Inorganic plugs removal using ultrasonic waves

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Abstract. It is essential to recover the lost productivity caused by formation damage in the proximity of the wellbore during different well operations. In comparison to conventionally used methods, the efficiency, reliability, environment friendly, and simple and convenient technique of ultrasonic waves make it more attractive in petroleum industries. In current study, ultrasonic waves were applied to mitigate the formation damage caused by deposition of calcium carbonate (CaCO3) nearby well bore. Results showed that 100 minutes exposure time could efficiently recover 38.1% of original productivity but further increase in irradiation time (120mins) would decrease the recovery to 37.1%. This aberration can be attributed to the particle-bridge formation formed by larger particles at later stages and tendency of acoustic wave to push back the fluid flow. Moreover, ultrasonic waves transducer#2 (Frequency 20KHz and Power 1000W) could recovery maximum recovery of 36.3%, however, high frequency transducer was not effective in this recovery. This inorganic removal can be attributed to the cavitation and thermal energy produced through three different ways including cavitation, boundary friction and transformation upon hitting the medium.

1. Introduction

Oil industries invest significant amount of total revenue to mitigate formation damage which happens during different well operations. Formation damage can be defined as the descent in initial productivity loss of the reservoir rock nearby wellbore [1,2]. This undesirable phenomenon can be owing to either pore obstruction, inorganic scaling deposition or others [1,2]. However, formation is mainly caused by inorganic plugs. Since CaCO3 as the main culprit be formed by mixing two different kinds of water sources. Where one source has calcium ions abundance while other riches in carbonate at the basic medium. In addition, it can also be formed by either change in reservoir pressure or pH value of the production fluid [3,4] as shown by the reaction (1).

\[ \text{Ca}^2+(aq) + 2\text{HCO}_3^-(aq) \rightarrow \text{CaCO}_3(s) + \text{H}_2\text{O} + \text{CO}_2 \]  \hspace{1cm} (1)

In order to prevent expensive and complex treatment, it’s wise to prevent inorganic deposition as first line defense. In spite of preventive measures, inorganic scale usually develops and damages the initial permeability then chemical treatment, thermal treatment and hydraulic fracturing are usually suggest to mitigate the damages. However, extensive laboratory work and tendency of bottom hole assemblies’ deterioration in conventionally applied technique make ultrasonic aided recovery more attractive [5,6].

This current study studies the application of efficient, reliable, relatively adaptive, environment friendly and convenient technique termed as ultrasonic wave technique for inorganic plugs removal. In addition,
optimum frequency and power along with suitable irradiation time were investigated for effective and promising results. The valid reasons behind optimum parameters were also vividly enlightened in this study.

2. Materials and methods

2.1. Materials and brine Preparations

Brine solution was prepared by dissolving NaCl, CaCl₂ and MgCl₂.6H₂O in corresponding proportion of 7, 0.6 and 0.4. Whereas, aqueous solution of Na₂CO₃ (200,000mg/l) and CaCl₂ (210,000mg/l) were separately prepared to acquire exact 1:1 stoichiometric ratio. Analytical-grade chemical reagents were obtained from Sinopharm Chemical Reagent Co., Ltd and was used as received. Artificial core samples were obtained from Haian Petroleum Research Instrument Co., Ltd and their characteristics are shown in Table 1.

Table 1 Characteristics of core samples.

| Constitutes | Permeability (μm²) | Length (cm) | Diameter (cm) | Porosity (%) | Pore Volume (cm³) | ρ (g/cm³) |
|-------------|--------------------|-------------|---------------|--------------|------------------|------------|
| Quartz      | 3×10⁻³             | 6.0         | 2.5           | 20           | 5.88             |            |
|             | 8×10⁻³             | 6.0         | 2.5           | 22           | 6.47             | 1.67       |
|             | 15×10⁻³            | 6.0         | 2.5           | 24           | 7.06             |            |

2.2 Methods

2.2.1. Critical velocity and threshold salinity determination. Core samples were initially vacuumed and brine solution (80,000mg/l) was pumped through it by maintaining annular pressure at least 3MPa greater than the inlet pressure. Afterwards, lines were primed with minimum flow velocity (<1ml/min) using vent valve. Subsequently, flooding velocity was increased gradually to 5ml/min through 0.5ml/min incremental step.

Different brine solutions with the concentration of 40,000mg/l, 30,000mg/l, 20,000mg/l, 10,000mg/l and 5,000mg/l were termed as C1, C2, C3, C4 and C5. Firstly, core sample was flooded with 0.8times of critical velocity of C1 solution and reading was noted down when flow became constant. Subsequently, C2 brine solution of 10-15 times the pore volume was injected through the core sample at 0.1ml/min - 0.2ml/min velocity and was remained in the same brine solution for 12hours. Afterward, C3 and C4 were injected through the core in similar manner prior to pumping the identical volume and flowrate of distilled water.

2.2.2. Dynamic experiment. Before saturating the core samples for 8hours, dry weight of core samples and gas permeabilities were measured to be 30×10⁻³μm², 80×10⁻³μm² and 150×10⁻³μm². Experimental setup for ultrasonic aided plug removal as shown in figure 1. Original permeability (K₀) of all three sets of core samples were measured by injecting brine (40,000mg/l) at 0.8times rate of the critical velocity (0.8*2ml/min).

In order to plugs the core sample, Na₂CO₃ (2*pore volume) was pumped at 0.8times the critical velocity to prevent channeling effect. In next stage, core samples were remained in CaCl₂ for 2hours by injecting CaCl₂ solution for complete synthesis of CaCO₃ as shown in following reaction (2). Similar procedure was repeated for other two sets of core sample. Afterwards, damaged permeability (Kd) of the core sample was measured.

\[
CaCl₂ + Na₂CO₃ → CaCO₃ + 2NaCl \quad (2)
\]

In next step, damaged core sample was irradiated for 6minutes and treated permeability (Kt) was measured. Eventually, percentage permeability recovery was calculated by applying equation (3) for the
selection of best-performing transducer.

\[ \frac{(K_t - K_d)}{K_o} \times 100\% \] (3)

Thereafter, optimum exposure time was determined using transducer #2 for variant time spans ranging from 60min to 120min and treated permeability (Kt) was measured.

3. Results and Discussion

3.1 Critical velocity and threshold salinity of the core

Critical flow velocity and threshold salinity were indispensably measured before recovering the damaged core samples. Critical velocities were investigated to be 2ml/min for Core 3-12 and each 2.5ml/min for Core 8-38 and Core 15-32. Whereas, threshold salinity for Core 3-11, Core 8-37 and Core 15-31 with the gas permeability of $30 \times 10^{-3} \mu m^2$, $80 \times 10^{-3} \mu m^2$ and $150 \times 10^{-3} \mu m^2$ were measured to be 15,000mg/l and 10,000mg/l respectively.

3.2 Dynamic experiment of ultrasonic waves for the inorganic plug mitigation

3.2.1 Frequency and power optimization. Acoustic wave with appropriate frequency and power has undoubtable potential to mitigate formation damaged caused by inorganic plugs near the wellbore proximity. For this purpose, six core samples with $30 \times 10^{-3} \mu m^2$ gas permeability were exposed to six different kinds of transducers with variant frequency and power in order to choose the optimum one as depicted in Table 2. First three transducers #1, #2 and #3 with the same power of 1000W but different corresponding frequencies of 18KHz, 20KHz and 25KHz irradiated the core samples. Consequently, #2 transducer recovered 34.1% of the natural permeability and led among the six given transducers while 31.1% and 33.3% proportions of the original permeability were acquired using #1 and #3 transducers respectively. The principal reason of relatively less recovery of the former is due to falling of 18KHz in the audible range which led to transformation in undesirable sound energy. While in the latter case, relatively large gap between core sample and transducer resulted into inefficient transformation of acoustic energy into heat and other unwanted forms which can adversely influence the effect of ultrasonic waves.

Afterward, same power but different frequencies of 30KHz and 40KHz were applied using #4 and #5 transducers and their recoveries’ proportion were witnessed to be 9.8% and 8.6% respectively. However, #6 (10.9%) had high potential to remove inorganic plugs in comparison to #4 and #5 owing to its high power.

![Figure 1. Experimental schematic of ultrasonic plug removal.](image-url)
Likewise, comparable results were obtained upon performing identical experiment on remaining two kinds of core samples with $80 \times 10^{-3} \mu m^2$ and $150 \times 10^{-3} \mu m^2$ gas permeabilities as depicted in Table 2 and Table 3. As far as Table 3 is concern, the proportion of damaged permeability recoveries were 31.7%, 36.3%, 32.4%, 9.7%, 7.6% and 10.9% by the application of #1, #2, #3, #4, #5 and #6 transducers. Considering Table 4, transducer #2 (20 KHz and 1000W) and #5 (40KHz and 60W) produced maximum and minimum recovery of 35.7% and 9.9% respectively. While #6 having maximum frequency (50KHz) and power (200W) improved only 12.9% of the original permeability. In addition, Transducer #1 and #3 with the same power (1000W) and the respective different frequencies of 18KHz and 25KHz recovered 31.5% and 34.4% proportions of the natural permeability of the core samples. In spite of identical power, acoustic wave with suitable frequency (20KHz) likely to mitigated the damaged core sample owing to matching of acoustic frequency with natural frequency of the particles and led to amplitude enhancement. Consequently, pore structure tried to follow the same pattern of the incident wave which resulted into peristaltic transport of the resident fluid when trough and crest of the two adjacent layers would coincide. Damaged permeability recovery can be attributed to drain down of loosely suspended core constituents due to occurrence of high local pressure caused by cavitation during wave propagation.

Cavitation mechanism can be referred to the bubble formation in low pressure zone due to existence of tiny nuclei containing undissolved gas [7,8]. Subsequently, prior to imploding of bubble with 5075K±156K temperature [9] and 1000atm pressure [9], it grows to certain size due to energy absorption. Furthermore, cavitation is broken up into two categories on the basis of cavity’s life. In transient cavitation, bubble can survive less than one acoustic cycle, however, those bubbles which can exist beyond one acoustic cycle come under the heading of stable cavitation. Transient cavitation controls cavitation intensity which can be produced by keeping driving acoustic frequency lower than the natural frequency [10]. The produced shocking wave radially propagates and causes improvement in the recovery of damaged permeability which can further be influenced by fluid nature and site nucleation as shown in figure 2. From the above results, in a nutshell, high power of ultrasonic wave transducer likely to improve lost natural productivity due to thermal energy generation via three different means. Heat energy is probably to produce when acoustic wave transforms upon hitting the targeted porous media. Another enormous source of heat is the implosion of bubbles during cavitation process and the third reason could be the existence of boundary friction. In addition, ultrasonic wave is generally proportional to the boundary friction and absorption. Consequently, high frequency tends to absorb more and causes greater boundary friction. Likewise, sound wave intensity is directly related to the heat energy generation and vicious of the cavitation [7].
Figure 2. Cavitation Process.

Table 2. Experiment results of ultrasonic-removed inorganic scale with cores of air permeability around $30 \times 10^{-3} \mu m^2$.

| Core # | Transducer | Frequency (KHz) | Power (W) | $K_o$ ($10^{-3} \mu m^2$) | $K_d$ ($10^{-3} \mu m^2$) | $K_t$ ($10^{-3} \mu m^2$) | ($K_t - K_d$)/$K_o$ (%) |
|--------|------------|----------------|-----------|-----------------|----------------|----------------|--------------------------|
| 3-14   | 1          | 18             | 1000      | 20.77           | 11.91          | 18.37          | 31.1                     |
| 3-33   | 2          | 20             | 1000      | 21.10           | 9.98           | 17.17          | 34.1                     |
| 3-34   | 3          | 25             | 1000      | 20.03           | 11.49          | 18.15          | 33.3                     |
| 3-30   | 4          | 30             | 60        | 19.84           | 10.83          | 12.78          | 9.8                      |
| 3-32   | 5          | 40             | 60        | 21.60           | 10.74          | 12.61          | 8.6                      |
| 3-29   | 6          | 50             | 200       | 21.03           | 10.15          | 12.31          | 10.2                     |

Table 3. Experiment results of ultrasonic-removed inorganic scale with cores of air permeability around $80 \times 10^{-3} \mu m^2$.

| Core # | Transducer | Frequency (KHz) | Power (W) | $K_o$ ($10^{-3} \mu m^2$) | $K_d$ ($10^{-3} \mu m^2$) | $K_t$ ($10^{-3} \mu m^2$) | ($K_t - K_d$)/$K_o$ (%) |
|--------|------------|----------------|-----------|-----------------|----------------|----------------|--------------------------|
| 8-143  | 1          | 18             | 1000      | 62.37           | 36.28          | 56.07          | 31.7                     |
| 8-26   | 2          | 20             | 1000      | 56.93           | 32.38          | 53.02          | 36.3                     |
| 8-106  | 3          | 25             | 1000      | 61.82           | 32.52          | 52.57          | 32.4                     |
| 8-144  | 4          | 30             | 60        | 66.71           | 35.49          | 41.95          | 9.7                      |
| 8-146  | 5          | 40             | 60        | 59.20           | 35.22          | 39.75          | 7.6                      |
| 8-10   | 6          | 50             | 200       | 64.42           | 34.44          | 41.48          | 10.9                     |

Table 4. Experiment results of ultrasonic-removed inorganic scale with cores of air permeability around $150 \times 10^{-3} \mu m^2$.

| Core # | Transducer | Frequency (KHz) | Power (W) | $K_o$ ($10^{-3} \mu m^2$) | $K_d$ ($10^{-3} \mu m^2$) | $K_t$ ($10^{-3} \mu m^2$) | ($K_t - K_d$)/$K_o$ (%) |
|--------|------------|----------------|-----------|-----------------|----------------|----------------|--------------------------|
| 15-80  | 1          | 18             | 1000      | 108.16          | 60.76          | 94.88          | 31.5                     |
| 15-37  | 2          | 20             | 1000      | 111.81          | 55.30          | 97.04          | 35.7                     |
3.2.2 Irradiation Time.

Prior to measuring the optimum ultrasonic waves’ irradiation time, best-performing transducer #2 with 20KHz frequency and 1000W power was already determined. Table 5 and Table 6 illustrate permeability recovery proportions using transducer#2 when core samples were irradiated for 60mins, 80mins, 100mins and 120mins. Considering Table 5, 60mins irradiation time to the ultrasonic wave brought 34.1% reduction in the damaged permeability while this proportion increased by 0.06% when exposure time increased to 80mins. In addition, maximum recovery (35.9%) was achieved by 100mins irradiation time and considered as the optimum time span. Despite further exposure, it dropped to 35.2% when exposure time was increased to 120mins. It can be concluded that irradiation beyond optimum exposure time may detach relatively larger particles which can provide resistance to the flow by forming particle-bridge at the later stages. Moreover, over exposure of the ultrasonic waves such as beyond 100mins irradiation has greater tendency to push back the fluid flow as well as waste of useful acoustic energy into undesired forms of energy upon transformation in the fluid present between the gap as demonstrated in figure 3.

Similar trend is shown in Table 6 for the core sample with 80×10⁻³μm² gas permeability, ultrasonic wave began to recover the damaged permeability by 36.3% and this recovery raised to 37.5% for 60mins and 80mins exposure time respectively. Furthermore, damaged permeability recovery jumped to the peak of 37.6% (100mins exposure time) but excess irradiation dipped the recovery to 35.5%. Likewise, ultrasonic waves showed identical trend in Table 7 for the core sample with 150×10⁻³μm² gas permeability. Whereas, recoveries for irradiation time of 60mins, 80mins, 100mins and 120mins were 34.4%, 36.6%, 38.1% and 37.1% respectively. Although effective irradiation time span is still in developmental stage and need more research work.

| Time  | Permeability Recovery Proportion |
|-------|---------------------------------|
| 60min | 34.1%                           |
| 80min | 35.2%                           |
| 100min| 35.9%                           |
| 120min| 35.2%                           |

![Figure 3](image-url)
Table 5. Experiment results of optimizing ultrasonic integrating treating time with cores of gas permeability around $30 \times 10^{-3} \mu m^2$.

| Core # | Time duration (min) | $K_o$ $(10^{-3} \mu m^2)$ | $K_d$ $(10^{-3} \mu m^2)$ | $K_t$ $(10^{-3} \mu m^2)$ | $(K_t-K_d)/K_o$ (%) |
|--------|---------------------|--------------------------|--------------------------|--------------------------|---------------------|
| 3-33   | 60                  | 21.10                    | 9.98                     | 17.17                    | 34.1                |
| 3-28   | 80                  | 18.89                    | 10.48                    | 17.45                    | 34.7                |
| 3-27   | 100                 | 19.94                    | 10.48                    | 17.64                    | 35.9                |
| 3-26   | 120                 | 22.34                    | 11.64                    | 19.49                    | 35.2                |

Table 6. Experiment results of optimizing ultrasonic integrating treating time with cores of gas permeability around $80 \times 10^{-3} \mu m^2$.

| Core # | Time duration (min) | $K_o$ $(10^{-3} \mu m^2)$ | $K_d$ $(10^{-3} \mu m^2)$ | $K_t$ $(10^{-3} \mu m^2)$ | $(K_t-K_d)/K_o$ (%) |
|--------|---------------------|--------------------------|--------------------------|--------------------------|---------------------|
| 8-26   | 60                  | 56.93                    | 32.38                    | 53.02                    | 36.3                |
| 8-38   | 80                  | 60.70                    | 36.03                    | 58.79                    | 37.5                |
| 8-39   | 100                 | 63.28                    | 32.56                    | 56.32                    | 37.6                |
| 8-42   | 140                 | 61.45                    | 34.09                    | 55.92                    | 35.5                |

Table 7. Experiment results of optimizing ultrasonic integrating treating time with cores of gas permeability around $150 \times 10^{-3} \mu m^2$.

| Core # | Time duration (min) | $K_o$ $(10^{-3} \mu m^2)$ | $K_d$ $(10^{-3} \mu m^2)$ | $K_t$ $(10^{-3} \mu m^2)$ | $(K_t-K_d)/K_o$ (%) |
|--------|---------------------|--------------------------|--------------------------|--------------------------|---------------------|
| 15-74  | 60                  | 111.76                   | 62.94                    | 101.41                   | 34.4                |
| 15-54  | 80                  | 117.34                   | 63.28                    | 106.27                   | 36.6                |
| 15-2   | 100                 | 121.43                   | 65.60                    | 111.90                   | 38.1                |
| 15-93  | 120                 | 127.35                   | 62.23                    | 109.52                   | 37.1                |

4. Conclusions
Following conclusions are drawn;
1. #2 transducer was considered as the best-performing transducer with frequency 20KHz and power 1000W on the basis of extent of inorganic plugs mitigation. The produced maximum permeability recoveries were 34.1%, 36.3% and 35.7% in the core samples with initial gas permeability of $30 \times 10^{-3} \mu m^2$, $80 \times 10^{-3} \mu m^2$ and $150 \times 10^{-3} \mu m^2$ respectively.
2. 100mins exposure time was witnessed to be optimum which led to maximum inorganic plugs removal of 35.9%, 37.5% and 38.1% in the core samples of $30 \times 10^{-3} \mu m^2$, $80 \times 10^{-3} \mu m^2$ and $150 \times 10^{-3} \mu m^2$ initial gas permeability respectively.

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