ENHANCED OIL RECOVERY
RESONANCE MACRO AND MICRO-MECHANICS OF PETROLEUM RESERVOIRS
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Scrivener Publishing
WILEY
Enhanced Oil Recovery
Abstract

This monograph discusses the scientific fundamentals of resonance macro- and micro-mechanics of petroleum reservoirs and its petroleum industry applications. It contains an overview of the research and engineering results of resonance macro- and micro-mechanics of petroleum reservoirs, which provides the scientific and applied foundations for the creation of groundbreaking wave technologies for production stimulation and enhanced oil recovery.

The monograph is intended for a wide audience: students, teachers, scientists and practitioners who are interested in the fundamentals, the development and application of leading-edge technologies in the petroleum industry and other industrial sectors.
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Preface

This monograph discusses one of the most important present-day research and engineering problems that affect the growth of the country’s economy: cost-effective oil production stimulation and enhanced oil recovery.

The authors and other scientists at the Scientific Center for Nonlinear Wave Mechanics and Technologies of the Russian Academy of Sciences (NC NVMT RAN) have developed the scientific and applied foundations for what is known as resonance macro- and micro-mechanics of petroleum reservoirs, a novel and challenging path to efficient oil recovery enhancement, which in some cases may incorporate and amplify the effects of other well-known conventional enhanced oil recovery methods (chemical, thermal, hydraulic fracturing, horizontal wells, etc.).

The truth of this statement is backed by the results of both theoretical research at the leading edge of the theory of nonlinear oscillations and experimental studies conducted in laboratories and in the field. This is described in detail in the introduction and in the following chapters of the monograph.

Resonance macro- and micro-mechanics of petroleum reservoirs is a new area of fundamental and applied research in nonlinear wave mechanics, ahead of the international state-of-the-art and led by Russia. The proposed field of resonance mechanics of petroleum reservoirs is based on the recently discovered multi-dimensional largescale resonance phenomena in heterogeneous oil reservoirs that have significant effect on the motion of various micro-inclusions, such as solid particles and droplets of fluids (water, oil, etc.) in the micro-pores of an oil formation (both near and far from the wellbore). In turn, the motion of micro-inclusions can drastically change the macro-mechanics of the porous medium. Therefore, there are dynamically linked resonance macro- and micro-processes in petroleum reservoirs (porous media), which can be controlled for the purposes of both oil production stimulation and enhanced oil recovery.
What is totally new and important about it is the theoretical and practical discovery of the phenomenon of significant amplification of multi-dimensional waves in porous media as the waves propagate and are transmitted over long distances (which is the second aspect of the discovery), which permits stimulation of large areas of reservoirs with various heterogeneities, contaminated by solid particles both near and far from the wellbores or containing capillary-trapped oil, for enhanced oil recovery purposes. These factors are the most common causes of declining production and recovery of oil in many cases, and it is difficult to select an economical stimulation method for their removal. The undertaken research and field trials have shown that the reservoir damage control methods proposed in this monograph (based on the science of nonlinear resonance mechanics of porous media) may be more efficient and economical than others.

To be able to create such multi-dimensional resonance conditions in the field, various controlled appliances and devices, broadband oscillation and wave generators with instrumentation and mathematical control systems have been developed. The corresponding software packages for typical field applications are constantly improved and updated depending on the geological settings of specific oil fields. This scientific base is used to design and build petroleum industry-oriented controlled appliances and devices that form a field of the so-called wave machine engineering sector. Wave machine engineering has also been founded by the NC NVMT RAN team and is rapidly evolving to the benefit of various industries [1, 2, 3, 4].

This book mostly discusses the fundamentals of resonance macro- and micro-mechanics of petroleum reservoirs, substantiation of its scientific and applied aspects, and prospects of its use in petroleum industry applications. However, it should be noted that the initial research and development base for the statement and solution of the problem of resonance macro- and micro-mechanics of petroleum reservoirs was formed by earlier results of the so-termed wave technology.

The wave technology, created by the NC NVMT RAN team for a wide range of applications in various industries including oil and gas, was quickly acclaimed by experts. As far back as in 1990 it was approved by a panel of experts of the USSR Ministry of Petroleum Industry for use at Soviet oil fields for production stimulation purposes.

At the initial stage of wave technology development by the academic research team as a new field of mechanics (the theory of nonlinear oscillations and waves and their technological applications), it was actively and specifically supported by the leaders of the USSR and by eminent
progressive statesmen. It was their idea to set up a research council (in 1984–1985) within the USSR Ministry of Petroleum Industry on the subject matter of using wave and vibrational processes in the petroleum industry (the council was chaired by R. F. Ganiev, then a professor and now a Member of the Russian Academy of Sciences) whose aim was to coordinate the research efforts of teams in various sectors of the industry. A trial site was established at Nizhnevartovsknefnegas Oil Production Association and about 100 wells were provided for tests by various subsidiaries of the association. The tests involved various aspects of the wave technology, including gas-lift applications (for a lower gas consumption), drilling applications (for cleaner reservoir penetration through the use of bridging capabilities), etc. It was first-generation wave technology, developed and extensively tested by the industry in 1985–1990. More than 3,000 wells located in different regions of the USSR, mainly in Western Siberia, were stimulated with very good results.

As mentioned above, the wave technology was acclaimed by oil industry experts (including refining and petrochemical) and was also actively copied by various empirical inventors (not always petroleum engineers), especially after 1991. Unfortunately, when some of these people started using the science-driven wave technology without understanding its scientific fundamentals and principles, it resulted in incorrect use, negative results in some cases, and even partial damage to reputation of the technology (as explained in more detail in the Introduction and the first chapter of the book).

R. Kh. Muslimov, a prominent scientist and a practicing expert in geology, a professor and a member of the Academy of Sciences of Tatarstan, reasonably and impartially wrote in his monograph that experts in oscillation mechanics, reservoir engineers and geologists should all joint their efforts to implement this high-end and promising technology [5].

Meanwhile, the NC NVMT RAN team continued to invest effort in the wave technology on a broad scale. A number of wave resonance effects in near-wellbore formation zones were found, wave capillary effects of multiple acceleration (by 100s to 1,000s times or more) of fluids (water and oil) in micro-pores were identified, along with other wave phenomena in porous media.

First-generation wave technology was then quite fully developed and verified by practice, progressing further on a new scientific basis. Cooperation (contracts) with Western oil companies, such as British Petroleum, Shell, Smith International (a drilling company) also played an important role in the development and perfection of the wave technology. Field trials of the enhanced oil recovery technique were conducted in
Alaska, the North Sea, the Sultanate of Oman (drilling improvement), and laboratory tests were carried out at the highly valuable and unique Shell test facilities in the company’s research center in Holland. Theoretical determinations of nonlinear dynamic characteristics of oscillation and wave generators were verified at these facilities in conditions as close as possible to real wells. Efficient removal of various types of contaminants from near-wellbore formation zones and multiple acceleration of flow processes in porous media were confirmed. It should be noted that these results were obtained on full-size models of near-wellbore formation, rather than on quite small core samples (as it is usually done).

The main results (scientific and practical) were published in various periodicals, backed by dozens of patents (including overseas patents) and inventors’ certificates of NC NVMT RAN scientists, and summarized in the authors’ monographs [6, 7, 8, 9, 10, 11].

That is why the Introduction and the first chapter contain only a brief overview of the principal scientific fundamentals and some results (scientific and practical) of wave technology application, as needed to substantiate the formulation of the main problem discussed here, resonance macro- and micro-mechanics of petroleum reservoirs, as a research and practical basis for oil production stimulation and enhanced oil recovery.

Several problems of resonance macro- and micro-mechanics of petroleum reservoirs and the wave technology have been solved in collaboration with our colleague I. G. Ustenko, an NC NVMT RAN staff member and senior research scientist (references to these studies are provided in the corresponding chapters of the book). NC NVMT RAN researchers Yu. S. Kuznetsov, D.Sc. (Eng.), N. A. Shamov D.Sc. (Eng.), S. A. Kostrov, Ph.D. (Eng.), G. A. Kalashnikov, Ph.D. (Eng.), Yu. B. Malykh, Ph.D. (Eng.), and others, as well as many reservoir engineers and production geologists from Western Siberia took active participation in field trials of drilling improvement and production stimulations techniques at the initial stage of wave technology use. A. I. Petrov, D.Sc. (Geo.), a prominent expert in geology and mineralogy, was our consultant in this area throughout our work. In preparing this monograph, the authors drew upon petroleum industry knowledge provided in the generalizing monographs of renown petroleum geologists R. Kh. Muslimov, D.Sc. (Geo.) [5] and R. S. Khisamov, D.Sc. (Geo.) [12]. The authors are very grateful to all those who are mentioned above.

The authors would like to thank R. I. Nigmatullin, a Member of the Academy of Sciences, for his review of this book and helpful advice.

The authors
Introduction:
A Brief Historical Background and Description of the Problem

The state of the Russian economy depends, to a large extent, on the efficient and stable functioning of the petroleum industry, one of few sectors able to meet the demands of both the internal market and exports. In the present and coming decades, the task of increasing hydrocarbon recovery efficiency, ultimate oil (for oil fields) and component (for gas condensate and gas condensate/oil fields) recovery factors is and will be one of the key challenges in achieving the country’s energy security. For this reason, an efficient use of various improved recovery techniques along with a science-based search for novel enhanced oil recovery methods is critical for the oil industry to grow in the current conditions.

Reservoir flow characteristics (porosity and permeability), pore space contamination, reservoir fluid composition, its viscosity and capillary properties at the fluid-rock interface are among the key factors controlling oil recovery processes.

The most common cause for declining flow rates of oil and gas production wells is contamination of the pore space in near-wellbore formation zones. Pore space contamination may occur from various causes such as invasion of drilling mud clay particles into the formation while drilling; mobilization of rock fines with the extracted reservoir fluids while producing; deposition of resins, asphaltenes and paraffines in the pore space; chemical processes in the rock, etc.

Traditionally, a number of techniques have been used to remediate near-wellbore formation damage: injection of special solutions, thermochemical and electro-chemical stimulation. In heavily contaminated lowpermeability rocks, performance of these methods depends on the chemistry of contaminants and on the correct selection of treatment fluids.
In 1984–85, a near-wellbore cleanup method using oscillations and waves was proposed by the A. A. Blagonravov Institute of Machines Science of the Academy of Sciences of the USSR (reorganized later into the Scientific Center for Nonlinear Wave Mechanics and Technologies of the Russian Academy of Sciences (NC NVMT RAN)). The method consists in placing a purpose-designed oscillation generator that excites pressure waves in the near-wellbore formation region into a well close to perforations. Passing through contaminated pores in near-wellbore formation, the waves act upon the contaminating particles stuck to pore walls and, provided they are of a sufficiently high power, can detach the particles from pore walls thereby ensuring cleanup. The success of wave stimulations obviously depends on the magnitude by which the force acting on a particle stuck to a pore wall is greater than the force of adhesion of the particle to the pore wall. These stimulations are called first-generation wave technologies. They have become quite common. Such stimulation jobs have been performed in Western Siberia, Tataria, Bashkiria and other regions of Russia, as well as in Oman, USA (in Alaska), Norway (on a North Sea platform), and in China. More than 3,000 wells have been treated. As a result of the stimulations, flow rates of production wells increased by 70–80% (in some cases, 2 to 5-fold); injectivity of injection wells increased by 80–90% (documents issued by the Ministry of Petroleum Industry are available to confirm the performance of the wave technology). In the 1990s, first-generation wave stimulations were accepted by the Ministry of Petroleum Industry of the USSR as a technology recommended for application throughout the Soviet Union.

A detailed review of the results obtained during the application of first-generation wave technology is provided in Chapter 1 below.

Thanks to its widespread use in the country, the first-generation wave technology was soon acclaimed enthusiastically by many inventors specializing in well workovers. They tried to modify the original technology that was built around the use of vortex and cavitation generators of various designs, running within certain operating envelopes dictated by the properties of the near-wellbore zone to be treated; the operating envelopes were defined through complex research aimed at determining the rates of fluid flow through the generator, input pressures, and geometric arrangements. A distinctive feature of these generators is a wide range of frequencies and the high amplitude of the excited pressure oscillations. For example, tests conducted at Shell test facilities in the Netherlands showed that pressure amplitudes of some spectral components in the 2–5 kHz band were greater than 15 atmospheres.

Attempts were made, most of which failed, to replace the proposed generator with other types such as rotary-pulse or ultrasonic generators, because radiation from rotary-pulse sources is mono-harmonic, while
the amplitude of ultrasonic generators is not high enough and, moreover, ultrasonic waves attenuate very quickly in near-wellbore formation. Even vortex cavitation generators, if running outside of pre-determined operating envelopes or not in a precise geometric arrangement, did not always bring positive results due to insufficient pressure wave amplitudes within a reservoir’s formation damage zone.

To summarize: the first-generation wave technology invented at NC NVMT RAN proved to be efficient in multiple field tests, however, a number of superficially similar near-wellbore formation wave stimulation techniques appeared under the name of “wave technology”. In most cases, these techniques fail to bring positive results because they either use inadequate generators or their generators run outside of the operating envelopes that ensure success. Either way, they fail to take into account the scientific basis of the technology.

Meanwhile, the originators of the first-generation wave technology continued to improve it. To date, they have made significant progress, capitalizing on recent advances in the science of resonance effects.

The next step in the development of this technology was the idea of using near-wellbore resonance phenomena to amplify wave amplitudes, thereby augmenting wave cleanup processes in the near-wellbore formation zone. In its simplest form, the idea was implemented for resonances at perforations [13]. As far as we know, the simple idea of using resonant and waveguide properties of near-wellbore formation zones has not been previously contemplated by anyone. Although, as mentioned in [14], the cleaning efficiency and cleaning rate are improved significantly with increased wavefield amplitude. And it is exactly resonance that allows achieving the highest amplitude with minimum energy, while waveguiding properties point to the wave excitation frequencies at which their amplitudes decay with distance slower than at others. Apparently, the fact that no one has tried to look at the problem at this angle can be explained by the prevailing opinion that the structure of a reservoir as a whole or even only of the near-wellbore zone is so complex that it is practically impossible to determine, with a sufficient accuracy, its resonant frequencies and to build a wave excitation source (generator) that can generate exactly one of these frequencies. However, as studies conducted at NC NVMT RAN have shown, the use of vortex cavitation generators with a wide multi-harmonic (practically continuous) radiation spectrum permits coverage of entire frequency bands, including near-wellbore formation resonant frequencies. As far as approximate determination of resonant frequency values is concerned, it was shown in [13] that they can be found quite accurately if every perforation hole that
is filled with a fluid interacting with a porous medium at the interfaces is considered to be a resonator.

It was later discovered that resonant frequencies, as well as the so-called critical waveguiding frequencies that ensure the lowest attenuation, can be approximated not only for the near-wellbore formation zone (covering the entire thickness of the formation) but for entire formations having a certain structure. As shown below, the new generation wave technology is based upon this discovery.

The next step in the evolution of first-generation wave technology became possible thanks to the development of drilling techniques. To be more specific, the enabling method behind this step was the creation in near-wellbore formation of networks of extended perforation tunnels providing reliable connectivity between the reservoir and the wells. In particular, it is proposed to use a perforation drilling system to create small-diameter perforation tunnels/waveguides, extending deep into the formation from the wellbore, followed by wave stimulation with a cavitation wave generator whose frequency band is within the pass-band of the created network of perforations/waveguides. Testbed trials have confirmed the feasibility of drilling deep perforation tunnels [15]. It should be noted that, unlike the near-wellbore resonant wave stimulation where the geometry of the perforations and hence the resonant frequencies of wave stimulation are fixed, this method opens up totally new possibilities. For example, it becomes possible to create a system of perforations with desired resonant frequencies, selecting the frequencies from a range close to the most powerful emissions in the spectrum of the available generator.

On the other hand, first-generation wave technology was tested in combination with chemical cleaning methods, i.e. injection of various chemical agents that react with near-wellbore contaminants and transform them into easily removable solutions. Combined application of wave technology and chemical methods has produced some techniques that perform much better than each initial method alone [9].

A combination of near-wellbore wave stimulation with jet pump operation laid the groundwork for yet another method of near-wellbore formation remediation called “Overbalanced/underbalanced wave cleaning of near-wellbore formation”. The method permits significant improvement of the cleaning of near-wellbore formation zones around the main borehole and side tracks, as well as special completion screens. Unique equipment for these operations has been designed and successfully tested in the field [16]. It has been prepared for extensive commercial use.
Along with the aforementioned studies that have significantly advanced near-wellbore formation wave stimulations, NC NVMT RAN scientists have made a major, groundbreaking step forward and have actually come up with new generation wave technologies that are an alternative to the best enhanced oil recovery methods (including hydraulic fracturing and other leading-edge techniques). This step in wave technology advancement became possible thanks to the discovery of multi-frequency resonances and critical waveguiding frequencies associated with a formation’s natural waveguiding properties that are controlled by its structural heterogeneities: horizontal and vertical stratification or compartmentalization. Moreover, multi-dimensional spatial resonance forms are capable of multi-fold amplification and critical waveguiding forms propagate in formations to considerable distances. The discovery of multi-frequency spatial resonance waveforms and critical waveguiding forms of motion in formations has allowed us to broaden significantly the wave technology’s potential for improving production rates and enhancing oil recovery. NC NVMT RAN possesses unique software for computing resonances and critical waveguiding frequencies for formations with known structural heterogeneities. Optimal designs of wave stimulation devices and oscillation generators have been developed.

One of such approaches was tested on fields operated by Tomskneft in Russia, as well as on fields in Texas and California and proved to be many times less expensive than hydraulic fracturing, with an on-par performance but without the risk of reservoir flooding.

In order to use natural resonant and waveguiding properties of formations, controlled by their structural heterogeneities including horizontal and vertical stratification or compartmentalization caused by vertical naturally-fractured zones and faults, it is proposed to conduct wave stimulations in a frequency band corresponding to the resonant frequencies of formations with structural heterogeneities. Thanks to the use of waveguiding properties of formations and the discovery of the resonant wave amplification phenomenon in spatial structures, it has become possible to stimulate much larger areas, to transmit resonant wave energy accurately to a predetermined zone containing capillary-trapped oil, and to mobilize capillary-trapped oil into the fluid flow stream towards production wells. In field conditions, this translates to a higher oil recovery and a lower water cut of fluid produced from a particular reservoir.

The unique equipment (and corresponding software) that has been developed to create resonant multi-frequency waves in rock formations, accompanied by significant changes in velocities and pressures of the