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Experimental investigation of ultrasonic treatment effectiveness on pore structure

Ali Ghamartale[a], Mehdi Escrochi[a,b,*], Masoud Riazi[a,b], Ali Faghih[c]

[a] EOR Research Center, IOR-EOR Research Institute, School of Chemical and Petroleum Engineering, Shiraz University, Iran
[b] Department of Petroleum Engineering, School of Chemical and Petroleum Engineering, Shiraz University, Iran
[c] Department of Earth Sciences, College of Sciences, Shiraz University, Shiraz, Iran

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ABSTRACT

During the whole life of oil production, enhancing the efficiency and optimizing the production of wells always have been discussed. Formation damage is one of the most frequent reasons for oil wells productivity reduction. This phenomenon can be caused by different factors such as fine migration, drilling mud invasion, asphaltene precipitation, capillary blockage reservoir fluids, and inorganic precipitation. Acidizing and hydraulic fracturing are two conventional well treatment methods usually applied to overcome the formation damage. However, due to destructive side effects of these methods, new methods such as Ultrasonic technology have helped to overwhelm these challenges. The usefulness of this method has been previously proven experimentally and operationally, but the effect of this technology on the pore structure has not been completely explored yet. In this paper, the effect of the ultrasonic wave on the pore structure during well stimulation is investigated. For this purpose, five samples of carbonate and sandstone with different rock textures were investigated to determine the effect of ultrasonic waves on flow behavior and microscopic pore structure through absolute permeability test, scanning electron microscope (SEM) images and petrography. The results showed that ultrasonic waves may affect pore structure through; initiation of micro-fracture and/or detachment of rock particle. The micro-fracture initiation is expected to increase the permeability while the detached particle may reduce or increase permeability through the clogging or opening the pore throat. For example, it was observed that ultrasonic waves significantly increase the permeability of Oolitic carbonate samples, while the controversial changes were observed in sandstone samples.

1. Introduction

Formation damage is one of the major problems for the production of newly drilled wells. Formation damage can occur for several reasons, including capillary blockage reservoir fluids, precipitation due to interaction between the drilling, or the completion fluids with the reservoir fluids, the deposition of hydrocarbon materials such as asphaltene, the closure of the pores and the pore throat due to drilling mud invasion, the penetration of the particles, or the clay migration during production. These damages mainly reduce the production capacity of the wells and occasionally kill the producing wells [1]. Various methods such as acid washing, acid fracture, and hydraulic fracture are typically used to treat damages, with their effects on improving well production. The main disadvantages of conventional methods especially the acidizing methods are included the safety and environmental concerns, well corrosion, and reduced efficiency during the repetition of treatment. Also, the need for plenty of surface facilities, the necessity of high-power pumps for injection especially during fracturing methods, significant operating costs, and operational problems of proppant are considered as disadvantages of conventional methods [1]. Moreover, traditional well stimulation methods, instead of eliminating the basic causes of the damage, will open up new paths for fluid flow in the reservoir, which will restrict the possibility of repeating the stimulation of the wells. In the recent years, investigators have focused on alternative less-costly treatment methods to eliminate potential sources of production reduction and the disadvantages of the conventional methods. One of the promising methods is based on ultrasonic wave technology. The economic comparison between the conventional methods and the ultrasonic wave method shows that this approach might be suitable (Table 1) [2].

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[*] Corresponding author at: EOR Research Center, IOR-EOR Research Institute, School of Chemical and Petroleum Engineering, Shiraz University, Mollasadra Street, Shiraz, Iran.

E-mail address: escrochi@shirazu.ac.ir (M. Escrochi).

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Table 1
The economic comparison between the treatments methods [2].

No.	Method	Production enhancement relating to the initial production	Cost (Euro)	Proficiency $\left(\frac{Euro}{Production\ Enhancement}\right)$
1	Acidizing	2.5	12,400	4960
2	Hydraulic fracturing	6	22,350	3725
3	Ultrasonic wave	2.4	8200	3417

The idea of using waves to improve production for the first time emerged as a result of changing the level of water and oil column following earthquakes or trains passing [3]. Laboratory studies of the ultrasonic treatment effect on the wells' production started since the 1950s, and field studies began since the 1970s [3]. Researchers investigated the effects of ultrasonic waves under different conditions and concluded that different mechanisms happened in the porous media as a result of ultrasonic waves and improved or reduced the production capacity of wells. The most important of these mechanisms are: tearing off the fluid layer stick to the rock [4], extracting precipitated minerals, agglomerate drops by oscillation [4], stimulating and displacing the trapped fluid [4,5], initiating perturbation in pores [6], acoustic streaming [1], cavitation [1], reduction of surface tension [7], alteration of the fluid viscosity [8], and initiating micro-fracture in rocks [9].

Using the sound waves in the frequency range of 1–5.5 MHz and intensity of 50 W during core flooding, Duhon [10] concluded that the injection rate, the oil recovery, and the relative permeability of water-oil are improved. In 1965, Duhon and Campbell [11] reported a decrease in the viscosity of oil as a result of exposure to ultrasonic waves. In the same year, Nosov [12] observed the same result in the polystyrene sample. Cherskiy et al. [13] investigated the effect of an ultrasonic wave in intensity range of 2–9 kW/m^2 during the core flooding process and observed that the water permeability severely increased. In the meantime, Gadiev [14] reported the reduction of oil-water surface tension and the increment of oil recovery during flooding in the presence of sound waves at various frequencies. Neretin and Yudin [15] and Sokolov [16] verified the results of Duhon et al. [10] in a wide frequency and intensity range. In addition, Snarskiy [17] investigated the sound waves between 9 and 40 kHz and stated that the rate of fluid flow through porous media increases by increasing wave frequency. Pogosyan et al. [18] suggested that the sound waves with a 120 kHz frequency accelerate the rate of separation of kerosene from the water. As a result of this new effect, Simkin et al. [19] conducted some experiments in 1991 and concluded that the presence of ultrasonic waves could cause agglomerating the oil drops in porous media. In 1995, Vanikitaraman et al. [20] studied the effect of sound waves in the frequency range of 10–100 kHz on the sandstone and carbonate samples, which suffered from mud invasion damage and showed that these waves increased the sample permeability 4 and 1.5 times, respectively. Roberts et al. [21] studied the effect of waves' frequency and intensity on the percentage of revitalizing permeability of the damaged rock. They showed that increasing the frequency only enhances the speed of reaching the ultimately regained permeability, while increasing the waves power increases the penetration depth of waves and consequently they concluded that the ultimate permeability of damaged rock increases by increasing the waves' power. Wong et al. studied the effect of ultrasonic waves on the permeability of damaged rocks during the static and dynamic conditions and observed that the ultrasonic waves increase the permeability in both static and dynamic conditions [22]. However, the range of recoverable permeability was dependent on the type of formation damage. They also investigated the effect of the applied electrical energy and concluded that by increasing the electrical energy, the speed of reaching the maximum recovered permeability would increase. In 2004, Van Der Bos et al. [23] investigated the effect of ultrasonic waves on the mud invasion damage and concluded that the effect of ultrasonic waves could be satisfactory. In the same year, Shedid [9] examined the effect of ultrasonic waves on the asphaltene damage in the core. He stated that the removal of sediments and the initiation of micro-fractures were the main mechanisms that improve permeability in these experiments. In 2018, Rezaei Dehshibi [24] tested the effectiveness of ultrasonic waves on asphaltene damage in micromodel. They concluded that the ultrasonic could detach and solve asphaltene deposition. Sohrabi et al. [7] for the first time in 2008 examined the effect of ultrasonic waves on micro-models saturated with gas condensate and examined the effect of this process on surface tension between gas and condensate. Hamida and Babadagli [4] investigated the effectiveness of ultrasonic on Berea sandstone and Indiana limestone during the capillary imbibition process. They observed that the ultrasonic could improve some cases while deteriorate the recovery in some cases. They related this phenomenon to the liquid phase and ultrasonic characterization. However, they never investigate the effect of ultrasonic on a rock which might be the reason for controversial results. In 2012, Hamidi et al. [25], studying the effect of frequency and power of ultrasonic waves on the core and micro-models, concluded that increased frequency and wave power improved the speed of production but did not affect final oil recovery. In 2013, Keshavarzi et al. [26] examined the effect of this wave on gravity drainage process during the vertical flooding and modified the Darcy equation. Some researchers stated that the effect of viscosity reduction during ultrasonic treatment is due to temperature rise. Accordingly, Hamidi et al. [8] studied the ultrasonic treatment process with and without controlling temperature and showed that other phenomena in addition to temperature also reduced viscosity as a result of ultrasonic treatment.

Moreover, ultrasonic treatment had been successful in field scale. In 2004, the effect of ultrasonic treatment was studied in the United States. The effectiveness of this method was evaluated by measuring the rate of production during sonication, the change in the level of the fluid column, and the bottom hole pressure. This motivational method has increased the production of some wells about ten times, as well as the bottom hole pressure, and the level of the fluid column as a result of the ultrasonic treatment [27]. In 2013, Abramov et al. [2] examined 85 wells with different permeability and porosity ranges. Ultrasonic treatment improved wells' production which permeability and porosity were more than 20 mD and 15% respectively. For wells with lower permeability and porosity, the combination of the ultrasonic method and the chemical method could improve the production of wells more than three times. Therefore, in 2014, Abramov et al. [28] proved the advantages of applying ultrasonic with chemical additive theoretically and operationally. Mullcaove et al. [29] reviewed more than 100 wells which were stimulated by ultrasonic treatment between 2010 and 2012 and presented tables based on the wells characteristics so that the effectiveness of this method can be examined before the operation Table 2 presents a summary of the efforts undertaken to implementation and development of ultrasonic technology.

Over the past 60 years, extensive studies conducted on ultrasonic treatment, and the results showed that these waves with various mechanisms could treat, improve, and boost production. However, the exact cause of failure and the role of variables have not been determined yet. Among these parameters, we can point out the unknown effects of lithology and rock texture on the efficiency of ultrasonic treatment. In the geosciences, the rock texture is evaluated based on the size, shape, and arrangement of the grains. Moreover, pore structure is also a general term to describe the porosity, pore size, pore size distribution, and pore morphology of the porous media. Therefore, in this research, the effect of the ultrasonic method on the pore structure and intrinsic flow behavior of rock was investigated on different types of carbonate and sandstone samples with different textures. This investigation was done by measuring the absolute permeability and studying the alteration of pore-grain interface. Ultimately, the results

Table 2
A summary of the efforts undertaken to development of ultrasonic technology.

Author (s)	Year	Scope	Wave frequency/Epicenter diameter	Wave intensity	Type of Experiment/Location	References
G. G. Parker and V. T. Stringfield	1950	Earthquake	12 km	–	Florida	[30]
K. V. Steinbrugge, and D. F. Moran	1954	Earthquake	80 km	8–11 (12-pt scale)	Kern County, California	[31]
R. D. Duhon	1964	Experimental	1–5.5 MHz	50 W (Transducer power)	Torpedo sandstone, Oolitic and Shelly limestone	[10]
V. A. Nosov	1965	Experimental	300 kHz	(20–120) * 10^3 W/m^2	Synthetic fluid, polystyrene	[12]
R. D. Duhon and J. M. Campbell	1965	Experimental	45–65 kHz	–	Torpedo sandstone core	[11]
M. Smimova	1968	Earthquake	10–15 km	5–7 (12-pt scale)	Cudermes field, Northeastern Caucasus	[3,32]
H. Fairbanks and W. Chen	1971	Experimental	20 kHz	150 W (Transducer power)	Sandstone core	[33]
H. K. Johnston	1971	Experimental	47 kHz, 880 kHz	80 W, 50 W, (Transducers power)	Synthetic fluid, polymer	[34]
G. I. Voytov et al.	1972	Earthquake	50–300 km	4–7 (12-pt scale)	Different fields in Daghestan and Northern Caucasus Earthquake of May 14, 1970	[35]
B. P. Morris	1974	Field	58 MHz	48 Kw (Tool Power)	Odessa, Texas	[3]
N. V. Cherskiy et al.	1977	Experimental	26.5 kHz	(2–9) * 10^3 W/m^2	–	[13]
S. Gadiev	1977	Experimental	40 Hz–15 kHz	10–40 W (Transducer power)	Core samples	[14]
S. Gadiev	1977	Experimental	30–60 Hz	10^{-1} W/m^2	Core samples	[14]
D. G. Osika	1981	Earthquake	100 km	3–5 (12-pt scale)	Anapa, Northern Caucasus	[3]
V. D. Neretin and V. A. Yudin	1981	Experimental	50–80 kHz	(0.8–1.2) * 10^3 W/m^2	Core samples	[15]
A. V. Sokolov	1981	Experimental	18 kHz	8 * 10^3 W/m^2	Fluid samples	[16]
A. N. Snarskiy	1982	Experimental	9–40 Hz	2 * 10^3	–	[17]
W. L. Medlin and G. L. Zumwalt	1983	Experimental	100 Hz	10^{-4} W/m^2	Sandstone core	[36]
O. L. Kuznetsov and S. A. Efimova	1983	Field	12.5–16.5 kHz	(1.2–5) * 10^3 W/m^2	Western Siberia	[3]
E. M. Simkin and G. P. Lopukhov	1989	Earthquake	30 km	6 (12-pt scale)	Starogrozenenskoye field, Northern Caucasus	[3]
J. S. Ashiepkov	1989	Experimental	30–400 Hz	10^{-4}–10^3 W/m^2	–	[3]
V. P. Dyblenko et al.	1989	Experimental	200 Hz	88 W/m^2	Core sample	[37]
A. B. Pogosyan et al.	1989	Experimental	120 kHz	10^4 W/m^2	Porous media	[18]
O. L. Kuznetsov, and E. M. Simkin	1990	Experimental	1.2 Hz	10^{-3} W/m^2	–	[38]
E. M. Simkin et al.	1990	Field	5–50 kHz	(1–10) * 10^3 W/m^2	Western Siberia	[39]
E. M. Simkin et al.	1991	Experimental	–	7.8 m/s^2 (particle acceleration sound field)	Porous media	[19]
Shaw Resource Services, Inc.	1992	Field	200 Hz–10 kHz	3–5 kW	Ventura County California; Bakersfield California	[3]
D. L. Galloway	1993	Earthquake	–	–	California aquifers, Landers Earthquake	[40]
A. Venkitaraman et al.	1995	Experimental	10–100 & 20 kHz	20 & 250 W/m^2	Sandstone and limestone cores	[20]
P. M. Roberts et al.	2000	Experimental	10–100 kHz & 20 kHz	100–5700 W/m^2 & 1800 W/m^2	Berea sandstone	[21]
S. A. Shedid	2004	Experimental	10–20 kHz	–	Carbonated core samples	[9]
S. W. Wong et al.	2003	Experimental	20 kHz	200–1500 W	Berea sandstone	[1]
S. W. Wong et al.	2003	Experimental	20 kHz	up to 2000 W	Berea sandstone	[22]
F. Van Der Bas et al.	2004	Experimental	20 kHz	up to 2000 W	Berea sandstone and sand screen	[23]
B. Black	2006	Field	20–35 kHz	30–50 kW/m^2	Klamath falls, Oregan	[27]
T. Hamida and T. Babadagli		Experimental	20 kHz	Up to 250 W/cm^2	Indiana limestone and Berea sandstone cores	[4]
M. Sohrabi and M. Jamiolahmady	2008	Experimental	20 kHz	200 W	Micromodel	[7]
Kh. Naderi and T. Babadagli	2010	Experimental	20–40 kHz	0–84 W/cm^2	Berea sandstone core	[41]
H. Hamidi et al.	2012	Experimental	25–40 kHz (Core) & 20–68 kHz (Micromodel)	1–500 W (Core) & 50–500 W (Micromodel)	Berea sandstone and micromodel	[25]
E. Mohammadian et al.	2013	Experimental	40 kHz	100–500 W	Synthetic quartz and sandstone core	[42]
B. Keshavarzi et al.	2013	Modeling	22 kHz	Nominal output power 1000 W	–	[26]
V. O. Abramov et al.	2013	Field	25 kHz	5–10 kW	Western Siberia, Samatlor oil field	[2]
H. Hamidi et al.	2014	Experimental	25 and 68 kHz	100–250 – 500 W	Capillary tube	[8]
M. Mullakaev et al.	2015	Experimental	24.3 kHz	4 kW	Steel batch reactor	[43]
M. Mullakaev et al.	2015	Field	13–26 kHz	2–10 kW	Western Siberia, Samara Region; Utah in the Green River Formation	[29]
V. O. Abramov et al.	2016	Field	18 kHz	10 kW	West Siberia	[44]
J. Tan	2016	Field	10–35 kHz	0–100 kW	Daqing oil field	[45]
A. Khorram et al.	2017	Modeling	25 kHz	–	–	[46]
M. Mullakaev et al.	2017	Field	15.5–17 kHz	1.4–1.6 kW	Samotlor oil field in Western Siberia	[47,48]
H. Hamidi et al.	2017	Experimental	40 kHz	500 W	Cylindrical sand pack	[49]
R. Rezaei Dehshibi et al.	2018	Experimental	30 kHz	100 W	Micro model	[24]
A. Agi et al.	2018	Experimental	40 kHz	500 W	Micromodel	[50]

Table 3
Characteristics of rock samples.

Type	No.	Length (cm)	Diameter (cm)	Porosity (%)	Texture
Indiana limestone	1	4.65	3.85	15.65	Crystalline
	2	4.67		15.46	
	3	4.88		15.32	
Oolitic limestone	1	4.83	3.85	19.63	Skeletal
	2	4.8		19.76	
	3	4.805		19.99	
Gray Dolomite	1	4.78	3.77	13.02	Crystalline
	2	4.89		12.12	
	3	4.92		11.99	
Berea sandstone	1	4.85	3.83	19.93	Clastic
	2	4.81		20.30	
	3	4.76		20.64	
Gray Sister Berea sandstone	1	4.74	3.83	21.27	Clastic
	2	4.84		21.00	
	3	4.85		20.16	

were evaluated to determine whether the ultrasonic treatment is considered as a suitable method for selected well or not.

2. Materials

In this study, five rock samples including Indiana limestone, Oolitic limestone, Gray Dolomite, Berea sandstone, Gray Sister Berea sandstone were used. Three samples of each type of rock were prepared for tests to check the repeatability of the results. The dimensions, porosity, and texture of samples are measured and reported in Table 3.

The distilled water was used to saturate carbonate samples and the distilled water containing 2% potassium chloride was used in sandstone samples to inhibit clay swelling because the clay in sandstone samples swells in the presence of distilled water.

3. Experimental setup and procedure

3.1. Thin sections

To evaluate and analysis the texture of different rocks some thin sections have been prepared and photographed which is shown on Fig. 3.

3.2. Core flood apparatus

In this research, a core flooding device and a syringe pump of Petrozema Co. were used for fluid injection to measure absolute permeability. Fig. 1 shows the schematic of the core flooding device. This device has four piston-cylinders which were used to inject the desired fluid. This device is included several pressure gauges to measure pressure at piston-cylinders, the inlet and outlet of the core holder. The hydraulic pump was used to supply the overburden pressure, and the pressure gauge in its path was designed to indicate the overburden pressure during the tests. Back pressure retaining system and a gas cylinder were used to measure high permeable samples, accurately.

3.3. Ultrasonic apparatus

The ultrasonic apparatus of UP-400A manufactured by Mafoghesote Co. was used to conduct the static ultrasonic treatment test. Fig. 2 shows the schematic of the device. The device supplies wave with a constant frequency of 20 kHz and adjustable power between 10 and 400 W. This device can emit the wave continuously or intermittent. Moreover, the duration of radiation and rest pulses during the operating time was adjustable. So, the ultrasonic wave power was adjusted on 300 W to make the different results comparable. Moreover, the authors decided to put the device on intermittent mode (seven seconds on – three seconds off) to test the effectiveness of the process in more economical and beneficial situation against continues mode [50].

3.4. Scanning electron microscope apparatus

The scanning electron microscope (SEM) of TESCAN-Vega 3 which is manufactured in the Czech Republic used in this study. This device is able to take pictures with a large magnification and high quality to investigate the effect of ultrasonic waves on the rock surface.

3.5. Experimental procedure

First, the dried samples were placed in a desiccator for 8 h to evacuate air from samples completely. Then, the desired fluid was added to the samples. The desired fluid was distilled water and brine for the carbonated and sandstone samples, respectively. Then, the samples were immersed in the same saturating fluid cylinder and pressurized at 3000 psi for 2–3 days. In the next step, the absolute permeability of samples was measured using Darcy law by measuring discharge pressures at different injection rates using the core flooding system. The samples were then removed from the core holder and put in the beaker which was full of saturated fluid. In this step, the inlet side of the core sample was allocated in the vicinity (lower than 1 cm) of the ultrasonic transducer. Then, the ultrasonic waves exposed to the samples for 10 min with 7 s of radiation and 3 s of rest. Then, the absolute permeability of the samples was measured with the core flooding system and the aforementioned procedure. Since the confining pressure has a significant effect on the permeability of core samples, the confining pressure for each sample was fixed before and after the ultrasonic treatment to avoid the permeability alteration because of core compaction. In this article, three samples of each type of rock were examined and the confining pressure was defined and adjusted based on the pore pressure which is dictated by a flowing rate for each type of rock. As it was mentioned, the repeatability and reproducibility of the results of each type of rocks were checked by examining three samples of them in the similar condition.

The appearance of the samples before and after the ultrasonic treatment was investigated and changes in the pore structure were examined by the scanning electron microscopy images. The effect was studied qualitatively by investigating the changes of the same location of rock surface using SEM images and quantitatively by measuring the permeability changes using core flood system. For this purpose, the effect of ultrasonic treatment was examined by considering two viewpoints including without pre-clearing and with pre-clearing the samples. In the first case, the rock surface was photographed, introduced to 20 kHz and 300 w ultrasonic for ten minutes with alternatively on/off condition (Seven seconds on, three seconds off) and then photographed again. In the second condition, before starting the aforementioned procedure the sample was introduced to ultrasonic for just three minutes to eliminate the preliminary effects of ultrasonic and validate the additional noteworthy effects of ultrasonic.

4. Results and discussion

4.1. Petrographic analysis

Indiana limestone has a crystalline texture. The composition of the Indiana carbonate sample includes bioclasts (foraminiferous fossils), ooids with micrity mud core, oncoid, algae, and intraclasts. Ooids and oncoids are elliptical and well rounded. The presence of ooids in the rock represents energetic sedimentary environments such as tidal environments. The cement in this sample is sparite (coarse calcite crystals). Sparitic cement shows the high turbulence and energy of sedimentation environment. According to the Folk and Dunham as rock classification methods, the Indiana limestone was grouped in

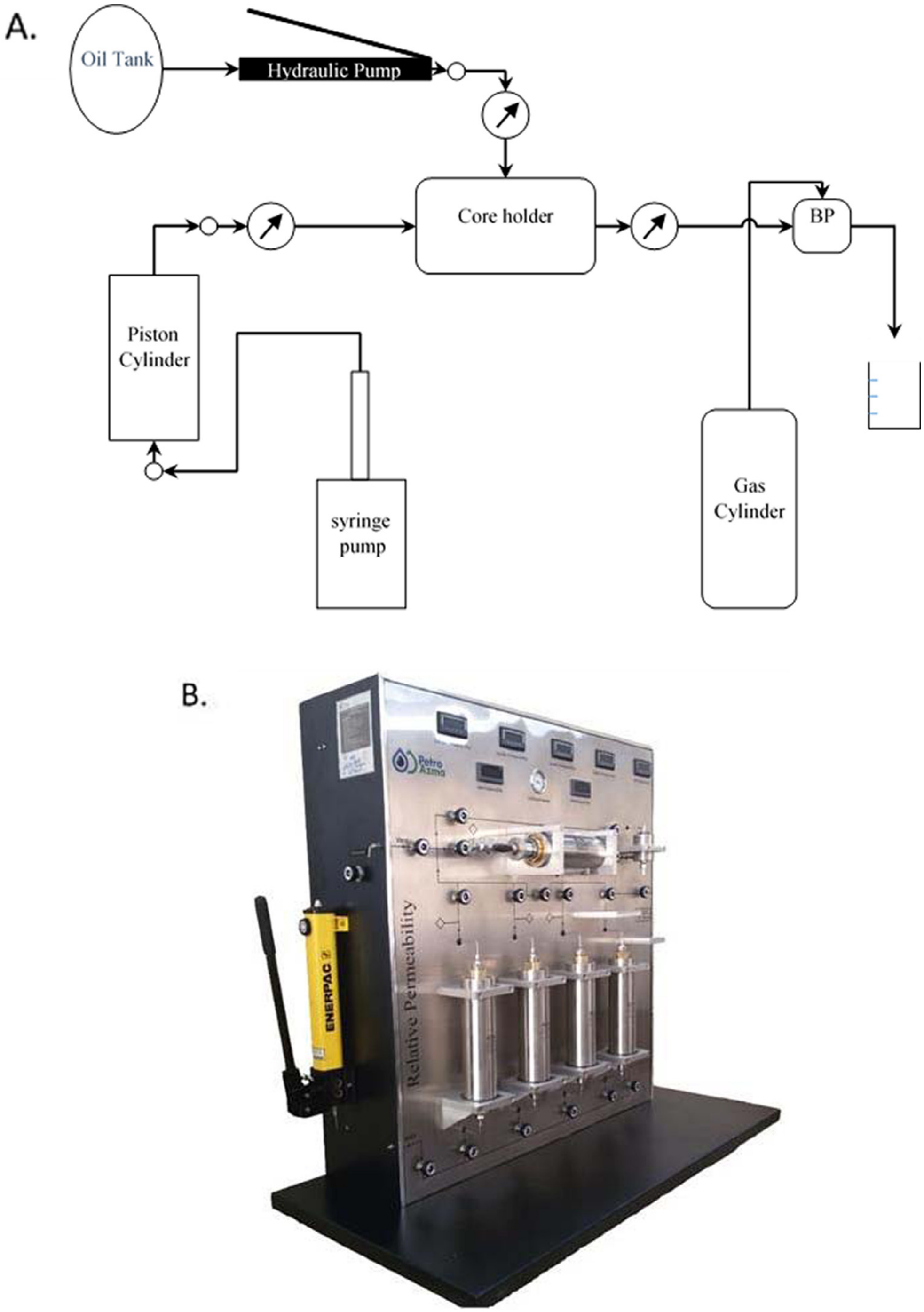

Fig. 1. A) Schematic of the core flooding device. B) Core flooding device.

oobiosparite, oolitic bioclastic grainstone, respectively (Fig. 3-A).

The composition of the Oolitic limestone consists of bioclasts (foraminiferous fossils), gastropod, pelecypod brachiopod, ooids with muddy micrity core, peloid, and algae. The cement in this sample is sparite (coarse calcite and dolomite) while many limestones have a micrity matrix (fine-grained calcite crystals). In this sample, the matrix has been altered to a coarsely grained crystal as a result of the neomorphism process; and the remaining effect of this process is called dismicrite. Micrite is created in many sedimentary environments from tidal plains to shallow lagoons, and deep sea basins. However, by increasing energy and turbulence of sedimentary environment, the coarse spity cement is placed instead of micrite. The texture of this sample is skeletal and based on the Folk and Dunham classification, the Oolitic limestone grouped in biosparite and bioclastic grainstone, respectively (Fig. 3-B).

Gray Dolomite is mainly composed of dolomitic rhombohedron crystals; hence it has a crystalline texture. The cement of this sample is carbonate (calcite and dolomite). Due to the high percentage of dolomite crystals, this sample can be named dolostone (Fig. 3-C).

Sandstones are mainly composed of single crystalline quartz grains with a few recrystallization signs, polycrystalline quartz grains with bordering boundaries, and mica blades (muscovite and biotite) with slight bending as the result of pressure. Moreover, they contain chert rock fragments, dark minerals (mainly iron oxide), potassium feldspar grains that are transformed to kaolinitic or sericitic, and some carbonate grains. These samples have a weak to good sorting and semi-

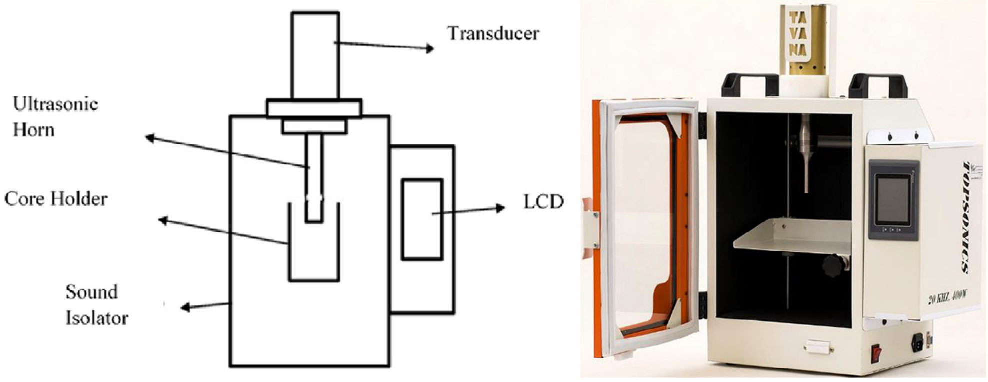

Fig. 2. Schematic of the ultrasonic device.

circular to angular grains.

In Berea sandstone, the cement is mainly composed of iron oxide, silica, and a little carbonated. Based on the Pettijohn classification, the sample is considered within the range of subarkose to lithic arkose. This sandstone is not wackstone because of the presence of much void space between the grains (Fig. 3-D).

In the Gray Sister Berea sandstone, the cement is mainly composed of silica and a little carbonate. Based on the Pettijohn classification, this sample is considered in the range of subarkose. Due to lack of mud in the void space between matrixes, this sample is not considered as wackstone, but as clastic (Fig. 3-E).

4.2. Dynamic test

The permeability of Indiana limestone before and after exposing samples to ultrasonic waves is plotted in Fig. 4. In this test, the overburden pressure was set at 500 psi. The result showed that the absolute permeability of samples increased slightly as a result of the ultrasonic treatment. By considering the initial absolute permeability of the

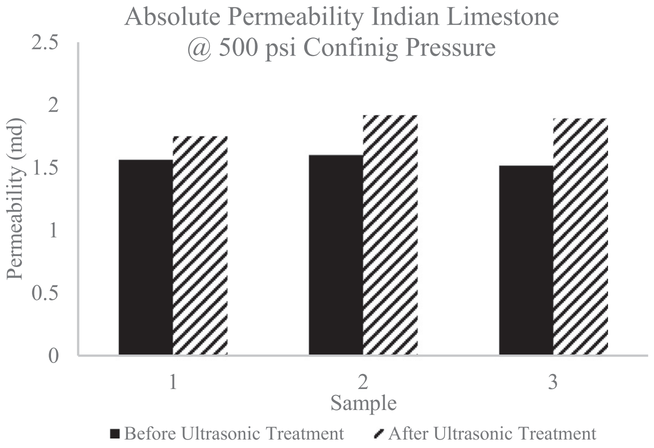

Fig. 4. Absolute permeability alteration of Indiana limestone as a result of Ultrasonic treatment.

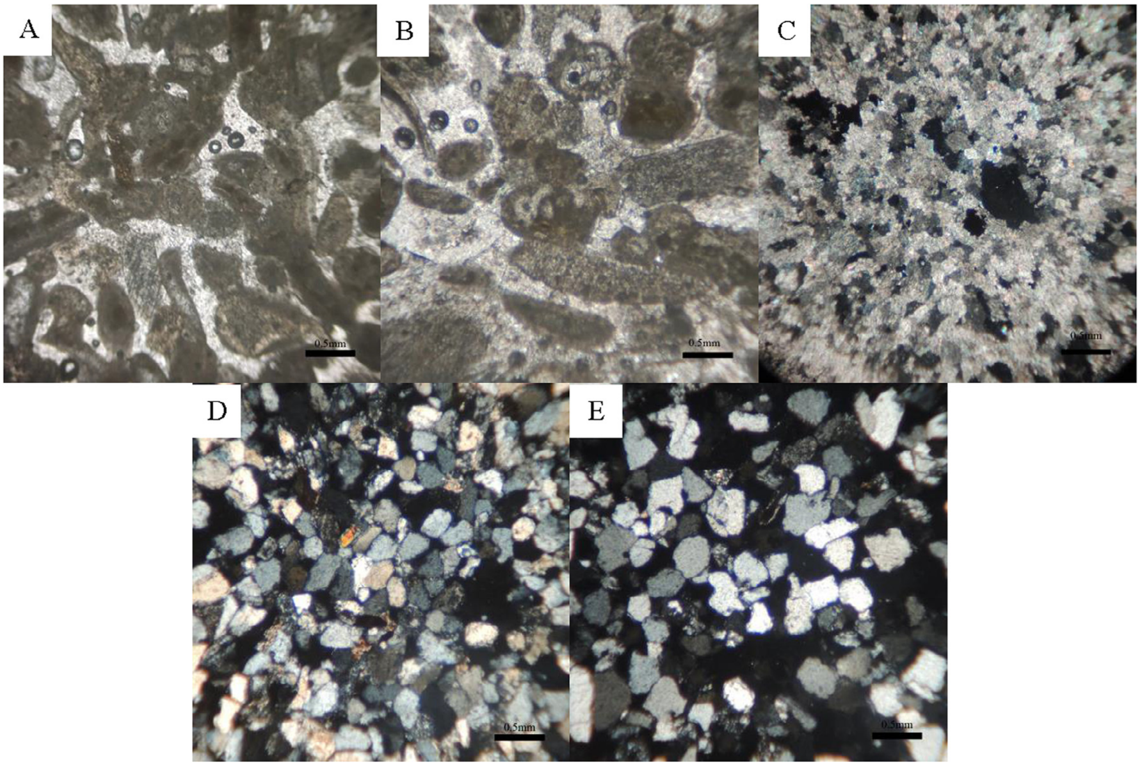

Fig. 3. Thin sections of different type of rock. A) Indiana limestone B) Oolitic limestone C) Gray Dolomite D) Berea sandstone E) Sister Gray Berea sandstone.

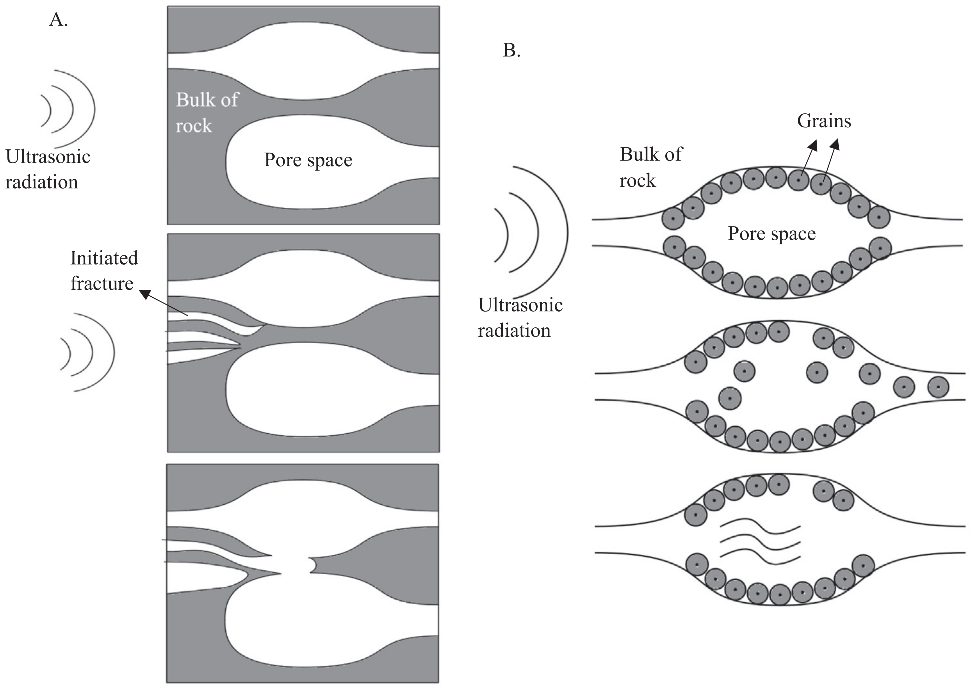

Fig. 5. Schematic of the expected ultrasonic effect on Limestone, A) increased pore connectivity due to a micro-fracture formation, B) increased flow cross section due to breakdown and removal of the pore throats.

samples, it can be concluded that the treatment method improved permeability at a relatively significant level, which is a promising result. This increment was measured to be 12.18%, 20.00%, and 25.17% for sample 1, 2, and 3 of this type of rock, respectively The permeability of all three samples increased and verified the obtained results. Based on the results, it can be concluded that the ultrasonic effect on this type of rock is repeatable and ascending.

In Fig. 6, the permeability is plotted before and after exposing the Oolitic limestone samples to ultrasonic waves. Since the permeability of these samples increased sharply, the vertical axis of Fig. 6 is plotted logarithmically. In this test, the overburden pressure was set at 250 psi. The result showed that the absolute permeability of samples at least increased more than 30 times as a result of the ultrasonic treatment. Since the incremental trend and intensity of all samples were similar to each other, it could be concluded that the observed trend in this type of rock is repeatable.

The absolute permeability of both limestone samples as result of their fragile texture increased by exposing them to the ultrasonic waves. It is concluded that the ultrasonic waves may change the limestones pore structure through two mechanisms; through the expansion of the micro-fractures network [9,51–55], and/or due to the breakdown and removal of the grain [20]. (Fig. 5) Due to the existence of fossil particles in the Oolitic samples, their texture is more fragile. Hence the micro-fractures are expanded more efficiently in this type of rock. Moreover, because of the high initial permeability and porosity, the detached particles were extracted easily, and the dynamic parameter of these samples such as aspect ratio improved as well as static characteristics of these samples such as storage capacity. In conclusion, the absolute permeability of Oolitic limestone samples increased more significantly with compared to Indiana limestone.

As a result of the fossil and bioclasts presence in Oolitic limestone, the heterogeneity in this sample is higher compared to that in the Indiana sample. Moreover, the grain compaction of Oolitic limestone is less than Indiana limestone. Therefore, since the Oolitic limestone has a weak texture because of the skeletal texture with a comparison to the crystalline texture of Indiana samples, the mechanical effects of the ultrasound treatment will be more intense on the Oolitic samples, and the permeability increases further.

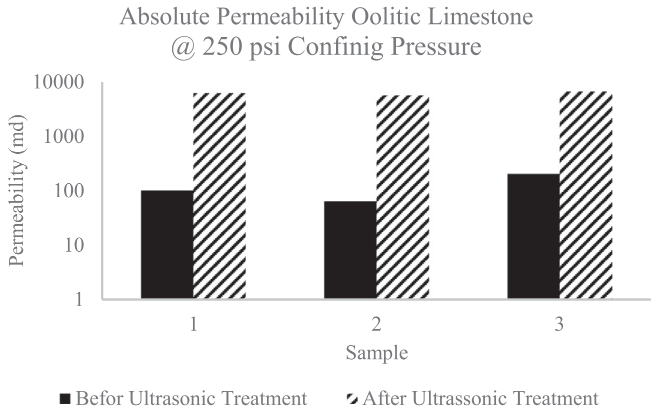

Fig. 6. Absolute permeability alteration of Oolitic limestone as a result of Ultrasonic treatment.

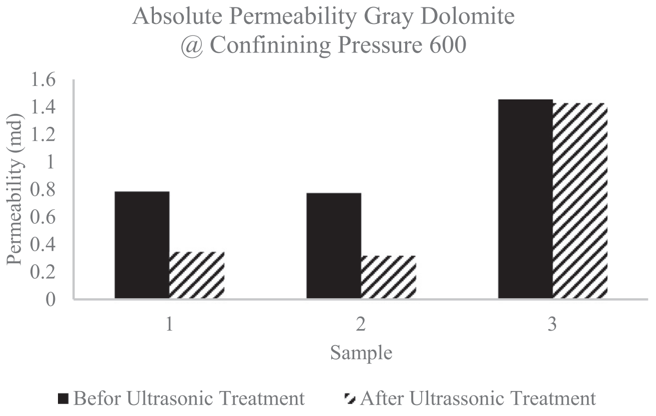

Fig. 7. Absolute permeability alteration of Gray Dolomite as a result of Ultrasonic treatment.

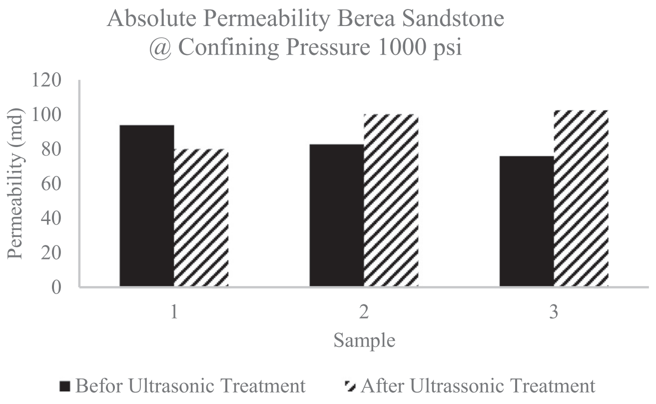

Fig. 8. Absolute permeability alteration of Berea sandstone as a result of Ultrasonic treatment.

In the Gray Dolomite samples tests, the overburden pressure was set to 600 psi. According to Fig. 7, the ultrasonic waves showed a destructive effect and reduced the permeability of all three samples. Due to the low initial permeability against high porosity of the samples, the effects of heterogeneity in these Dolomite samples were well observed. As a result, a considerable heterogeneity prevented the formation of a good network between the pores even by the effect of micro-fracture initiation and particles excavation on these samples as a result of the ultrasonic stimulation. Since the dolomite texture was crystalline, dense, and heterogeneous, the physical effects of ultrasonic waves' mechanisms reduced. For instance, the detached particles might partially or completely close the pore throat and reduce the permeability, and due to the more robust texture of dolomite samples than the limestone samples, the micro-fracture might not be able to initiate or improve the connectivity between pore structures.

In the Berea sandstone samples tests, the overburden pressure was set to 1000 psi. According to Fig. 8, the effectiveness of the ultrasonic waves on the permeability of these samples was controversial. In sample 2 and 3, the permeability increased 17.23 mD and 26.45 mD, which was not related to their initial condition, and in one sample the permeability reduced 18.87 mD as result of ultrasonic waves. The probability of fine migration of small particles was studied by measuring the permeability of the sample in two different directions, and it was concluded that the ultrasonic treatment would increase the fine migration problem in this type of rock.

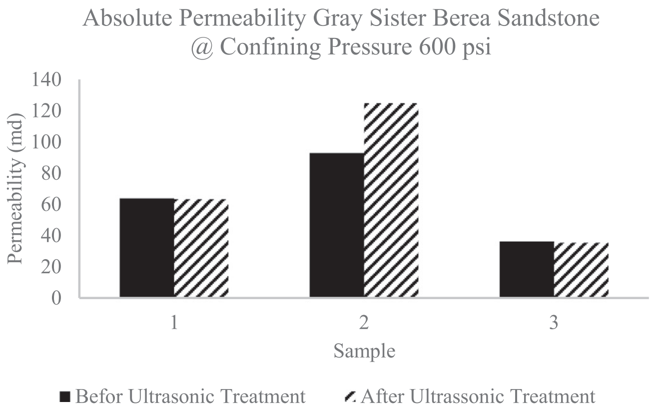

Fig. 9. Absolute permeability alteration of Gray Sister Berea sandstone as a result of Ultrasonic treatment.

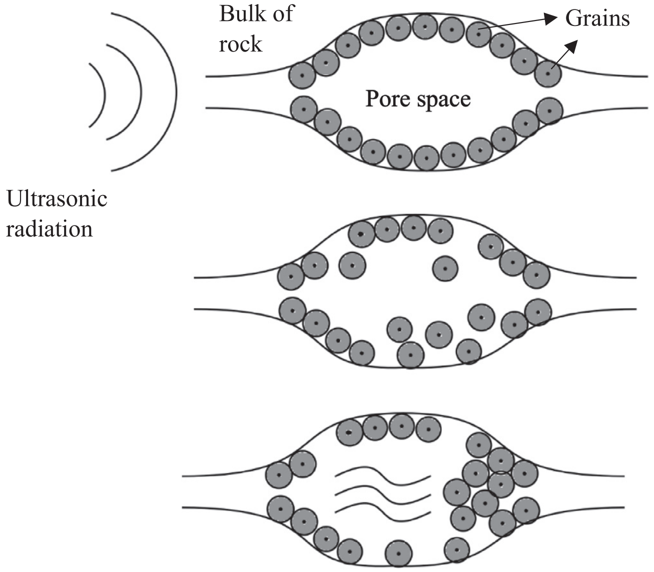

Fig. 10. Schematic of the expected ultrasonic effect on sandstone, reduced flow cross section due to a closure of the pore throats.

In the Gray Sister Berea sandstone samples tests, the overburden pressure was set to 600 psi. According to Fig. 9, one sample showed the incremental effect as a result of the ultrasonic treatment while there was not a significant change in the two other samples. The possibility of fine migration studied, the sample in which the ultrasonic could increase permeability showed the fine migration while the two other samples did not show a significant effect of fine migration.

The sandstone samples results showed the ultrasonic waves worsen fine migration problem in this type of rock. (Fig. 10) Ultrasonic will not be suggested as a suitable stimulation method of sandstones due to the unstable results. Also, due to the presence of litic elements in the Berea sandstone, the possibility of fine migration increases in this kind of sandstone compared to Gray Sister Berea sandstone. Moreover, the amount of silica in Gray Sister Berea sandstone cement was higher than Berea sandstone that might be caused by the firmer network and prevents fine migration. Finally, the percentage of improvement or permeability reduction for each sample is given in Table 4.

The results of the SEM images for the Dolomite sample before and after ultrasonic stimulation are shown in Fig. 11. The image before exposing a sample to the ultrasonic waves is shown in Fig. 11-A and the image after exposing the sample to the ultrasonic waves for 10 min is displayed in Fig. 11-B. This image was taken on a micrometer scale with a magnification of 300 times. Initially, the surface of the stone was

Table 4
Results and modification percentage of absolute permeability of different samples.

Type	No.	Absolute permeability Before treatment (mD)	Absolute permeability After treatment (mD)	Deviation percentage (%)
Indiana limestone	1	1.56	1.75	12.18
	2	1.60	1.92	20.00
	3	1.51	1.89	25.17
Oolitic limestone	1	101.89	6238.45	6022.73
	2	64.85	5658.21	8625.07
	3	205.45	6614.19	3119.37
Gray Dolomite	1	0.79	0.35	−55.92
	2	0.78	0.32	−58.84
	3	1.45	1.43	−1.86
Berea sandstone	1	93.83	79.96	−14.78
	2	82.76	99.99	20.82
	3	75.88	102.33	34.86
Gray Sister Berea sandstone	1	63.84	63.31	−0.83
	2	92.95	124.71	34.17
	3	36.37	35.45	−2.53

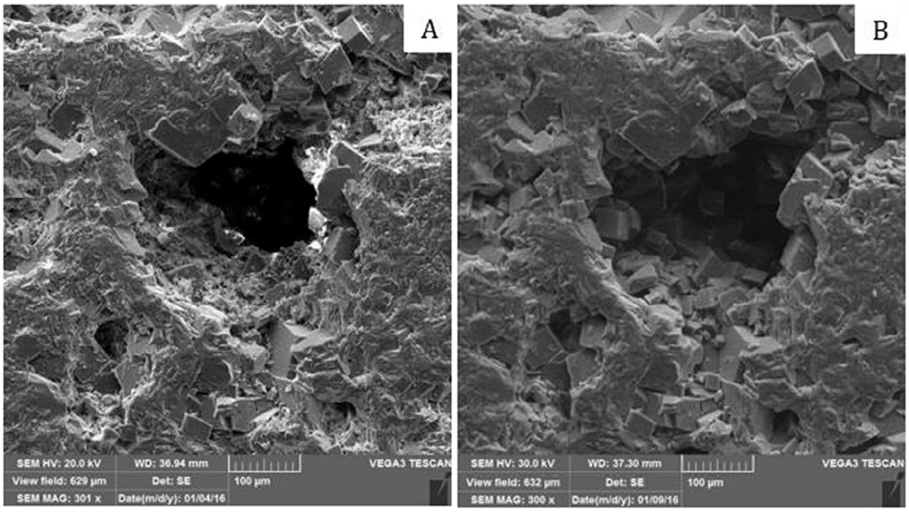

Fig. 11. SEM images of Dolomite sample which show ultrasonic purification effect, A) Before ultrasonic treatment B) After ultrasonic treatment.

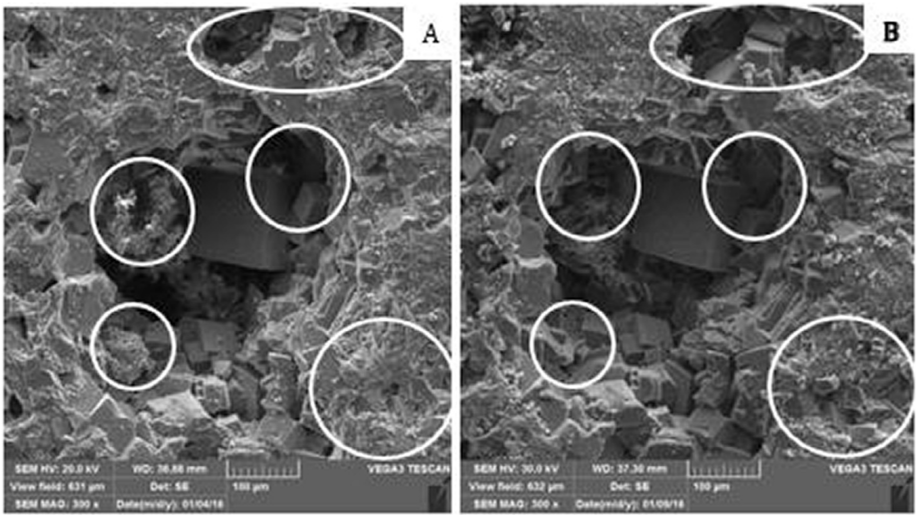

Fig. 12. SEM images of Dolomite sample which show ultrasonic physical and purification effect, A(Before ultrasonic treatment B(After ultrasonic treatment.

covered with contaminated particles (Fig. 11-A). However, due to the exposing the sample to the ultrasonic waves, some particles were degraded which showed the physical effect of the ultrasonic treatment such as cleaning and detaching. To verify the proposed mechanisms for ultrasonic, another Dolomite sample was examined. At this stage, the sample was exposed to ultrasonic waves before the initial imaging for 3 min, so that the ultrasonic cleaning effect was eliminated to examine the effect of detaching particles. The image of the sample before and after stimulation with the same specification of the previous image is shown in Fig. 12. After the sample was exposed to ultrasound waves for 10 min, it was shown that ultrasonic waves, in addition to cleaning, can show other effects. By comparing the same point which is identified with the same sign in Fig. 12-A and B, the different phenomena such as fracture initiation (Elliptical sing), closure of openings with fine particles, detachment and removal of unstable particles (Circular signs) are observed. Each of these processes can dramatically change the permeability of the sample.

The Dolomite sample has a crystalline and compact texture, and the sandstone texture is granular. As a result, the effect of particle detachment in sandstones is several times greater than the crystalline dolomite, which is verified by the core flooding results. Also, because of the fossil existence and more fragility in the limestone samples, the micro-fracture initiation would be more likely with compared to the compact Dolomite samples as verified by the core flooding results.

5. Conclusions

The investigation of the ultrasonic effect on carbonate rocks showed significant and repeatable positive results, due to the creation of a wider fracture network, significant changes in aspect ratio and changes in the capacity storage, which was proportional to the initial situation of these samples. In Dolomite samples, due to heterogeneity and the crystalline and compact texture, ultrasonic waves were not able to effectively expand the fracture network and increase permeability. It means that if the micro-fractures initiate it would not be effective due to not existence good intrinsic connectivity as a result of high heterogeneity on dolomite samples. Also, based on the sandstone texture study, the appearance of sand and litic as a loose element in this kind of rock in comparison with the other samples makes the fine migration hypothesis stronger for this type of rock. Therefore, the ultrasonic treatment worsens the fine migration problems, which could result in the closure of the pore throat and reduces permeability. In the following, the results of comparing the absolute permeability were verified according to the SEM image results before and after exposing the sample to the ultrasonic treatment. For instance, based on the SEM images in Dolomite sample, even if the ultrasonic waves could detach particles or initiate a fracture, it would not be effective because of high heterogeneity. Moreover, in the limestone, the ultrasonic effect would be stronger as a result of its fragile texture.

In this article, the effect of ultrasonic on a rock has been studied from a new viewpoint for the very first time. This idea has strong potential to follow for instance the effectiveness of combination chemical fluid with ultrasonic during the initiation of fracture and particle detachment might be interesting, the optimum condition of sonication for each type of rocks should be identified and, the possibility of proposed ultrasonic effect should be verified in presence of crude oil or multiphase. In addition, the mechanisms which have been stated in this article should be verified by the high technology devices.

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