

THE ULTRASONIC WAVES EFFECTS ON OIL-WATER
EMULSIFICATION, COALESCENCE, DETACHMENT, MOBILIZATION
AND VISCOSITY IN POROUS MEDIA

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This thesis is dedicated to my beloved wife who has been a great source of motivation and inspiration. Also, this thesis is dedicated to my parents who have supported me all the way since the beginning of my studies.

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ABSTRACT

Ultrasonic wave technique is an unconventional EOR method, which has been of interest to researchers for more than six decades. Emulsification and demulsification are phenomena which occur at the interface of oil and water under the influence of ultrasonic waves. Therefore, the conditions in which emulsification becomes dominant over demulsification due to ultrasonic radiation in porous media should be further investigated. However, surfactants are the principal agents that enable oil and water to mix and are often the most expensive component in an emulsion. Therefore, selecting an appropriate surfactant formulation capable of mobilization of oil without significant surfactant loss due to adsorption and phase separation in the reservoir is very important. Estimation of solubilization parameters are great tools in designing economical emulsion flooding compositions. In this study, the effect of ultrasonic waves on the amount of oil and water solubilized by a unit of surfactant were investigated. It was observed that the emulsion volume and amount of oil solubilized in emulsion were increased by increasing salinity under short periods of ultrasonic wave radiation, and demulsification of the emulsion occurred after longer period of radiation. In addition, Hele-Shaw model tests were conducted to show microscopically the effect of long and short periods of ultrasonic waves' radiation at the interface of paraffin oil and surfactant solution/brine. Diffusion of phases, formation of emulsion and gas bubbles were observed after short periods of ultrasonic waves' radiation. However, demulsification and coalescence of surfactant solution/brine droplets inside emulsion was initiated after long periods of ultrasound radiation. Another objective of this study was to investigate directly the effect of ultrasonic waves on viscosity changes in three types of oil (paraffin oil, synthetic oil, and kerosene) and a brine sample. It was observed that the viscosity of all the liquids was decreased under the influence of ultrasonic waves in both uncontrolled and controlled temperature conditions. However, the reduction was found to be more significant for uncontrolled temperature condition cases. In addition, micro-model experiments were conducted to show other oil recovery mechanisms such as oil droplet coalescence, oil mobilization, and oil detachment from dead end pores under the influence of ultrasonic waves. The results revealed that these mechanisms happen in porous media under the influence of ultrasonic waves. Therefore, it was concluded that the use of ultrasonic waves could be suggested, not as a substitute for conventional EOR methods, but as an alternative or complimentary tool, which in certain instances may make conventional methods more effective and less costly.

ABSTRAK

Teknik gelombang ultrasonik adalah kaedah EOR bukan konvensional yang telah menarik minat ramai penyelidik sejak lebih dari enam dekad. Emulsifikasi dan demulsifikasi adalah fenomena yang terbentuk pada antaramuka diantara minyak dan air di bawah pengaruh gelombang ultrasonik. Dengan itu, keadaan di mana emulsifikasi menjadi dominan berbanding demulsifikasi akibat sinaran ultrasonik dalam media berliang harus dikaji selanjutnya. Namun begitu, surfaktan adalah agen penting yang membolehkan minyak dan air bercampur dan umumnya merupakan komponen yang paling mahal dalam emulsi. Oleh demikian, memilih formulasi surfaktan yang sesuai bagi membolehkan mobilisasi minyak tanpa kehilangan surfaktan yang signifikan disebabkan jerapan dan pemisahan fasa dalam reservoir adalah sangat penting. Menganggar parameter pemelarutan adalah alatan penting dalam merekabentuk komposisi banjiran emulsi secara ekonomik. Dalam kajian ini, kesan gelombang ultrasonik ke atas jumlah minyak dan air terlarut oleh satu unit surfaktan adalah dikaji. Hasil cerapan didapati isipadu emulsi dan jumlah minyak terlarut dalam emulsi adalah meningkat dengan peningkatan kemasinan di bawah radiasi gelombang ultrasonik dalam jangkamasa pendek. Selain itu, ujian secara mikroskopik menggunakan model Hele-Shaw menunjukkan yang kesan radiasi gelombang ultrasonik pada masa jangka masa yang panjang dan pendek pada antaramuka minyak parafin dan larutan/air garam surfaktan. Penyebaran fasa, pembentukan emulsi dan buih-buih gas dapat diperhatikan selepas radiasi gelombang ultrasonik dalam jangka masa pendek. Namun begitu, demulsifikasi dan pegabungan titisan larutan/air garam surfaktan di dalam emulsi telah terjadi selepas radiasi ultrabunyi pada jangka masa panjang. Objektif seterusnya bagi kajian ini adalah untuk mengkaji secara langsung kesan gelombang ultrasonik ke atas perubahan kelikatan ke atas tiga jenis minyak (minyak parafin, minyak sintetik, dan kerosen) dan satu sampel air garam. Didapati kelikatan bagi semua cecair adalah berkurang dengan pengaruh gelombang ultrasonik bagi kedua-dua keadaan suhu sama ada suhu terkawal atau tanpa kawalan. Sebagai tambahan, eksperimen mikro-model telah dijalankan bagi menilai mekanisme perolehan minyak yang lain seperti pegabungan titisan minyak, mobilisasi minyak dan pengenyahan minyak dari hujung liang di bawah pengaruh gelombang ultrasonik. Dengan itu, dapat dibuat kesimpulan yang penggunaan gelombang ultrasonik boleh dicadangkan, bukan sebagai pengganti bagi kaedah EOR konvensional, tetapi sebagai satu pilihan atau alatan sampingan, yang mana dalam keadaan tertentu boleh membuat kaedah konvensional lebih berkesan dan dengan kos yang rendah.

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LIST OF SYMBOLS

AOS	-	Alpha Olefin Sulfonate
C	-	Circumference of ring
Ca	-	Capillary number
CMC	-	Critical Micelle Concentration
D	-	Density of water at 25°C
d	-	Density of test specimen at 25°C
EOR	-	Enhanced Oil Recovery
f	-	Frequency
IFT	-	Interfacial Tension
L	-	Capillary tube length
n	-	Power-Law fluid index
NUS	-	Non-Ultrasound
OW	-	Oil Wet
P	-	Scale reading
PO	-	Paraffin oil
ΔP_s	-	External pressure gradient
ΔP	-	Differential pressure
Q	-	Flow rate
R^{right}	-	Radius of the right meniscus
R^{left}	-	Radius of the left meniscus
R	-	Radius of ring
r	-	Radius of wire of ring
$TCMS$	-	Trichloromethylsilane
US	-	Ultrasound
V_o	-	Amount of oil in microemulsion
V_w	-	Amount of water in microemulsion

WW	-	Water Wet
μ	-	Viscosity
θ	-	Contact angle

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CHAPTER 1

INTRODUCTION

1.1 Background

In the oil industry, the reduction of oil production is of major concern as world necessity for oil increases. Therefore, developing and applying new techniques to mobilize residual oil left in the reservoir and make best of the original oil in place (OOIP) is very crucial.

As the world's human population growing, decreasing of production in oil recovery processes is of major concern. Crude oil production and development of a petroleum reservoir is divided into three distinct stages such as primary, secondary and tertiary or Enhanced Oil Recovery (EOR). During primary recovery, the natural pressure of the reservoir, combined with pumping equipment, brings oil to the surface. Primary recovery is the easiest and cheapest way to extract oil from the ground. However, this method of production typically produces only about 10 percent of a reservoir's OOIP reserve. In the secondary recovery phase, water or gas is injected to displace oil, making it much easier to drive it to a production wellbore. This technique generally results in the recovery of 20 to 40 percent of the OOIP. Consequently, the oil left in the reservoir is the goal of tertiary recovery (EOR) process. In addition to maintaining reservoir pressure, this type of recovery seeks to alter the properties of the oil in ways that facilitate additional production. The three major types of tertiary recovery are chemical flooding, thermal recovery (such as a steamflood) and miscible displacement involving carbon dioxide (CO₂), hydrocarbon or nitrogen injection. All of the conventional EOR methods include

some limitations. Some of them are expensive to use, need a wide range of surface apparatus, generate dangerous environmental results, and have technical limitations (Xiao *et al.*, 2004). Therefore, some unconventional methods have been proposed to EOR.

One of the unconventional methods is the application of wave energy for enhancing oil recovery in reservoirs. This method has been of interest for more than six decades. There are numerous investigations to show the effect of earthquakes on increasing oil recovery (Steinbrugge and Moran, 1954; Voytov *et al.*, 1972; Simkin and Lopukhov, 1989). An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves. However, the question is that how long one should wait until an earthquake happens. Therefore, the waves were generated artificially. The wave energy can be sent to an oil reservoir by using seismic method, and in-situ sonication (ultrasonic wave method). The seismic waves can be applied into the reservoir by surface vibrators or explosives. The method utilizes low frequency compressional waves. The in-situ sonication method uses an acoustic transducer, which is delivered into the bottom of the hole and producing ultrasonic waves with high frequency and high intensity. Therefore, the ultrasonic waves move within the porous media and stimulate the fluids mechanically (Hamida, 2006).

There are some advantages of using this method compared to the other conventional techniques that can be reviewed here:

- (i) In the methods using fluids, hydraulic force is in charge of delivering the driving force in the conventional methods and fluids always choose the least resistance pathway and suffer from bypassing effects. Therefore, numerous EOR techniques are unsuccessful in heterogeneous formations and running off great oil pools unaffected. However, in the methods using waves, the energy is distributed in all directions and is unchanged by permeability of medium or pore network. Therefore, it is easy to affect every point in the reservoir at the same time (Beresnev *et al.*, 2005).

- (ii) The need for chemical stimulation (acid, solvents, and etc.) is replaced by using waves. Because chemical stimulation is not compatible in some cases with the reservoir rock or fluid (Beresnev *et al.*, 2005).
- (iii) The waves can be applied to the reservoir while the well is producing (Beresnev *et al.*, 2005).

On the other side, the main limitation of using wave energy is the quick attenuation in porous media particularly at high frequencies (20 kHz up to several gigahertz)(Dunn, 1986). Therefore, the application of ultrasonic method is restricted to near-wellbore area because of its high attenuation in porous media. By studying Biot's theory, one recognizes that the length of attenuation of ultrasonic waves with frequency about 20 kHz is 2 to 10 cm (Biot, 1956b; Biot, 1962). Therefore, a great number of researches have been performed using low frequency waves that are able to propagate in reservoir several kilometers. On the other hand, it is recognized that ultrasonic waves exist in the reservoir after applying seismic waves (low frequency waves) to the reservoir because low frequency waves dispersion generate ultrasonic noise (high frequency waves) in porous media (Nikolaevskii and Stepanova, 2005). Ultrasonic waves have short wavelengths and considerably play an important role in mechanical perturbation at the pore scale. Consequently, it is supposed that the effect of ultrasonic waves (high frequency waves) is more significant compare to low frequency waves at pore scale (Duhon and Campbell, 1965; Beresnev *et al.*, 2005; Xiaoyan *et al.*, 2007). Nevertheless, the mechanisms caused by ultrasonic waves in porous media are not well recognized yet and requires deep investigations to disclose the physics and mechanisms process included in recovery of oil.

1.2 Statement of Problem

The interest in using ultrasonic waves as an unconventional method for stimulation of oil reservoirs dates back to 1950's. Most of the studies that have been performed over these years are limited to macromodel studies such as measuring oil recovery after applying ultrasonic waves. In addition, the oil recovery mechanisms mentioned in the previous studies are theoretical and lacks fundamental

researches (microscopic or pore scale studies) (Naderi, 2008). Studying the mechanisms that lead to oil mobilization by ultrasonic waves is very important and is essential for field purposes. However, in spite of many studies, questions about the effective mechanisms causing increase in oil recovery still existed. Therefore, it is very crucial to perform basic experiments (pore scale) to achieve a good knowledge and deep insight into the mechanisms.

Emulsification is one of the oil recovery mechanisms happening in porous media under the influence of ultrasonic waves. Numerous macromodel studies have demonstrated that the emulsion has been generated at the interface of two immiscible fluids under the influence of ultrasonic waves (Wood and Loomis, 1927; Richards, 1929; Bondy and Sollner, 1935; Campbell and Long, 1949; Neduzhii, 1962; Li and Fogler, 1978; Cucheval and Chow, 2008; Ramisetty and Shyamsunder, 2011; Mohammadian *et al.*, 2012). In addition, chemical flooding involves injection of a surfactant solution, which can cause the oil/aqueous interfacial tension to drop and allowing emulsification and displacement of the oil. Surfactants are the principal agents that enable oil and water to mix and are often the most expensive component in an emulsion. Estimation of solubilization parameters is a great tool in designing the economical emulsion flooding compositions. In EOR, one of the most important designing factors for chemical flood is to select an appropriate surfactant formulation capable of mobilization oil without significant surfactant losses due to adsorption and phase separation in the reservoir. An optimum condition for the oil recovery is observed when the middle phase contains the added surfactant and equal amounts of oil and water (Reed and Healy, 1977). Therefore, the effect of ultrasonic waves on the amounts of oil and water solubilized by a unit of surfactant should be investigated and the results must be compared with the case using no ultrasonic waves.

In addition, the majority of the studies on the effect of ultrasonic waves on emulsification are macroscopic and no work (microscopic) to show exactly what happens at the interface of two immiscible liquids. Therefore, it is necessary to study the effect of ultrasonic waves at the liquid-liquid interface to show the phenomena happening there by using Hele-Shaw models. Hele-Shaw experiments very

accurately show what happens at the liquid-liquid interface, without the additional complexity arising from a porous (channeled) structure.

Another mechanism through which ultrasonic waves improves the recovery of oil from porous media is viscosity reduction (Duhon and Campbell, 1965; Xiao *et al.* 2004; Naderi, 2008; Mohammadian *et al.*, 2012). In all of the previous studies, the viscosity was measured using either indirect methods i.e. calculating the viscosity from temperature changes or it was measured in a static condition. In other words, in spite of numerous studies, it is not yet clear that whether the viscosity reduction in ultrasonic stimulated fluids is due to the thermal effect of waves or due to other reasons. For example, Poesio *et al.* (2002) convincingly demonstrated that, the only reason for reduction of viscosity is temperature increase in the media. Mohammadian *et al.* (2012) considered viscosity reduction as one of the possible contributing mechanisms in the recovery. They further concluded that viscosity of brine and oil are reduced as a result of sonication. They also inferred that the reduction in viscosity of fluids is not solely due to heat generated as a result of sonication. Moreover, in previous researches the effects of power of waves, as an independently factor, has not been discussed on viscosity. In the other word, viscosity reduction was reported as a side effect of ultrasonic waves radiation. The area therefore could be explored further.

There are also some other oil recovery mechanisms under the influence of ultrasonic waves in porous media such as oil coalescence, mobilization and detachment. Unfortunately, the mechanisms mentioned are almost theoretical or speculative. For example, there is no micromodel study under microscope to show oil droplets coalescence due to the Bjerknes forces (forces between the vibrating oil droplets under the influence of ultrasonic waves that lead to their attractions) or there is no micromodel study to show oil detachment from dead end pores (Naderi, 2008). Therefore, it is crucial to demonstrate these mechanisms in 2D glass micromodels and prove that if ultrasonic waves can cause oil droplet coalescence and detachment. If these questions answered then it is possible to improve oil recovery techniques in the field and interpret the laboratory experiments more confidently.

1.3 Research Objectives

The objective of this research can be subdivided into four (4) groups as following:

- (i) To investigate the effect of ultrasonic waves on the volume of emulsion and amount of oil and water solubilized in emulsion by a unit of surfactant.
- (ii) To investigate changes in the viscosity of various liquids exposed to radiation of ultrasonic waves of various power outputs and constant frequency.
- (iii) To study the effect of ultrasonic waves at the liquid-liquid interface microscopically to show the mechanisms happening there using Hele-Shaw models.
- (iv) To show the effect of ultrasonic waves on oil droplet coalescence, mobilization, and detachment from dead end pores, in porous media.

1.4 Scope of Study

To investigate the effect of ultrasonic waves on oil recovery mechanisms, three series of experiments were conducted.

Firstly, emulsion tests were performed to investigate the effect of ultrasonic waves (40 kHz and 500 W) on the volume of emulsion and amounts of paraffin oil and aqueous solution (a solution of the surfactant (1000 ppm AOS) and sodium chloride solutions at varying concentrations (5000, 10000, 15000, 20000, 25000, 30000 ppm) in de-ionized water) in emulsion using test tubes. All the experiments were conducted under 60 mins mechanical agitation (50 RPM) of the test tubes by Rotospin-rotary mixer inside the ultrasonic bath (40 kHz and 500 W) under three periods of ultrasonic waves radiation (0 (NUS), 15, 60 mins).

Secondly, a smooth capillary tube was employed for investigating the viscosity changes under the influence of ultrasonic waves (constant frequency of 40 kHz). Some parameters were changed such as type of fluids (synthetic oil, paraffin oil, kerosene, and brine), and ultrasonic waves power outputs (100, 250, 500 W).Pouisselle's equation was taken into account for the calculation of the viscosity. In these experiments, the process was examined for different conditions such as controlled and uncontrolled temperature conditions.

As a third attempt, to have a better insight into the oil recovery mechanisms a series of experiments were conducted at pore scale in Hele-Shaw and 2D glass micromodels. For the experiments using Hele-Shaw models, the emulsification mechanism at liquid-liquid interface under the influence of ultrasonic waves (40 kHz and 500 W) was investigated under microscope using two different etched thickness (500 and 26 μm) models. Some experiments were performed to show more oil recovery mechanisms under the influence of ultrasonic waves such as oil droplet coalescence, oil mobilization, and oil detachment from dead end pores under microscope in two 2D glass micromodels with triangular and circle patterns. The experiments were performed in different wettability conditions (oil-wet and water-wet) and flow conditions (static and dynamic).

1.5 Significance of the Study

In enhanced oil recovery (EOR) using surfactant, low interfacial tension at low surfactant concentrations, and acceptable adsorption levels are considered to be important design parameters in optimizing chemical systems for recovering trapped oil from petroleum reservoirs. In addition, surfactants are the principal agents that enable oil and water to mix and are often the most expensive component in an emulsion. Therefore, attempts should be made to increase the volume of emulsion and prevent from phase separation for a specific concentration of surfactant in order to have an economical surfactant flooding. On the other hand, emulsification is one of the oil recovery mechanisms under the effect of ultrasonic waves. Therefore, in this study the effect of ultrasonic waves on phase behavior of surfactant-brine-oil

system was investigated, which is an important step in optimizing performance of emulsion systems for enhanced oil recovery.

The viscosity reduction is another oil recovery mechanism happening under influence of ultrasonic waves. In all of the previous studies, the viscosity was measured using either indirect methods i.e. calculating the viscosity from temperature changes or it was measured in a static condition. In this study, the viscosity changes of the fluids in controlled (constant) and uncontrolled temperature conditions under influence of ultrasonic waves was investigated.

There are also some other oil recovery mechanisms under the influence of ultrasonic waves in porous media such as oil coalescence, mobilization and detachment. However, the mechanisms mentioned are almost theoretical or speculative. Therefore, in this study these mechanisms were demonstrated under influence of ultrasonic waves using Hele-Shaw models and micromodels.

In conclusion, this study contributes:

- (i) To make clarifying the oil recovery mechanisms under the influence of ultrasonic waves and
- (ii) To find the factors or circumstances in which ultrasonic waves are effective for the purpose of increase in oil recovery.

REFERENCES

- Aarts, A. C. T. and Ooms, G. (1998). Net flow of compressible viscous liquids induced by traveling waves in porous media, *J. Eng. Math.* 34, 435–450.
- Aarts, A. C. T., Ooms, G. Bil, K.J., and Bot, E.T.G. (1999). Enhancement of Liquid Flow Through a Porous Medium by Ultrasonic Radiation. *SPE Journal* , 4(4): 321-327.
- Abdel-Aal, H. K., Aggour, M., and Fahim, M. (2003). Emulsion Treatment and Dehydration of Crude Oil, *Petroleum and Gas Field Processing book*, p 143.
- Abismail, B., Canselier, J.P., Wilhelm, A.M., Delmas, H., Gourdon, C. (1999). Emulsification by Ultrasound: Drop Size Distribution and Stability. *Ultrason. Sonochem.* 6 (1-2) 75–83.
- Amro, M. and Al-Homadhi, E. S. (2006). Enhanced Oil Recovery Using Sound-Wave Stimulation. *Final Research Report No. 53/426*. King Saud University, College of Engineering, Research Center.
- Amro, M., Al-Mobarky, M., and Al-Homadhi, M. (2007). Improved oil recovery by application of ultrasound waves to water-flooding, SPE 105370, *SPE Middle East Oil & Gas Show*, Bahrain,
- Andarcia, L., Kamp, A.M., Huerta, A., and Rojas, G. (2002). The Effect of Clay Fraction on Heavy Oil Depletion Test, SPE paper 78968 presented at the SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference held in Calgary, Alberta, Canada.
- Anderson, W. (1986). Wettability Literature Survey - Part 1 Rock/Oil/Brine Interactions and the Effects of Core Handling on Wettability. *Journal of Petroleum Technology*.
- Anderson, W. (1987). Wettability Literature Survey - Part 5: The Effects of Wettability on Relative Permeability. *Journal of Petroleum Technology*.
- Baram, A.A. (1965). Mechanism of Emulsification in an Acoustic Field, *Soviet Physics-Acoustics*, No.4, 343

- Becher, P. (1962). Non Ionic Surface Active Compounds. V. Effect of Electrolytes, *J. Colloid Science*, 17:325.
- Bera A., Ojha K., Mandal A., and Kumar T. (2011). Interfacial Tension and Phase Behavior of Surfactant-Brine–Oil System, *Colloids and Surfaces A: Physicochem. Eng. Aspects* 383, 114–119.
- Beresnev, I. A. (2006). Theory of Vibratory Mobilization on Nonwetting Fluids Entrapped in Pore Constrictions. *Geophysics*, 47- 56.
- Beresnev, I. A. and Johnson, P. A. (1994). Elastic-Wave Stimulation of Oil Production - a Review of Methods and Results. *Geophysics* 59(6): , 1000-1017.
- Beresnev, I.A., Vigil,D., and Li,W. (2005). The Mechanism of Recovery of Residual Oil by Elastic Waves and Vibrations. *SEG Expanded Abstracts* , 24, 1386-1390; DOI:10.1190/1.2147946.
- Billiotte, J.A., Ecole, des M., DeMoegen, H., Gaz, F., and Oren, P. (1990). Experimental Micromodeling and Numerical Simulation of Gas/Water Injection/Withdrawal Cycles as Applied to Underground Gas Storage, *SPE paper 20765 presented at the 65th Annual Technical Conference and Exhibition*, New Orleans, LA.
- Biot, M. A. (1962). Mechanics of Deformation and Acoustic Propagation in Porous Media. *Journal of Applied Physics* , 33(4): 1482.
- Biot, M. A. (1956a). Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid .1. Low-Frequency Range. *Journal of the Acoustical Society of America*, 28(2): 168-178.
- Biot, M. A. (1956b). Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid .2. Higher Frequency Range. *Journal of the Acoustical Society of America* , 28(2): 179-191.
- Bird, R. B., Stewart, W. E., and Lightfoot, E. N. (1960). Transport Phenomena; *John Wiley and Sons*, New York.
- Bjerknes, V. F. (1906). Fields of Force. *New York, Columbia University Press* .
- Blake, F. G. (1949). Bjerknes Forces in Stationary Sound Fields. *Journal of the Acoustical Society of America* , 21(5): 551-551.
- Bondy, E. and Sollner, K. (1935). On the Mechanism of Emulsification by Ultrasonic Waves, *Trans. Faraday Society*, 31, 835-843.

- Bora, R., Maini, B.B., and Rasi, T. (2000). Flow Visualization Studies of Solution Gas Drive Process in Heavy Oil Reservoirs Using a Glass Micromodel, *SPEREE*, pp.224-229.
- Bora, R., Chakma, A., and Maini, B.B., (2003). Experimental Investigation of Foamy Oil Flow Using a High Pressure Etched Glass Micromodel, *SPE 84033 presented at the SPE Annual Technical Conference and Exhibition* held in Denver, CO., 5-8.
- Buckingham, M. J. (2005). Compressional and Shear Wave Properties of Marine Sediments: Comparisons between Theory and Data. *Journal of the Acoustical Society of America* , 117(1): 137-152.
- Buckingham, M. J. (1997). Theory of Acoustic Attenuation, Dispersion, and Pulse Propagation in Unconsolidated Granular Materials Including Marine Sediments. *Journal of the Acoustical Society of America* , 102(5): 2579-2596.
- Buckingham, M. J. (1999). Theory of Compressional and Transverse Wave Propagation in Consolidated Porous Media. *Journal of the Acoustical Society of America* , 106(2): 575-581.
- Buckley, J.S. (1991). Multiphase Displacements in Micromodels. *Interfacial Phenomena in Petroleum Recovery*. Marcel Dekker, Inc., New York.
- Campbell, H. and Long, C.A. (1949). Emulsification by ultrasonics, *Pharm. J.* 163 (8) 127–128.
- Cash, Jr., Cayias, J.L., Hayes, M., and Schares, T. (1975). Spontaneous Emulsification—A Possible Mechanism for Enhanced Oil Recovery, paper SPE 5562 presented at the 50th annual fall meeting of the Society of Petroleum Engineers of AIME, held in Dallas, Texas.
- Chatzis, I. (2011). Mobilization of Residual Oil Mechanisms Seen in Micro-models. *Department of Chemical Engineering* , 1-8.
- Chatzis, I., Morrow, N. R., and Lim, H. T. (1983). Magnitude and Detailed Structure of Residual Oil Saturation. *Society of Petroleum Engineers Journal*. 23. pp 311-326.
- Chan, K.S. and Shah, D.O. (1977). Improved Oil Recovery Research Program. Semi-annual Report, A. University of Florida, Gainesville, Fla., 22 pp.
- Cherskiy, N. V., Tsarev, V. P., Konovalov, V. M., and Kusnetsov, O. L. (1977). The Effect of Ultrasound on Permeability of Rocks to Water. *Transactions of the U.S.S.R. Academy of Sciences* (pp. 201-204).

- Cooke, Jr., William, R.E., and Kolodzie, P.A. (1974). Oil Recovery by Alkaline Waterflooding, *J. Pet. Tech.*, 1365–1374.
- Crum, L. A. and Nordling, D. A. (1973). Bjerknes Forces between Two Pulsating Air Bubbles in Liquid, *J. Acoust. Soc. Am.* 54(1) 324-324.
- Cucheval, A., and Chow, R.C.Y. (2008). A Study on the Emulsification of Oil by Power Ultrasound. *Ultrasonics Sonochemistry* , 916-920.
- Dehghan, A. A., Kharrat, R., and Ghazanfari, M. H. (2009). Studying the Effects of Pore Geometry, Wettability and Co-Solvent Types on the Efficiency of Solvent Flooding to Heavy Oil in Five-Spot Models, *SPE 123315, presented at Asia Pacific Oil and Gas Conference & Exhibition, Jakarta, Indonesia.*
- Dijke, M.I.J., Sorbie, K.S., Sohrabi, M., Tehrani, D., and Danesh, A. (2002). Three-Phase Flow in WAG Processes in Mixed-wet Porous Media: Pore-Scale Network Simulations and Comparison with Micromodel experiments, SPE paper 75192 presented at the 2002 SPE/DOE Improved Oil Recovery Symposium, Tulsa, U.S.A.
- Dong, M. and Liu, P. (1988). Spontaneous Emulsification Caused by Micellar Solubilization, *presented at the 3rd National Conference of Surface and Colloid Chemistry, Shanghai, China.*
- Duhon, R. D. and Campbell, J. M. (1965). The Effect of Ultrasonic Energy on Flow Through Porous Media. SPE 1316, *second Annual Eastern Regional Meeting of SPE/AIME.* Charleston, WV.
- Duhon, R. D. (1964). An Investigation of the Effect of Ultrasonic Energy on the Flow of Fluids in Porous Media. *Ph.D. thesis, University of Oklahoma .*
- Dunn, K. J. (1986). Acoustic Attenuation in Fluid-Saturated Porous Cylinders at Low- Frequencies. *Journal of the Acoustical Society of America* , 79(6): 1709-1721.
- Ensminger, D., (1988). *Ultrasonics, Fundamentals, Technology, Applications,* second ed., Marcel Dekker Inc., New York.
- Ensminger, D. and Bond, L. J. (2011). *Ultrasonics: Fundamentals, Technologies, and Applications,* Third Edition. CRC Press, Science.
- Fainerman, V.B. and Reynders, E.H. (2002). Adsorption of Single and Mixed Ionic Surfactants at Fluid Interfaces. *Adv. Colloid Interface Sci.* 96, 295.

- Fairbanks, H. V. and Chen, W. I. (1971). Ultrasonic Acceleration of Liquid Flow Through Porous Media. *A.I.Ch.E. Sonochem. Eng.* , 67: 105.
- Farajzadeh, R., Krastev R., and Zitha, P.L.J. (2008). Foam Films Stabilized with Alpha Olefin Sulfonate (AOS). *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 324, 35–40.
- Foster, W. (1973). A Low-Tension Waterflooding Process. *Journal of Petroleum Technology*: , 205-210.
- Gaikwad, S. G. and Pandit, A. B. (2008). Ultrasound Emulsification: Effect of Ultrasonic and Physicochemical Properties on Dispersed Phase Volume and Droplet Size, *Ultrason Sonochem*, 15, 554–563.
- Garde,S.,García, A. E., Pratt, L. R., and Hummer, G. (1999). Temperature Dependence of the Non-Polar Solubility of Gases in Water. *Biophysic. Chem.*, 78 (1-2).
- Green, D. W. and Willhite, G. P., (1998). Enhanced Oil Recovery, Society of Petroleum Engineers, SPE Textbook Series Vol. 6, 545 pp.
- Gulseren, I., Guzey, D., Bruce, B. D., and Weiss, J. (2007). Structural and Functional Changes in Ultrasonicated bovine serum albumin solutions. *UltrasonicsSonochemistry*, 14 (2): 173-83.
- Gurkov, T.D., Dimitrova, D.T., Marinova, K.G., Bilke-Crause, C., Gerber, C., and Ivanov, I.B.(2005). Ionic Surfactants on Fluid Interfaces: Determination of the Adsorption; Role of the Salt and the Type of the Hydrophobic Phase,*Colloids Surf. A: Physicochem. Eng. Aspects*, 261, 29.
- Haghighi, M. and Yortsos, Y.C. (1997). Visualization of Steam Injection in Fractured Systems Using Micromodels, SPE paper 37520 presented at the International Thermal Operations and Heavy Oil Symposium, Baskerfield, CA.
- Hall, D. E. (1980). Musical Acoustics: An Introduction. Belmont, California: Wadsworth Publishing Company, ISBN 0534007589 .
- Hamida, T. (2006). Effect of Ultrasonic Waves on Immiscible and Miscible Displacement in Porous Media. *Master thesis, University of Ulberta, Canada.*
- Handy, L., and Datta, P. (1966). Fluid Distribution during Immiscible Displacements in Porous Media, Vol. 6. Chevron Research Co., La Harba, California.
- Healy, R.N. , Reed, R.L., and Carpenter, C.W. (1975). A Laboratory Study of Microemulsion Flooding. *Soc. Pet. Eng. J.* , 87–100.

- Huang, X. L. S. (1993). Mechanism and Experimental Study of Acoustic Oil Recovery. *Acta Petrolei Sinica* (Doi: 0253-2697.0.1993-04-015).
- Jamaloei, B. Y. and Kharrat, R. (2009). Analysis of Microscopic Displacement Mechanisms of Dilute Surfactant Flooding in Oil-wet and Water-wet Porous Media. *Springer Science and Business Media*, 1-19.
- Johnston, H. K. (1971). Polymer Viscosity Control by the Use of Ultrasonics. *Chemical Engineering Progress Symposium Series 67*, 39-45.
- Karbstein, H. (1994). Untersuchungen zum Herstellen und Stabilisieren von Oil-in-Wasser-Emulsionen. *Ph.D. Thesis, University of Karlsruhe*.
- Kouznetsov, O. E. (1998). Improved Oil Recovery by Application of Vibro-Energy to Waterflooded Sandstones. *J. Petrol. Sci.* 19 (3-4) 191-200.
- Kumar, P., and Mittal, K. L. (Eds.) (1999). *Handbook of Microemulsion Science and Technology*. New York: CRC Press.
- Larsen, J.K., Bech, N., and Winter, A., (2000). Three-Phase Immiscible WAG Injection: Micromodel experiments and Network Models, SPE paper 59324 presented at the 2000 SPE/DOE Improved Oil Recovery Symposium held in Tulsa.
- Leighton, T. G. (1995). Bubble Population Phenomena in Acoustic Cavitation. *Ultrason. Sonochem.*, 2(2), 123-136.
- Levitt, D.B., Jackson, A.C., Heinson, C., Britton, L.N., Malik, T., and Dwarakanath, A.V. (2006). Identification and Evaluation of High-Performance EOR Surfactants. *SPE-100089*.
- Li, M.K., and Fogler, H.S. (1978). Acoustic Emulsification: I. The Instability of the Oil-Water Interface to Form the Initial Droplets. *J. Fluid Mech.*, 88, 499-511.
- Li, W. Q., Vigil, R. D., Beresnev, I. A., Iassonov, P., and Ewing, R. (2005). Vibration-Induced Mobilization of Trapped Oil Ganglia in Porous Media: Experimental Validation of a Capillary-Physics Mechanism. *Journal of Colloid and Interface Science*, 289(1): 193-199.
- Lighthill, S. J. (1978). Acoustic Streaming. *J. Sound Vib.*, 61, 391- 418.
- Lin, C.Y. and Chen, L. W. (2005). Engine Performance and Emission Characteristics of Three-Phase Diesel Emulsions Prepared by an Ultrasonic Emulsification Method. *Journal of Fuel*. Volume 85, Issues 5-6, March-April 2006, Pages 593-600.

- Lin, T. J. and Lambrechts, J. C. (1969). Migration of Surfactants in a Two-Phase System, *J. Soc. Cosmetic Chemists* 20, 627-638.
- Mace, R.E. and Wilson, J.L. (1991). Clay and Immiscible Organic Liquids : Greater Capillary Trapping of the Organic Phase. *Transport and Remediation of Subsurface Contaminants*.
- Malykh, N., Petrov, V. and Sankin, G. (2003). On Sonocapillary Effect. *presented at WCU* , 7-10.
- Marle, C. M. (1991). Basic Concepts in Enhanced Oil Recovery Processes. *M. Baviere Ed., Elsevier Applied Science, London* .
- Mason, T. J. (1997). Ultrasound in Synthetic Organic Chemistry. *Chemical Society Reviews*, 26(6), 443-451.
- Mason, T. J., (1999). Sonochemistry, First Edition, Oxford Science Publications, New York, USA,
- Mason, T. J., and Cordmas, E. (1996). Ultrasonic Intensification of Chemical Processing and Related Operations-a Review. *Transactions of the Institute of Chemical Engineers*, 74(A), 511-516.
- McAuliffe, C. D. (1973). Oil-in-Water Emulsions and Their Flow Properties in Porous Media, *J. Pet. Tech.*, 727-733.
- Mettin, R., Akhatov, I., Parlitz, U., Ohl, C. D., and Lauterborn, W. (1997). Bjerknes Forces Between Small Cavitation Bubbles in a Strong Acoustic Field. *Physical Review E* , 56(3): 2924-2931.
- Mohammadian, E., Junin, R., Rahmani, O., and Idris, A.K. (2012). Effects of Sonication Radiation on Oil Recovery by Ultrasonic Waves Stimulated Water-Flooding, *Ultrasonics* 53 (2) 607-614.
- Moore, T.F. and Slobod, R.C.(1956). The Effect of Viscosity and Capillarity on the Displacement of Oil by Water, *Producers Monthly* 20-30.
- Morrow, N. R. (1979). Interplay of Capillary, Viscous and Bouyancy Forces in the Mobilization of Residual Oil. *The Journal of Canadian Pet. Technology*, 19, 35.
- Morrow, N.R. (1991). Introduction to Interfacial Phenomena in Petroleum Recovery. *Interfacial Phenomena in Petroleum Recovery*. Marcel Dekker, Inc., New York.
- Najafi, I. (2010). A mathematical analysis of the mechanism of ultrasonic induced fluid percolation in porous media, in: *SPE 141126, SPE Annual Technical Conference and Exhibition*, Florence, Italy.

- Naderi, K. (2008). Core and Pore Scale Investigations on Immiscible Displacement and Enhanced Oil/Heavy-Oil Recovery under Ultrasonic Waves. *Master Thesis, University of Ulberta, Canada.*
- Neduzhii, S. (1962). The State of the Disperse Phase During the Formation of an Emulsion in an Acoustic Field. *Soviet Phys./Acoust.*, 378.
- Nguyen, Q.P., Thissen, M., H.G., and Zitha, P.L.J., (2002). Effect of Trapped Foam on Gas Tracer Diffusion in a Visual Microflow Model, SPE paper 75208 presented at at the 2002 SPE/DOE Improved Oil Recovery Symposium. Tulsa, U.S.A.
- Nikolaevskii, V. N. and Stepanova, G. S. (2005). Nonlinear Seismics and the Acoustic Action on the Oil Recovery From an Oil Pool. *Acoust. Phys.*
- Norris, A. N. (1989). Stoneley-Wave Attenuation and Dispersion in Permeable Formations. *Geophysics* , 54(3): 330-341.
- Patsoules, M. G. and Cripps, J. C. (1982). The Application of Resin Impregnation to the Three-Dimensional Study of Chalk Pore Geometry. *Engineering Geology*, 19, 15-27.
- Pelekasis, N. A. and Tsamopoulos, J. A. (1993). Bjerknes Forces Between Two Bubbles. Part 1. Response to a Step Change in Pressure, *J. FluidMech.* 254. 467-499.
- Poesio, P. and Ooms, G. (2005). Influence of high-frequency Acousticwaves on the flow of a Liquid through porous material: Experimental and theoretical Investigation, *Physicochemical and Electromechanical Interactions in Porous Media*, 61–66.
- Poesio, P., Ooms, G., Barake, S., and Bas, V.D. (2002). An Investigation of the Influence of Acoustic waves On the Liquid Flow through a Porous Material. *Journal of the Acoustical Society of America* , 111 (5), Pt.1, May 2002: 2019-2025.
- Probig Fine Chemical Co., Ltd. (2013). (Guangzhou, Producer, & Probig Fine Chemical Co., Ltd.) Retrieved from: http://gzprobig.en.alibaba.com/product/96744826213707914/Sodium_alpha_olef_in_sulfonate_AOS_35_liquid.html.
- Prosser, A. J. and Franses, E.I. (2001). Adsorption and Surface Tension of Ionic Surfactants at the Air-Water Interface: Review and Evaluation of Equilibrium Models. *Colloids Surf. A: Physicochem. Eng. Aspects*, 178, 1–40.

- Ramisetty, K.A. and Shyamsunder, R. (2011). Effect of Ultrasonication on Stability of Oil in Water Emulsions. *International Journal of Drug Delivery*, 3, 133-142.
- Reed, R.L. and Healy, R.N. (1977). Some Physicochemical Aspects of Microemulsion Flooding: A Review. *In Improved Oil Recovery by Surfactant and Polymer Flooding. AIChE Symposium*. Academic Press, Inc.
- Ren, W., Bentsen, R., and Cunha, L.B. (2003). Pore-level Observation of Gravity Assisted Tertiary Gas Injection Processes, SPE paper 81007 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference held in Port of Spain, Trinidad, West Indies.
- Richards, W.T. (1929). The Chemical Effects of High Frequency Sound Waves: II. A Study of Emulsifying Action, *J. Am. Chem. Soc.* 51 1724–1729.
- Richards, W.T. and Loomis, A.L. (1927). The Chemical Effects of High Frequency Sound Waves: I. A Preliminary Report, *J. Am. Chem. Soc.* 49 3086–3100.
- Romero-Zerón, L.B. (2004). The Role of Porous Media Wettability on Foamed Gel Propagation and Fluid Diverting Performance. Ph.D. Dissertation, University of Calgary, Calgary, AB, Canada.
- Rose, W. and Witherspoon, P. A. (1956). Trapping Oil in a Pore Doublet, *Producers Monthly* 21, No. 2, 32-38.
- Scheidegger, A. (1974). The Physics of Flow Through Porous Media. *3rd Ed.*
- Schramm, L. (1992). Emulsions: Fundamentals and Applications in the Petroleum Industry. *Advances in Chemistry Series No. 231*.
- Simkin, E. M. (1993). A Possible Mechanism of Vibroseismic Action on an Oil-Bearing Bed. *Journal of Engineering Physics and Thermophysics*, 64(4): 355-359.
- Simkin, E. M. and Lopukhov, G. P. (1989). Vibro-Wave and Vibro-Seismic Methods of Oil Reservoirs Stimulation (A Review), *Oil Industry*, no. 15: All-Union Research Institute of Organization, Management and Economics of Oil and Gas Industry.
- Simkin, E. M. and Surguchev, M. L. (1991). Advanced Vibroseismic Technique for Water Flooded Reservoir Stimulation, Mechanism and Field Tests Results. *The 6th European IOR Symposium*. Stavanger, Norway.
- Sohrabi, M., Tehrani, D.H., Danesh, A., and Henderson, G. D. (2001). Visualization of Oil Recovery by Water Alternating Gas (WAG) Injection Using High Pressure Micromodel-Oil Wet and Mixed-Wet Systems, SPE paper 71494

- presented at the SPE Annual Technical Conference and Exhibition held in New Orleans, LA.
- Steinbrugge, K. V. and Moran, D. F. (1954). An Engineering Study of the SouthernCalifornia Earthquake of July 21, 1952, and Its Aftershocks: *Bull. Seis. Soc. Am.*, 44, 279-283.
- Stegemeier, G.L. (1977). Mechanisms of Entrapment and Mobilization of oil in porous media. In *Improved Oil Recovery by Surfactant and Polymer Flooding. AIChE Symposium*. Academic Press, Inc.
- Sun, W., Qu, Z., Xian, P.R.C., and Tang, G. (2004). Characterization of Water Injection in Low Permeable Rock Using Sandstone Micro-Model, SPE 86964, SPE International Thermal Operations and Heavy Oil Symposium Bakersfield, California, U.S.A.
- Suslick, K. S. (1989). The Chemical Effects of Ultrasound, *Sci. Am.* 260 (2) 80-86.
- Voytov, G. I., Osika, D. G., Grechukhina, T. G., and Plotnikov, I. A. (1972). Some Geological and Geochemical Consequences of the Daghestan Earthquake of May 14, 1970, Transactions of the USSR Academy of Sciences, Earth Science Sections, 202, 576-579.
- Wang, X., and Mohanty, K.K., (2000). Pore-Network Model of Flow in Gas/Condensate Reservoirs, SPEJ, pp.426-434.
- Wardlaw, N. C. (1980). The Effect of Pore Structure on Displacement Efficiency in Reservoir Rocks and in Glass Micromodels. *Paper SPE8843, presented at the First Joint SPE/DOE Symposium on EOR*. Tulsa, Oklahoma, April 20-23.
- Wood, R.W. and Loomis, A.L. (1927). The Physical and Biological Effects of High Frequency Sound Waves of Great Intensity. *Philosophical Mag.* 4, 417.
- Xianghong, Y. and Zhang (1996). Experiment of Reduction Viscosity by Ultrasonic Wave. *Oil & Gas Surface Engineering*, 15, 20-21.
- Xiao, G., Du, Z., Li, G., and Shu, Z. (2004). High Frequency Vibration Recovery Enhancement Technology in the Heavy Oil Field of China. *SPE 86956-International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting*. Bakersfield, California.
- Xiaoyan, Tu, Ooms, G., and Bas, F. (2007). Experimental Evidence of Ultrasonic Stimulation of Brine-Oil Flow Through a Porous Rock in Laboratory Conditions. *Transp Porous Med*, 70:323-333.

Yan, X., and Yaping, Z. (1996). Experiment of Reduction Viscosity by Ultrasonic Wave. *Oil & Gas Surface Engineering*, Vol.15 No.5: 20-21.