную оптоакустическую волну с учётом эффекта Кнудсена. Отмечено, что акустическое воздействие на нефтяной пласт в сочетании с нагреванием призабойной зоны пласта, с целью увеличения нефтеотдачи пласта является малоэффективным. Низкая эффективность последнего способа воздействия на пласт на практике обусловлена некорректной формулировкой физической и математической модели, а именно, не принятием во внимание возникающего эффекта Кнудсена, который существенно влияет на исследуемый процесс. Проведённые теоретические расчёты показали, что при охлаждении забоя скважины (когда температура нефти на забое и устье скважины мало отличаются друг от друга) импульсная, оптоакустическая волна с минимальной потерей энергии доходит до забоя скважины. Уточнением физической и математической моделей установлено, что импульсное, оптоакустическое воздействие на

нефтяной пласт, в сочетании с охлаждением призабойной зоны, является более эффективным по сравнению с другими методами.

Ключевые слова: оптоакустическая волна, охлаждение забоя, эффект Кнудсена нефти, повышение продуктивности скважин

Introduction

A great number of works have been devoted to the study of enhanced oil recovery (EOR), one of the most important problems of the oil industry. Let us note some of them which are of interest for substantiation of the enhanced oil recovery method we propose below. In (Kuanys, 2019), it is noted that during the existence of a well, its bottom hole zone changes its structure, scale and hydrodynamic properties. This fact indicates the thermohydrodynamic connection of the borehole with the oil reservoir and has a significant impact on its productivity (Faverne, 2004; Siman George, 1974: 8; Zeynalov, 2010: 7). The above-mentioned peculiarity of good behaviour allows making a conclusion that by applying different physical or chemical methods to the bottom hole zone of the oil formation it is possible to increase its filtration properties. Currently, several methods of influencing the formation are used to improve its filtration properties, such as chemical, mechanical, thermal and combined methods (Kuanys, 2019, Semenovskaya, 1965). The physical essence of these methods lies in the fact that under the influence of these impacts, the bottom hole formation zone is cleaned from various impurities, resulting in an increase in the filtration properties of rocks. There is a large number of experimental works, an overview of which is given in (Semenovskaya, 1965), testifying to the fact that the impact on the oil-bearing formation of vibration increases the flow of oil to the well. It should be noted that, to date, there is no single mathematical model that allows calculating the effect of vibroacoustic impact on increasing oil production (Kuanysh, 2019).

Materials and basic methods

In the work (Abramov et al., 2012) it is noted that the existing methods for increasing oil recovery and well yield are labour-intensive, energy-consuming and environmentally unsafe. That is why the task of developing and improvement of known technologies based on physical impact on reservoirs, which would allow extracting of the residual oil reserves with higher efficiency, is urgent. Application for these purposes of physical fields can be considered as resource-saving technologies, at that, less energy-consuming and, accordingly, economically more expedient in comparison with other known methods. According to the work (Dyblenko, 2000: 381), the acoustic impact method is one of the most promising wave methods for increasing good output. At the same time, the efficiency of the method itself can be substantially improved by the proper selection of a mathematical model of the process of acoustic impact on oil and the development of a highly effective apparatus.

In the work (Zakenov et al., 2013) an analysis of the current state of research on the application of acoustic influence to increase well productivity is given, which is based on the use of acoustic theory and wave mechanics. The paper notes that the oil industry is characterised by the successive entry of many oil reservoirs into the complex late phase of development when more than half of their reserves have already been depleted and recovery of the remaining reserves requires considerable effort. According to works (Gadiev, 1972: 158; Gorbachev, 2002), the existing methods of vibropneumatic stimulation are not effective enough and, at present, it is necessary to develop new methods of impact on the bottom hole zone in order to intensify oil production.

It is noted by (Gulyaev et al., 2018) that the decrease in oil flow rate during prolonged good operation is associated with the quasi-cementation of pores in the oil reservoir, which leads to a decrease in its permeability. In order to restore the flow rate, downhole ultrasonic emitters can be used, performing acoustic impact on the bottom hole zone, whereby a significant restoration of its permeability can be expected. In the work (Abbasov et al., 2015), the pressure field in a reservoir with a deformable reservoir was determined by vibro-wave treatment. It was found that the degree of elastic wave attenuation in the reservoir, with deformable reservoirs, is significantly greater compared to that of non-deformable reservoirs.

In our opinion, the use of pulsed optoacoustic waves to excite residual oil for its further recovery and cleaning of both the bottom hole and bottom hole zone of oil-bearing formation from contamination by solid particles is the most effective. A pulsed optoacoustic wave is an acoustic wave produced by the interaction of powerful laser radiation with a thin layer of a highly absorbing medium (Gusev et al., 1991:304). The practical advantage of this wave is that the acoustic pressure can reach values as high as $10^8 \div 10^9$ Pa, and the laser radiation parameters are controllable. This high acoustic pressure is due to the high power of the pulsed laser radiation and the short duration of the pulse, which is not available by other methods.

Results

The thermo-optical excitation and propagation of a pulsed optoacoustic wave in a viscous and thermally conductive fluid are described by the mathematical model proposed in (Gusev et al., 1991: 304). For the one-dimensional case in a homogeneous medium with constant thermal and acoustic properties of the fluid, this equation has the form:

$$\frac{\partial^2 \varphi}{\partial t^2} - c_0^2 \frac{\partial^2 \varphi}{\partial t^2} - \frac{1}{\rho}(\xi + \frac{4}{3}\eta)\frac{\partial^3 \varphi}{\partial t \cdot \partial z^2} = -\frac{a c_0^2 \beta}{c_p \rho} J_0 e^{-az} f(t) \tag{1}$$

the following symbols are given here: φ(z,t) - the scalar potential of a velocity field, c_0 – the speed of propagation of the optoacoustic wave in the liquid, α – laser ray absorption coefficient, ŋ – shear viscosity of the liquid, ξ – its volumetric viscosity, p - liquid density, c_0 – initial heat capacity, c_p– heat capacity at constant pressure, β - coefficient of volumetric expansion, J_0 – laser radiation intensity, $J = J_0 f(t)$ – the change over time in the intensity of the laser light.

In the work (Gorbachev, 2002; Rasulov et.al., 2020: 7) considered a case of occurrence and propagation of a pulse acoustic wave in a homogeneous liquid with constant thermophysical properties without considering the influence of viscosity, in other words, the liquid was taken ideal $\eta = 0$, $\xi = 0$. For fluids in an oil well, this approximation is incorrect because oil (like many other fluids involved in the oil industry) is substantially heterogeneous, which must be taken into account in the mathematical model.

The above-presented mathematical model of optoacoustic wave propagation in an inhomogeneous medium, described by equation (1), is generalized to the case of variable thermophysical parameters which takes place at the interaction of powerful radiation with medium

$$\frac{\partial^2\varphi}{\partial t^2} - c_0^2\frac{\partial^2\varphi}{\partial t^2} - \frac{1}{\rho(z)}(\xi(Z) + \frac{4}{3}\eta(Z))\frac{\partial^3\varphi}{\partial t\cdot\partial z^2} = -\frac{ac_0^2\beta(z)}{c_p(z)\rho(z)}J_0e^{-az}f(t) \quad (2)$$

The heterogeneity of oil in a well is mainly due to two reasons: 1) the change in temperature in the well with depth, which leads to a change in the volume expansion coefficient (we will call it thermal heterogeneity) and 2) the oil in the well contains solids (rock particles, salts, sands, etc.) that are not evenly distributed along the wellbore. The solids that remain suspended in the borehole are in the ground gravity field and therefore subject to the Boltzmann distribution. This heterogeneity will be called gravitational heterogeneity.

If the origin of coordinates is placed at the wellhead, then with reference to the conditions of an oil well, the above-mentioned inhomogeneities can be mathematically described by the following formulas

$$\beta(z) = \beta_0\exp(k_1 z), \quad \rho(z)c_p(z) = \rho_0 c_{p0}\exp(k_2 z) \quad (3)$$

where k_1 and k_2 – coefficients defining thermal and gravitational heterogeneity.

It is logical to assume that the other thermophysical parameters of the oil also change with well depth according to the Boltzmann distribution

$$\eta(z) = \eta_0\exp(k_3 z) \quad \xi(z) = \xi_0\exp(k_4 z) \quad (4)$$

Applying the spectral method to the solution of the differential equation (2) with variable coefficients at zero initial and appropriate boundary conditions, we can in principle construct an exact analytical solution to the problem. However, the resulting solution will be mathematically cumbersome and inefficient for practical analysis.

The solution to the problem can be somewhat simplified if we consider the case where the influence of oil viscosity on the propagation of optoacoustic waves can be neglected. In this approximation, the particle velocity of the medium is defined by the formula

$$v(z,t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{\alpha(\alpha+k_1-k_2)\beta_0 J_0\tilde{f}(\omega)}{c_{p0}\rho_0\left[(\alpha+k_1-k_2)^2+\frac{\omega^2}{c_0^2}\right]}\exp\left[-i\omega(t-\frac{z}{c_0})\right]d\omega \qquad (5)$$

Taking into account the fact that in a flat running wave, the vibrational velocity and the acoustic pressure are related by the relation $\rho=\rho_0 c_0 \upsilon$ for the acoustic pressure we obtain

$$P(z,t)=\frac{1}{2\pi}\frac{c_0}{c_{p0}}\int_{-\infty}^{+\infty}\frac{\alpha(\alpha+k_1-k_2)\beta_0 J_0\tilde{f}(\omega)}{\left[(\alpha+k_1-k_2)^2+\frac{\omega^2}{c_0^2}\right]}\exp\left[-i\omega(t-\frac{z}{c_0})\right]d\omega \qquad (6)$$

For the case of short laser pulses, the intensity spectrum of the laser beams can be assumed to be constant over the entire frequency range of sound excitation

$$J_0\tilde{f}(\omega)=J_0\tilde{f}(\omega=0)=J_0\int_{-\infty}^{+\infty}f(t)dt=E_0=const \qquad (7)$$

Taking into account the last formula (7), the acoustic pressure is determined by the formula

$$P(z,t)=\frac{\alpha\beta_0 c_0^2 E_0}{2c_p}\exp\left[-(\alpha+k_1-k_2)c_0(t-\frac{z}{c_0})\right] \qquad (8)$$

In the case of a homogeneous liquid $k_1=0$, $k_2=0$ formula (8) becomes even more simplified and takes the form

$$P(z,t)=\frac{\alpha\beta_0 c_0^2 E_0}{2c_p}\exp\left[-\alpha c_0(t-\frac{z}{c_0})\right] \qquad (9)$$

The relative change in the amplitude of the acoustic pressure during the propagation of a signal in an inhomogeneous liquid can be calculated as follows

$$\frac{P(z,t)}{P_0(z,t)}=\exp\left[-(k_1-k_2)c_0(t-\frac{z}{c_0})\right] \qquad (10)$$

From formula (10) it follows that the relative change in the amplitude of the acoustic pressure depends not only on the duration of the laser pulse $c_0(t-\frac{z}{c_0})$ but also on the difference in inhomogeneities caused by the temperature gradient coefficient k_1 and by the density gradient coefficient k_2 (Gasanov et al., patent Az 2021 0007). There are three possible cases here:

1) the coefficients mentioned are equal $k_1=k_2$ to each other, that is, the measures of thermal and gravitational inhomogeneities are equal, they compensate for each other, and therefore it follows from equation (10) $\frac{P(z,t)}{P_0(z,t)}=1$ that physically this means that the noted inhomogeneities do not affect the change in the amplitude of the optoacoustic pressure.

2) $k_1 > k_2$, that is, the measure of thermal inhomogeneity is greater than the gravitational one. At the same time, with an increase in the duration of the laser pulse, the relative change in the acoustic pressure exponentially decreases (Figure 1).

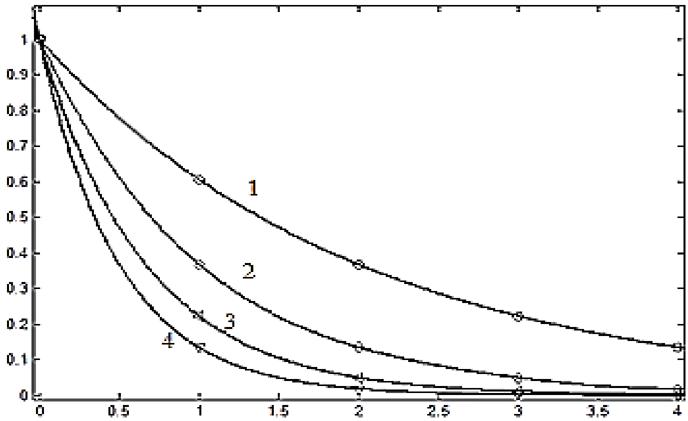

Fig. 1 - The graph shows the dependence of $\frac{P}{P_0}$ on for different values $C_0(t - \frac{z}{c_0})$ of ΔK= 0.5 (curve 1), ΔK=1 (curve 2),ΔK=1.5 (curve 3), and ΔK =2 (curve 4).

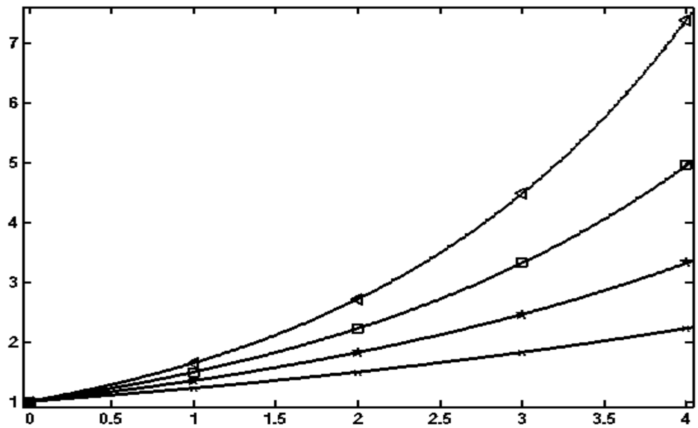

Fig. 2 - The graph shows the dependence of $\frac{P}{P_0}$ on $C_0(t - \frac{z}{c_0})$ for different values of ΔK= -0.2 (curve 1), ΔK = - 0,3 (curve 2), ΔK =- 0,4 (curve 3), and ΔK = - 0,5 (curve 4).

3) $k_1 > k_2$, That is, the measure of thermal inhomogeneity is smaller than the gravitational one. At the same time, the relative change in the amplitude of the acoustic pressure exponentially increases with an increase in the duration of the laser pulse (Figure 2).

The analysis of research dedicated to increasing oil recovery through the influence of various physical fields has shown that thermoacoustic treatment of the near-wellbore zone of the reservoir is quite effective as a method. Thermoacoustic treatment is a combined method, in which thermal treatment is combined with acoustic treatment. There is a large amount of experimental work that indicates that the impact on the oil-bearing formation with frequencies ranging from one to several thousand hertz increases oil inflow to the well and reduces its water cut (Kuanys, 2019; Voropaev et al., 1988:6). However, there is still no unified mathematical model that would allow the correct calculation of the influence of vibroacoustic treatment on the hydrodynamics of oil flow increase. According to (Dyblenko et al., 2000:381), the acoustic impact method is one of the most promising among wave methods used to increase well productivity. At the same time, the effectiveness of the method can be significantly increased by selecting the correct physical and mathematical models of the acoustic impact process and by applying physical effects correctly in the well-reservoir system.

In (Abramov et al., 2012), it is noted that existing methods for increasing oil recovery and well productivity are energy- and labour-intensive, environmentally unsafe, and inefficient. Therefore, research aimed at developing new and/or improving known technologies based on physical effects on the reservoir and allowing for more efficient extraction of remaining oil reserves is relevant. It is physically accepted that the main factor contributing to increased oil recovery during thermoacoustic treatment of the reservoir is a reduction in the viscosity coefficient of residual, immobile oil. For the simplest case of filtration under a stationary pressure field, the productivity is determined by a known formula.

$$Q_1 = \frac{2\pi kh}{\mu(T)} \frac{P_k - P_C}{\ln \frac{R_k}{R_C}} = \frac{2\pi kh}{\mu(T)} \frac{\Delta P}{\ln \frac{R_k}{R_C}} \qquad (11)$$

where the following notations are introduced: *k* - permeability, *h* - thickness of the reservoir, *μ (T)* - viscosity coefficient, P_k, R_k - respectively, pressure and radius of the feeding contour, P_c, R_c - respectively, pressure and radius of the well. It is evident from formula (11) that with a decrease in the viscosity coefficient *μ (T)*, the flow rate Q_1 increases.

However, another thermodynamic effect is not taken into account, which is caused by the temperature difference between the well and the reservoir, namely, the Knudsen effect. Applied to the well-reservoir system, the Knudsen effect manifests itself in the fact that the temperature difference between the well and the reservoir, i.e. T_{well} - T_{layer}, creates a pressure difference P_1, determined by the formula (Pol, 1971: 478).

$$P = \alpha(T_{well} - T_{layer}) \qquad (12)$$

Taking into account equation (12), formula (11) can be written as

$$Q_1 = \frac{2\pi kh}{\mu(T)} \frac{(\Delta P - \Delta P_1)}{\ln \frac{R_k}{R_C}} = \frac{2\pi kh}{\mu(T)} \frac{\Delta P - \alpha(T_{well} - T_{layer})}{\ln \frac{R_k}{R_C}} \tag{13}$$

Taking into account that the use of physical fields to increase oil recovery of the reservoir is less resource- and energy-intensive and more economically feasible compared to other methods, we investigated the generation and propagation of optoacoustic waves in an inhomogeneous medium, which is a well. In an oil well, the inhomogeneity is due to the variation of density and coefficient of volume expansion of oil with depth. Theoretical calculations showed that the absorption of optoacoustic waves strongly depends on these noted inhomogeneities. The relative change in the amplitude of optoacoustic pressure during signal propagation in an inhomogeneous medium is determined by the formula

$$\frac{P(z,t)}{P_0(z,t)} = \exp\left[-(k_1 - k_2)c_0(t - \frac{z}{c_0})\right] \tag{14}$$

In this formula, the coefficients k_1 and k_2 are constants that characterize the heterogeneities caused by the change in temperature and density of oil with depth in the well, i.e., they are measures of the corresponding heterogeneities. A computer study of formula (14) shows that to increase the effectiveness of the pulsed optoacoustic wave, it is necessary for the heterogeneity of the oil in the well caused by temperature change with depth to be minimal, which corresponds to the proximity of the oil temperatures at the wellbore and surface. To achieve this, it is necessary to cool the wellbore, for example, by blowing in cold air. With this condition satisfied, the acoustic pressure reaches the wellbore with minimal energy losses. In this case, the pulsed optoacoustic wave, by cleaning the wellbore and near-wellbore zone of the reservoir, excites the stationary residual oil, imparting a certain amount of energy to it. On the other hand, cooling the wellbore creates a temperature difference between the reservoir and the well. This temperature difference, due to the Knudsen effect, creates a difference in pressures.

$$\Delta P_2 = \alpha(T_{layer} - T_{well}), \; T_{layer} > T_{well}, \tag{15}$$

In this case, there is a pressure differential acting on the residual oil

$$\Delta P = (P_{layer} - P_{well}) + \alpha(T_{layer} - T_{well}), \; T_{layer} > T_{well}, \tag{16}$$

It should be noted that when the wellbore is heated, the residual oil begins to move under the action of the pressure difference

$$\Delta P = (P_{layer} - P_{well}) - \alpha (T_{well} - T_{layer}) \quad , \quad T_{layer} < T_{well} \tag{17}$$

Taking into account the above, for the simplest case, the well productivity is determined by the formulas

$$Q_1 = \frac{2\pi kh}{\mu(T)} \frac{\Delta P - \alpha \Delta T_1}{\ln \frac{R_k}{R_C}} \tag{18}$$

when the wellbore is heated

$$Q_2 = \frac{2\pi kh}{\mu_0} \frac{\Delta P + \alpha \Delta T_2}{\ln \frac{R_k}{R_C}} \tag{19}$$

when it is cooled down

Comparing formulas (18) and (19), we have

$$\frac{Q_1 \mu(T)}{Q_2 \cdot \mu_0} = \frac{\Delta P - \alpha \Delta T_1}{\Delta P + \alpha T_2} \tag{20}$$

Clearly, for any values of ΔT_1 and ΔT_2, the inequality holds.

$$\Delta P - \alpha \Delta T_1 \prec \Delta P - \alpha \Delta T_2 \tag{21}$$

$$Q_1 \prec Q_2 \frac{\mu_0}{\mu(\Delta T_1)} \quad \text{or} \quad Q_1 \mu(\Delta T1) \prec \mu_0 Q_2 \tag{22}$$

Experiments to determine the viscosity coefficient of oils conducted on samples from different oil fields have shown that the temperature dependence of oil viscosity can be expressed by the following formula.

$$\mu(T) = \mu_0 \exp(-\frac{\Delta T_1}{100}) \tag{23}$$

Taking into account the last relationship, condition (12) can be rewritten in the form of

$$Q_1 \prec Q_2 \exp(\frac{\Delta T_1}{100}) \tag{24}$$

Discussion

Comparing Figures 1 and 2, it follows that in order to increase the efficiency of pulsed optoacoustic wave application, it is necessary to implement the condition $k_1 > k_2$ i.e., the inhomogeneity of oil in the well, caused by a temperature change with depth, should be minimal, which corresponds to the proximity (ideally, equality) of the oil temperature at the well bottom and surface. To achieve this, it is necessary to cool the bottom of the well, for example, by blowing cold air. When this condition is met, the acoustic pressure reaches the bottom of the well with minimal losses. In this case, the pulsed optoacoustic wave, by cleaning the bottom of the well and the near-wellbore zone of the oil reservoir, excites the immobile (residual) oil, imparting a certain amount of energy to it, as residual oil absorbs the energy of the acoustic wave. On the other hand, when the bottom of the well is cooled, a temperature difference is created between the reservoir and the well. This temperature difference, according to the Knudsen effect (Gulyaev et al., 2018), creates a pressure difference.

$$\Delta P = \alpha (T_{layer} - T_{well}) \tag{25}$$

here α- is coefficient of Knudsen. As a result of these two effects, the residual oil, under the action of the pressure difference, starts to move, which ultimately leads to an increase in the well productivity.

$$\Delta P_0 = (P_{layer} - P_{well}) + \alpha (T_{layer} - T_{well}) \tag{26}$$

If the bottom of the well is heated, as is done with current technologies, then the effect of extracting residual oil is actually reduced due to the resistance associated with the aforementioned Knudsen effect. In the latter case, $T_{well} > T_{layer}$ and accordingly

$$\Delta P_0 = (P_{layer} - P_{well}) - \alpha (T_{layer} - T_{well}) \tag{27}$$

here T_{well} - well temperature, T_{layer} - layer temperature, P_{layer} - layer pressure, P_{well} - well pressure

This method of oil extraction is apparently going to be more efficient, especially for hard-to-recover fractured reservoirs.

From (14) it can be concluded that cooling the near-wellbore zone of the reservoir in combination with the impact of pulsed optoacoustic waves is more effective for enhancing oil recovery than the currently used simple heating of the near-wellbore zone. Indeed, for any value of $\Delta T_1 > 0$, i.e., (T_{well} - T_{layer}) > 0, from condition (14) we have $Q_1 < Q_2$. It is absolutely clear that the condition $Q_1 = Q_2$ can only be met in the case of $T_{well} = T_{layer}$.

Based on the analysis of the results of existing methods of reservoir stimulation to increase its oil recovery, the following conclusions can be drawn:

Conclusion

1. Even combined vibro-wave impacts with the involvement of heating in the bottom hole zone are insufficiently effective. At the same time, the influence of

one of the important effects of thermophysics - the Knudsen effect, is not taken into account, the essence of which is that the temperature difference between the reservoir and the well creates an additional pressure difference. When heating the wellbore, a back pressure is created, which reduces the filtration properties of the reservoir.

2. In order to increase the efficiency of using vibro-wave impacts on an oil reservoir, we propose to use an impulse optoacoustic wave, taking into account the Knudsen effect.

3. In accordance with the methodology we propose, it is necessary to first minimize thermal heterogeneity by cooling the wellbore (for example, by blowing cold air) with the aim that the temperature at the wellbore $T_{w.bore}$ does not differ significantly from the temperature at the surface so that the condition is satisfied $\Delta T = T_{w.bore} - T_{w.head} \rightarrow \min$. In this case, a favourable condition is created for maximum impact on the oil recovery of the reservoir from the Knudsen effect.

After that, the impulse optoacoustic wave with a speed of c_0 = 1250÷1300 m/s and a pressure amplitude of $10^8 \div 10^9$ Pa, propagating in the well, reaches the bottom hole in about 3÷4 seconds. Penetrating into the oil reservoir and imparting some energy to the immobile (residual) oil, this wave excites it. The excited, previously immobile oil begins to move under the influence of the total pressure difference, determined by the formula (12).

Our theoretical calculations have shown that with wellbore cooling (when the temperature of the oil at the wellbore and the wellhead differ little from each other), the pulsed optoacoustic wave reaches the wellbore with minimal energy loss.

Refinement of the physical and mathematical models has shown that the pulsed optoacoustic impact on the oil reservoir, in combination with wellbore cooling, is more effective compared to other methods.

REFERENCES

Abbasov E.M., Agayeva N.A. (2015). The effect of vibrational impact on the pressure distribution pattern in a non-uniform permeable formation. — *Journal of Engineering Physics and Thermophysics*. — Vol 88. — No. 5.

Abramov V.O., Mullakaev M.S., Bayazitov V.M., Timashev E.O., Kuleshov S.P., Prokoptsev V.O. (2012). Experience of ultrasonic impact application for productivity restoration of oil wells in Western Siberia and Samara region. Oil Industry. — No 12.

Dyblenko V.P., Kamalov A.N., Sharifullin R.Ya., Tufanov I.A. (2000). Increasing productivity and reanimation of wells using vibrational impact. — Moscow, "Nedra". — P. 381.

Faverne J.P. (2004). The Ekonomist of EOR, Conference of chanced Oil recovery (EOR). — London, — 6 December.

Gasanov H., Zeynalov A. (2021). Method for increasing reservoir productivity. — Patent Az 2021 0007.

Gadiev S.M. (1972). The use of vibration in oil production. — Moscow, "Nedra". — P. 158.

Gorbachev Y.I., Ivanova N.I., Nikitin A.A., Kolesnikov T.V. (2002). Acoustic methods for enhancing reservoir productivity and oil recovery intensification. Oil Industry. — No. 5.

Gulyaev D.N., Lazutkina N.E., Zhuykov Yu.F., Ilyinsky N.V., Rukhman A.A., Shikhanov A.E., Shikanov E.A. (2018). Investigation of the ultrasonic impact on an oil reservoir. Oil Industry. — No. 8.

Gusev V.E., Karabutov A.A. (1991). Laser optoacoustic. — Moscow, "Nauka". — P. 304.

Kuanys S. (2019). Methods of impact on the bottom hole zone of the reservoir for increasing production. Oil and Gas Technologies and Analytics. — No. 8.

Voropaev V.N., Gabalov O.S., Kanygin R.B. (1988). The influence of elastic oscillations of sound frequencies on the filtration process. Nature of geophysical fields of the Northeast of the USSR, Magadan. — Pp. 95–100.

Pol R.W. (1971). Mechanics, acoustics, and the theory of heat. — Moscow, "Nauka". — P. 478.

Siman George O. (1974). Sand control. Part 1. When to apply control measure and why proper and completion methods are critically important. World oil. — Vol. 179. — Pp. 63–70.

Semenovskaya P.T. (1965). The influence of vibration on heat and mass transfer in a capillary-porous material. Engineering Physics Journal. — Vol. 9. — No. 2.

Zeynalov A.N. (2010). Hydrodynamic study of sand production during oil well operation. Construction of oil and gas wells on land and at sea. — Moscow: OAO "VNIIOENG". — No. 9. — Pp. 15–21.

Zakenov S.T., Nurshakhanova L.K., Gusmanova A.G. (2013). Analysis of studies on the acoustic impact on the near-wellbore zone of the well. Azerbaijan Oil Industry. — No. 11.

Rasulov S.R., Hasanov G.T., Zeynalov A.N. (2020). Acoustic testing of rheological properties of oil along the deep well hole, — *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences*. — Vol 2. — No. 440. — Pp.141–147.

CONTENT

Publication Ethics and Publication Malpractice in the journals of the National Academy of Sciences of the Republic of Kazakhstan

For information on Ethics in publishing and Ethical guidelines for journal publication see http://www.elsevier.com/publishingethics and http://www.elsevier.com/journal-authors/ethics.

Submission of an article to the National Academy of Sciences of the Republic of Kazakhstan implies that the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis or as an electronic preprint, see http://www.elsevier.com/postingpolicy), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder. In particular, translations into English of papers already published in another language are not accepted.

No other forms of scientific misconduct are allowed, such as plagiarism, falsification, fraudulent data, incorrect interpretation of other works, incorrect citations, etc. The National Academy of Sciences of the Republic of Kazakhstan follows the Code of Conduct of the Committee on Publication Ethics (COPE), and follows the COPE Flowcharts for Resolving Cases of Suspected Misconduct (http://publicationethics.org/files/u2/New_Code.pdf). To verify originality, your article may be checked by the originality detection service Cross Check http://www.elsevier.com/editors/plagdetect.

The authors are obliged to participate in peer review process and be ready to provide corrections, clarifications, retractions and apologies when needed. All authors of a paper should have significantly contributed to the research.

The reviewers should provide objective judgments and should point out relevant published works which are not yet cited. Reviewed articles should be treated confidentially. The reviewers will be chosen in such a way that there is no conflict of interests with respect to the research, the authors and/or the research funders.

The editors have complete responsibility and authority to reject or accept a paper, and they will onh accept a paper when reasonably certain. They will preserve anonymity of reviewers and promote publication of corrections, clarifications, retractions and apologies when needed. The acceptance of a paper automatically implies the copyright transfer to the National Academy of sciences of the Republic of Kazakhstan.

The Editorial Board of the National Academy of sciences of the Republic of Kazakhstan will monitor and safeguard publishing ethics.

Правила оформления статьи для публикации в журнале смотреть на сайте:

www:nauka-nanrk.kz

ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)

http://reports-science.kz/index.php/en/archive

Подписано в печать 15.04.2024.

Формат 60x88 1/8. Бумага офсетная. Печать - ризограф.

15,0 п.л. Тираж 300. Заказ 2.

РОО «Национальная академия наук РК» 050010, Алматы, ул. Шевченко, 28, т. 272-13-19