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Ultrasound based technology for removal of scale from downhole production tubing, an experimental verification

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A R T I C L E I N F O

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A B S T R A C T

Deposition and blockages due to scale formation inside the production tubing are the most common problems experienced during the production of oil and gas, and this significantly leads to a decline in the production rate. Progressive scale formation limits production which subsequently leads to abandonment of the well. There is a great cost attached to preventing the occurrence and remediation of scales. Chemical and mechanical techniques for scale removal in production tubing have drawbacks like environmental concerns, equipment damage, and incomplete removal of stubborn scale. In contrast, ultrasound-based methods offer potential benefits such as non-destructiveness, enhanced efficiency, reduced chemical usage, and increased safety for workers. Despite the extensive research about the application of ultrasound to improve oil recovery, there remains a significant gap in the comprehensive exploration of optimum ultrasound parameters (frequency, power, radiation time, interval time, and location) for the removal of in-situ built scales in a simulated production tubing under different flow rates. This study addresses this gap by investigating the impact of ultrasound parameters on its performance for removal of calcium carbonate ($CaCO_3$) and gypsum scales in a simulated production tubing system under different flow rate (100% and 50%). The ultrasound parameters include frequency (in the range of 20 kHz–120 kHz), power (50 W and 100 W), operation time, and location (externally attached and inserted into the production tubing).

Initial tests revealed that adjusting the operating frequency improves the impedance matching, resulting in enhanced scale removal. The experiments also explored the influence of flow rate on scale removal, showing a general increase in removal with higher flow rates, specially at operating frequencies 20 kHz and 28 kHz. It was also demonstrated that the higher frequencies of 40 kHz, 68 kHz, and 120 kHz exhibit limited removal efficiency. The effectiveness of scale removal exhibited nonlinear variation over time, with the 28 kHz, 100 W transducer demonstrating the most significant improvement.

In-pipe ultrasonic rod, operating at a constant frequency of 26 kHz, was employed to assess its performance for scale removal. Pulsed treatment was introduced to manage rod heating issues. Results demonstrated that both interval times and flow rates influenced $CaCO_3$ removal, with shorter intervals yielding better results. The ultrasonic rod's efficacy was also observed in removing gypsum scale layers, suggesting potential applications in treating scales with various strengths. The results of this study can contribute to a better understanding of how the frequency, power, operating time and interval, and flow rate influence ultrasonic scale removal. The experimental findings provide valuable insights in optimizing practical applications for removal of scales from production tubing.

1. Introduction

Scale formation poses a significant challenge in oil production, with substantial financial implications. For instance, in 2017, the North Sea wells incurred approximately £106 million in costs due to scale issues (Turbyne). In an illustrative case, the Miller oil field experienced a rapid decline in production rates, declining to zero within 24 h because of scale buildup (Wylde et al., 2006). The cost of shutdown for such a well will be around $2.4 million per day, assuming a capacity of 30,000 barrels per day (BPD) and a $80 per barrel rate. British Petroleum (BP) allocates around £2 million per year on scale control in the North Sea; with approximately 20% of its wells incurring losses for scale removal and scale inhibition treatments. According to the OGA's Insights Report

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Nomenclature

SB	Switch Board
pH	potential of Hydrogen
Ca	Calcium
BPD	Barrels Per Day
TRL:	Technology Readiness Level
Sr	Strontium
OGA	Oil & Gas Authority
kHz	Kilohertz $CO_{2:}$ Carbon Dioxide
BOE	: Barrel of Oil Equivalent
MHz	Megahertz
$SrSO_4$	Strontium sulphate
UT	Ultrasonic Transducer
W	Watt
$BaSO_4$	Barium sulphate
AG	Amplifier/Generator
μm	Micrometer
$CaSO_4$	Calcium sulphate
GUI	Graphic User Interface
MPa	Mega Pascal SO_4^{2-}: Sulphate
RP	Reflected Power
N	Newton Ca^{2+}: Calcium cation
LP	Load Power
S	Seconds Sr^{2+}: Strontium cation
SS	Surface Stabilizer
mm	Millimeter Ba^{2+}: Barium cation
SEM	scanning electrode microscope
Br	Bromine

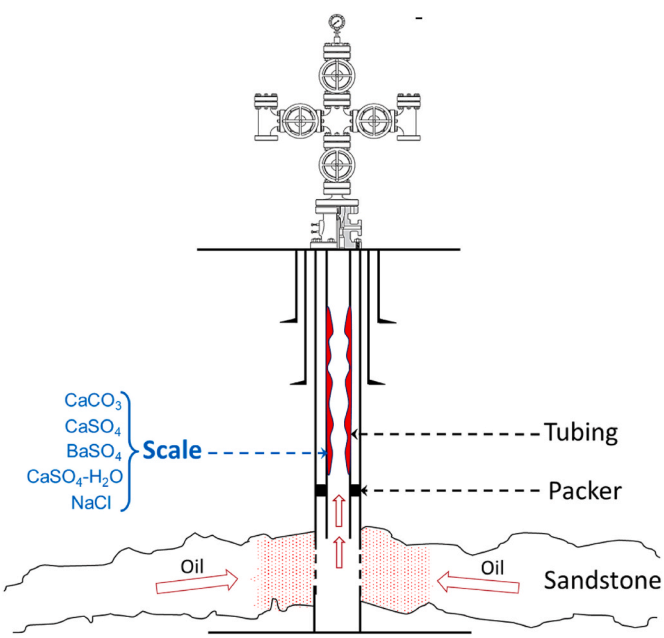


Fig. 1. Scale precipitation in downhole production tubing.

2018, there was a total production loss of 33 million barrels of oil equivalent (BOE) in 2017 due to various factors, with scale accounting for 8.38% of this total (Oil & Gas Authority 2018).

Scales increase surface roughness and decrease the flow area of tubing, as illustrated in Fig. 1. This can result in flow restriction and complete blockage of the tubing, leading to reducing/ceasing production (Crabtree et al., 1999; Cenegy et al., 2012). Scale formation depends on factors such as oversaturation level and chemical composition of waters, pH, pressure and temperature, fluid flow, and surface properties of scale (Pečnik et al., 2016). Injected waters can contain carbonate/sulphates that mix with formation water containing ions (e.g. Br, Ca or St ions), therefore causing precipitation (Merdhah and Mohd. Yassin, 2008). The mixing ratio for supersaturation, as a measurement of precipitation, varies among formation waters (Yuan, 1996). For example, sea water (high SO_4^{2-} and low Ca^{2+}, Ba^{2+}, Sr^{2+}) and formation water (low SO_4^{2-} and high Ca^{2+}, Ba^{2+}, Sr^{2+}) precipitates $CaSO_4$, $BaSO_4$ and/or $SrSO_4$ (Merdhah and Mohd. Yassin, 2008).

Changes in pressure and temperature, either during creation of new wells or in the production tubing, can cause precipitation (Merdhah and Mohd. Yassin, 2008;Yuan, 1996; Kodel et al., 2012; Heath et al., 2013). Salts like $CaCO_3$ have reverse solubility, where solubility decreases with temperature (Merdhah and Mohd. Yassin, 2008; Heath et al., 2013). Others salts such as $BaSO_4$ show varied temperature solubility behavior (Crabtree et al., 1999). In summary, the physical process of scaling generally involves supersaturation, ion pairing, agglomeration, crystal growth and deposition (Heath et al., 2013). Nucleation can occur as homogeneous and heterogenous nucleation (Merdhah and Mohd. Yassin, 2008), the latter at boundaries, caused by surface defects and turbulent flows (Crabtree et al., 1999). Subsequently, scaling ions are further adsorbed by nucleated scales leading to their growth (Heath et al., 2013). Common scales are calcium sulphate, strontium sulphate, barium sulphate and calcium carbonate, with the latter two being most prevalent in the North Sea (Yuan, 1996).

Current treatment methods include scale inhibitors, acids, milling tools, abrasive slurries, and some 'green' technologies. Scale inhibitors

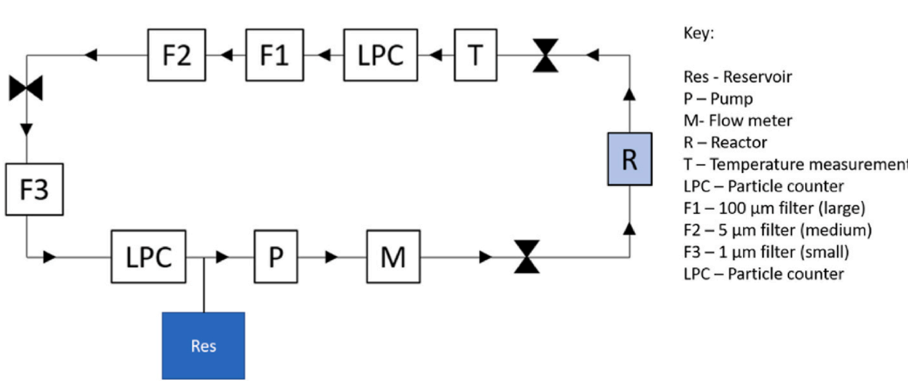


Fig. 2. Schematic of the experimental flow loop system.

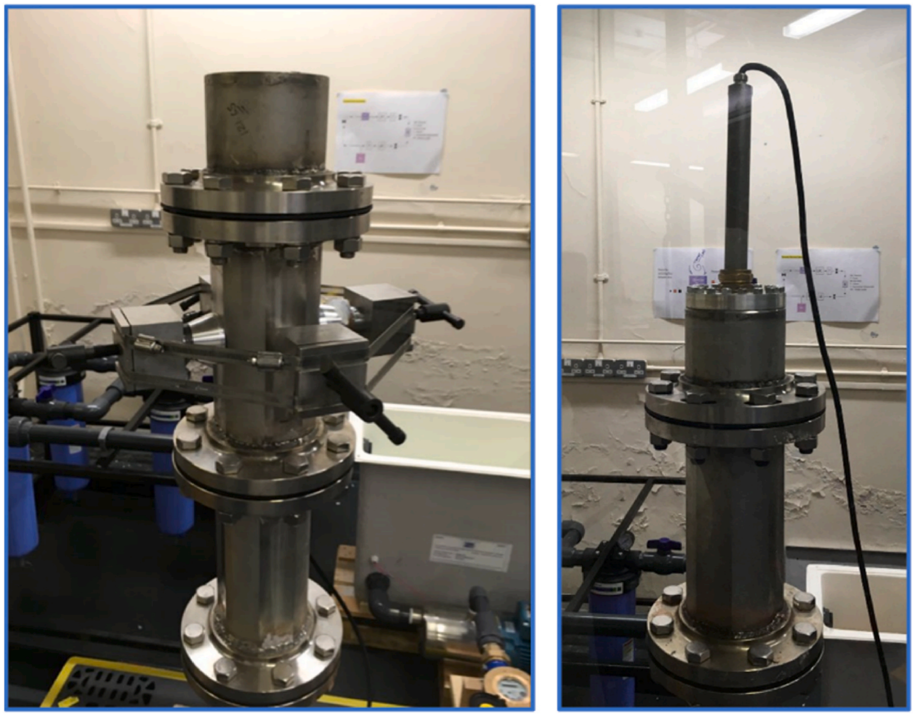


Fig. 3. Reactor, with attached ultrasonic transducers to the outer side (left), and with ultrasonic rod – as in-pipe solution (right).

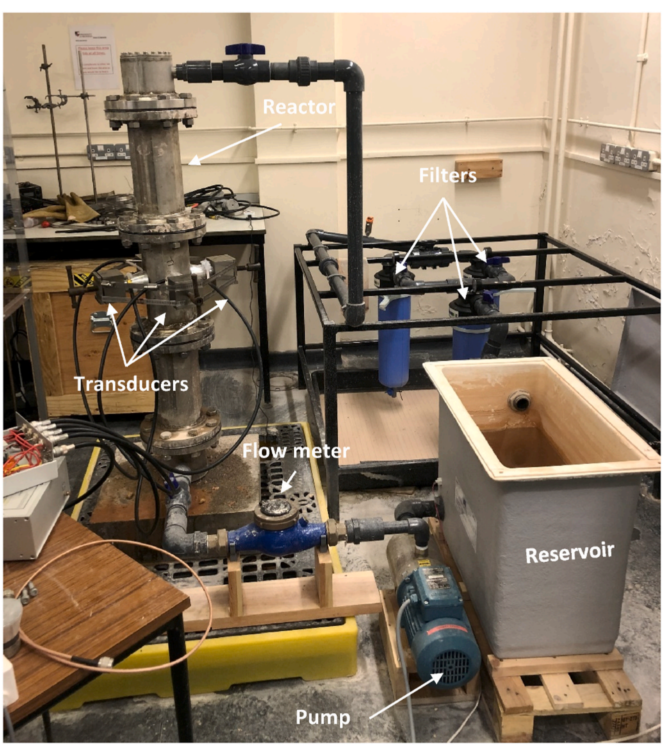


Fig. 4. Complete laboratory set-up.

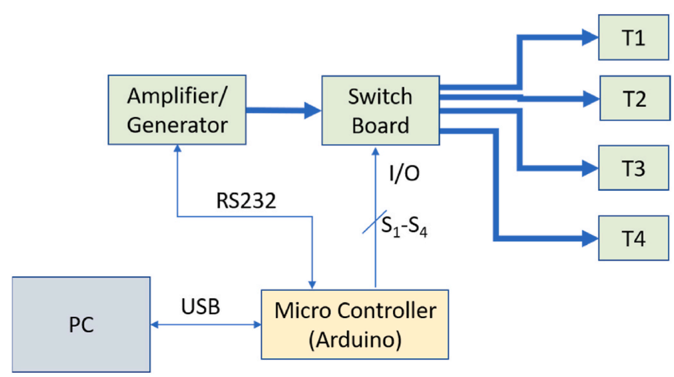


Fig. 5. Switch system configuration.

function by adsorbing or binding to active growth sites, thereby reducing both growth and nucleation (Enyi et al., 2012). Inhibitor chemicals are used in large quantities and injected with produced water (Paipetis et al., 2012). However, their persistence in the environment raises concerns about potential environmental impacts (Hasson et al., 2011). The dissolving of scales using strong acid have limited efficiency, particularly for scales like $BaSO_4$ (Crabtree et al., 1999) that do not readily dissolve with acid (Hasson et al., 2011). Furthermore, acid treatment can lead to produce scale by-products for new scale formation, and therefore "soak time" may be required, resulting in halting production (Crabtree et al., 1999).

Scales can be removed using tools like PIG, but at the risk of damaging its blades and brushes (Paipetis et al., 2012) which may prevent them from reaching all scales (Crabtree et al., 1999). This remaining layer could induce further rapid heterogeneous growth. Adding small amounts of small solid to a water jet can be highly effective, but they can damage the tubing. Antiscalants or inhibitors that readily degrade (Crabtree et al., 1999), along with approaches such as jet blasters and atomisers (Enyi et al., Sep 3, 2012), offer reduced environmental impact and more effectiveness. However, these technologies are often expensive or still in the research phase.

Ultrasound technology is an environmentally friendly and widely recognized method for cleaning applications (Yusof et al., 2016), particularly for surface cleaning where it effectively removes the adhered contaminants from the surface (Awad and Nagarajan, 2010). Heat exchangers are important part of geothermal, manufacturing, and automotive industries (Jalili et al., 2018a,b), which are prone to scale

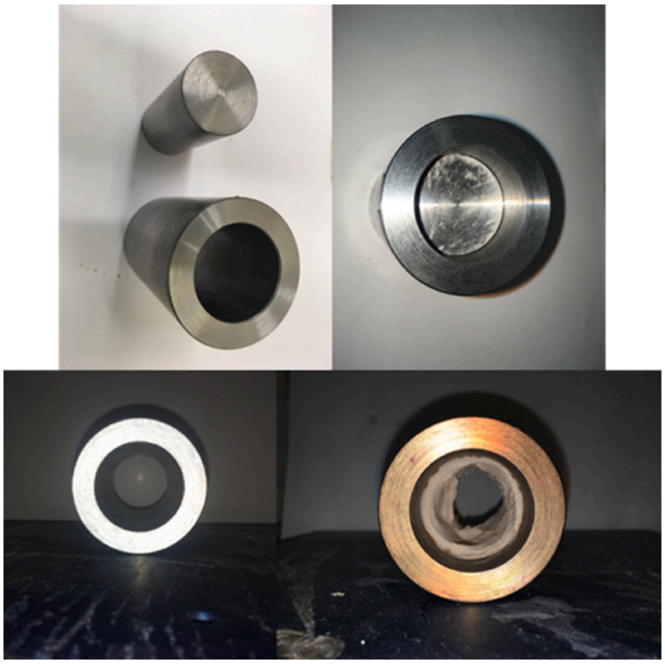


Fig. 6. A stainless-steel cylinder pipe was fabricated that allows a cylindrical piece of metal to pass through it.

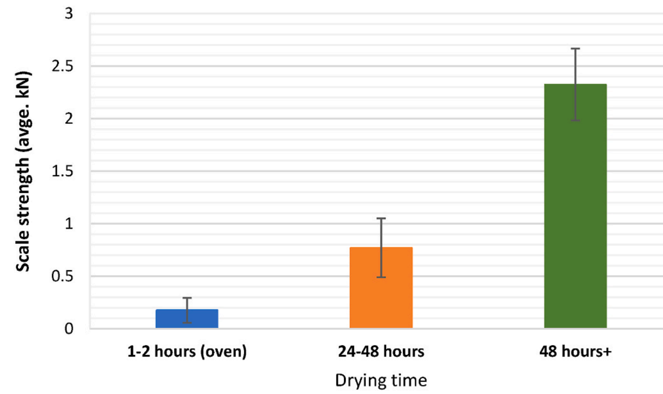


Fig. 8. Scale strength vs. drying time for several gypsum layer test samples.

formation, requiring continuous cleaning. In 2023, Banakar et al. explored the application of ultrasound for in-situ cleaning of a heat exchanger handling a supersaturated $CaSO_4$ solution. They investigated the impact of ultrasound power, operating time, and also the flow rate. Lab-scale ultrasound significantly cut fouling resistance, targeting gypsum-dominated scale. Optimal parameters (10 min, 200 W, 4-h cycle) efficiently reduced scale formation, enhancing heat transfer. However, the study did not encompass the impact of different operating frequency.

Another crucial application of ultrasound is in improved oil recovery. In recent years, Hamidi and his co-workers have performed several experiments to investigate the impact of ultrasonic stimulation on improved oil recovery (Otumudia et al. (2023); Otumudia et al. (2022); Hamidi et al. (2021); Hamidi et al. (2017)) and promising results have been obtained. The ultrasonic waves' effectiveness in removing potassium chloride (KCl) scales, a common cause of formation damage in oil and gas reservoirs, was studied by Taheri-Shakib et al. (2018). They demonstrated that the combination of ultrasonic waves with water injection is significantly more efficient than water injection alone, particularly in lower-permeability cores. However, their study is limited to only KCL scales. Kunanz and Wölfel (2014) explored the application of ultrasound as a physical cleaning method for borehole scaling in oil and gas industry, aiming to reduce or replace chemical treatments. They investigated the impact of vibration amplitude, treatment duration, and the presence of flow in removing gypsum scales. The study concluded that ultrasonic waves could serve as an environmentally friendly alternative to traditional wellbore cleaning methods. It also emphasized the need for further research on more challenging scaling types like $CaCO_3$, $BaSO_4$, and $SrSO_4$. This involves examining the influence of ultrasound parameters (like frequency and power) and exploring the application of ultrasound from outside of the tubing.

Upon reviewing previous works, it becomes evident that there is a lack of comprehensive published research on the application of ultrasound for the removal of various in-situ built scales from production tubing. This deficiency is particularly notable in the study of the impact of the ultrasound parameters like type, operating frequency, power, treatment time, interval ON/OFF time, and transducer location. This

(a) (b) (c)

Fig. 7. Compression test of cylinder lined with scale; before (a), during (b) and after (c) test.

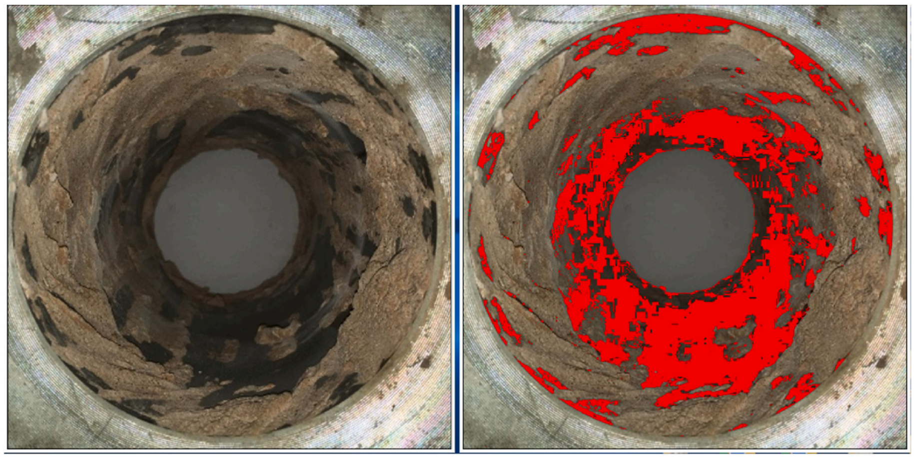


Fig. 9. Quantifying gypsum and calcium carbonate scale removal Using ImageJ.

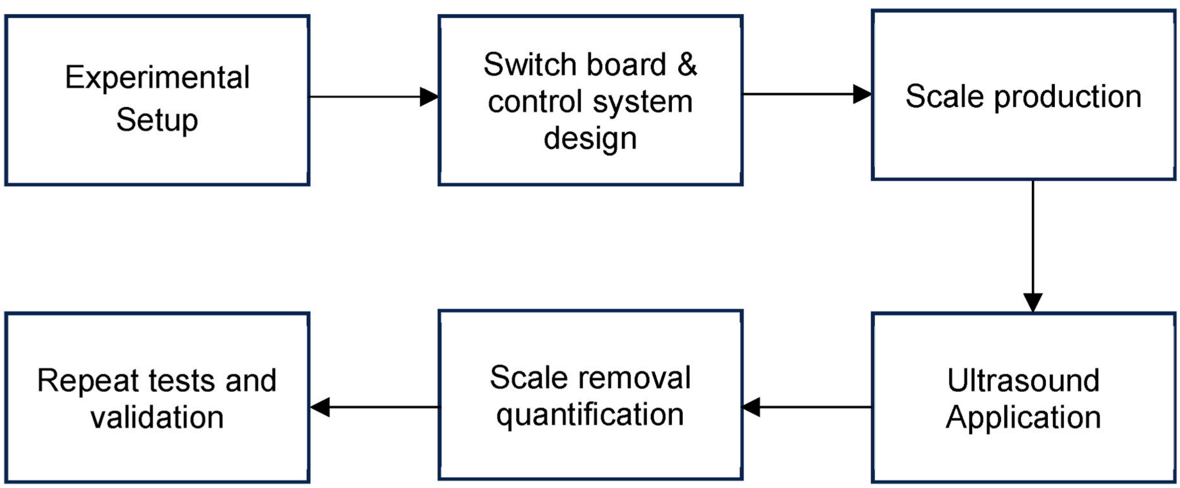


Fig. 10. Experimental methodology overview.

empirical study aims to assess the effectiveness of ultrasound technology in removal of two main types of scales, Calcium Carbonate and Calcium Sulphate, from production tubing and suggest the optimum ultrasound parameters (power, frequency, and radiation time) required for removing each specific type of scale. The investigation utilizes two types of ultrasound equipment: first, permanent ultrasound transducers installed on the outer side of the tubing and then an immersible in-pipe ultrasonic rod that moves freely within the tubing.

The proposed ultrasound-based technology offers substantial potential advantages over existing conventional methods. It is a green technology with minimal to no environmental impact. The versatility of the technology is noteworthy, as the in-pipe ultrasonic rod can be adapted for use in both new and existing wells, while the ultrasound transducers are best suited for new wells. It is crucial to emphasize that the technology is currently in the research phase, necessitating experimental validation in both the laboratory and full-operational stages. Furthermore, there are a few potential practical implementation limitations, such as determining the optimal number of ultrasound transducers required for the entire well, their arrangement and fitting, and the amount of power required for operating these transducers. These factors may pose challenges in real applications. This study aims to assess the feasibility of the proposed technology in a laboratory environment and explore the impact of the number of transducers, operating frequency, and applied power on its performance.

The subsequent sections of the paper are structured as follows: Chapter 2 presents the experimental setup used in this study. In chapter 3, the scale generation process within the tubing, its strength and the quantification of scale removal are provided. Chapter 4 presents the main findings, focusing on the practical examination and discussion of the impact of ultrasonic wave parameters, such as frequency, power, operating time, etc., on scale removal utilizing permanent transducers and in-pipe ultrasonic rod. Chapter 5 is dedicated to the conclusion and recommendations, providing a succinct summary of the research findings.

2. Experimental set-up

Fig. 2 shows the schematic of the experimental flow loop system developed to test the scale removal. The pump P is used with a variable speed drive to regulate the flow rate within the system. Prior to each experimental run, the flow meter was calibrated using a known volumetric flow rate. A precise volume of water was allowed to flow through the system, and the readings from the flow meter were compared against the expected values. Any discrepancies observed during calibration were addressed by adjusting the flow meter settings or making necessary corrections to ensure accurate flow rate measurements.

The filters F1, F2, and F3 are of different sizes (1 μm, 5 μm, and 100 μm) to remove the scale particles from the flow loop to protect the pump. The flow meter M and Temperature measurement T are for monitoring purposes. The reservoir Res is used to keep the water level in the flow system at the desired level. There are also 3 valves to shut the flow before changing the main components of the system. It is especially

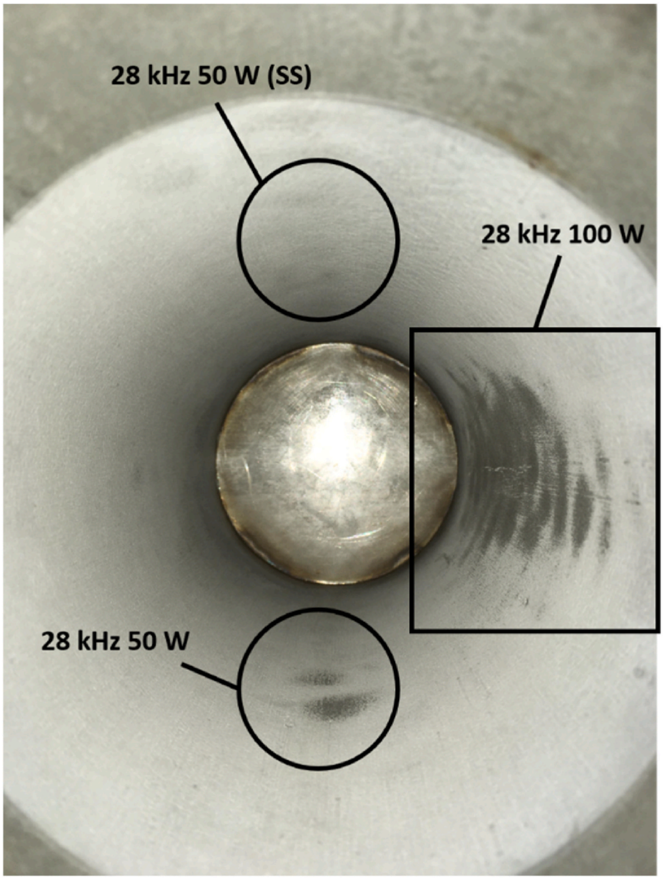


Fig. 11. Successful localised removal of scale layer, with a single transducer, at 28 kHz 50 W and 28 kHz 100 W.

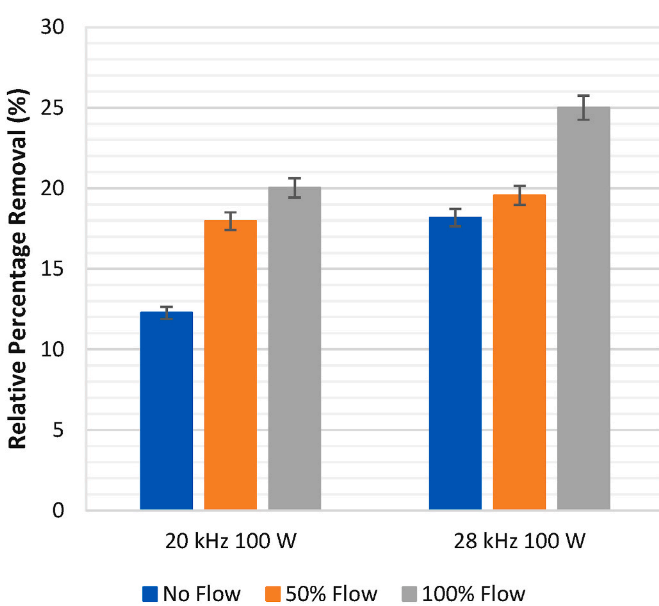


Fig. 12. The effect of flow rate on the removal of $CaCO_3$ scale for 20 kHz and 28 kHz frequencies and different flow rates.

useful for repeating the test with renewed scales in the reactor R.

The reactor R is composed of three sections of tubing, each 30 cm, as shown in Fig. 3. Each tubing section has two flanges for connecting to the other sections. The outer side of the sections are flattened for attaching ultrasonic transducers (UTs) with maximum contact area. At the top of the tubing, a suitable hatch was considered to attach the ultrasonic rod. The left side of Fig. 3 shows the reactor with 4 attached UTs on the outer side and the right-side figure shows it with attached ultrasonic rod. It has the capability of attaching both UTs and ultrasonic rod, either of them or none of them. The overall equipment set-ups are shown in Fig. 4.

One of the critical components of the project is the ultrasound amplifier/generator (AG). This class "AB" amplifier offers a wide range of applied frequencies (15 kHz - 3 MHz) with adjustable output power from zero up to 2000 W, suitable for the operation of single or multiple ultrasound transducers. The unit also provides the capability to monitor the reflected power, as an indicator of potential poor impedance matching with the transducers, and the temperature of the amplifier output stage to protect the equipment. Additionally, a GUI (graphic user interface) is employed to configure the AG and monitor the measured data. The ultrasound amplifier/generator (AG) was calibrated to ensure accurate frequency and power output. Known standard test loads were used to verify the power output levels at different frequencies, and adjustments were made to the amplifier settings as needed. The calibration also involved monitoring and validating the amplifier's ability to measure reflected power, which serves as an indicator of impedance matching with the transducers.

Piezoelectric sandwich transducers operating at various frequencies (28 kHz, 40 kHz, 68 kHz, and 128 kHz) and powers (50W and 100W) are utilized to apply ultrasound to the outer side of the production tubing to investigate the effects of multiple treatment frequencies. Additionally, a Piezo ultrasonic rod (YTSB-2000-26G) with a working frequency of approximately 20 kHz and working power of up to 2500 W is used for in-pipe ultrasound cleaning of deposited scale. The rod can be raised and lowered to treat affected scale regions.

To secure multiple transducers in place and under pressure (see Fig. 3), a supporting belt system was developed. To prevent the attachment belt to snap under pressure or from cutting forces, a two-belt system is utilized. In this test setup, each metal attachment belt can withstand 1150 MPa, or equivalently a force of approximately 6000 N per transducer.

In the case of multiple transducers, it would be necessary to apply power to each transducer in a pre-determined time sequence. To do this, an external switch board (SB) was designed and employed. The system block diagram with the SB is shown in Fig. 5. In this design, several transducers up to 4, can be connected to the AG via the SB where it enables the connection or disconnection of one or more transducers to the AG. The switching between the transducers can be done in a pre-determined time slot. A microcontroller (Arduino) controls the SB and communicates with the AG via RS232 link.

It is noteworthy that all the experimental results in this research have been validated by checking them against theoretical expectations and also providing a logical explanation for each outcome. Furthermore, each test is repeated at least two times to ensure the accuracy and repeatability of the test results.

3. 3 scale production, testing, and quantification

3.1. Scale production

Several methods for scale production were initially considered including; mixing of incompatible waters (Muryanto et al., 2012), heating of saturated solutions (Mwaba et al., 2006, Lais et al., 2018) and electrochemical deposition (Lais et al., 2017). Also, the feasibility of application of a calcium carbonate scale paste was examined (Kunanz and Wölfel, 2014). Mixing of incompatible solutions under high-temperature conditions did not create a uniform layer and only a dry residue remained that was easy to remove. A similar type of effect occurred for heating of saturated solutions. One of the main issues was reaching sufficient temperatures for layer upon layer deposit. Testing

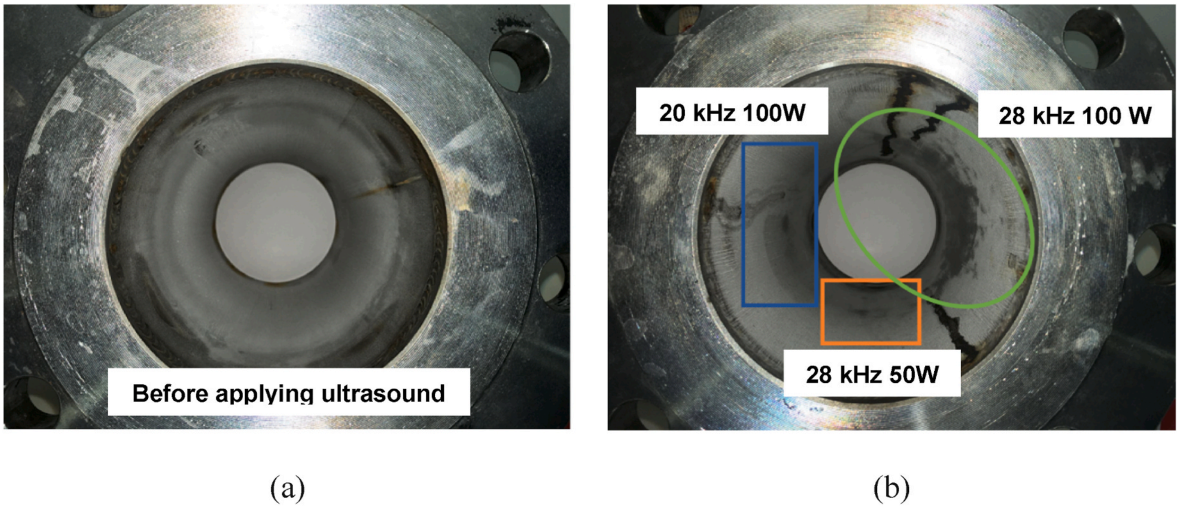


Fig. 13. Removal of $CaCO_3$ layer for 20 kHz and 28 kHz transducers with 100% flow rate for 1 h, (a) before applying ultrasound, (b) after applying ultrasound.

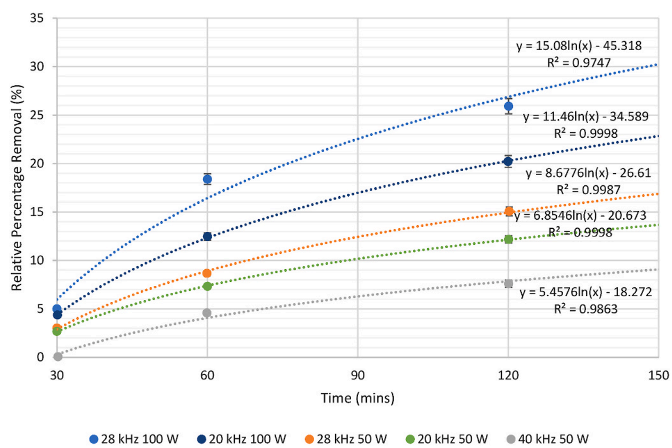


Fig. 14. Impact of time on scale removal for a single transducer with various frequencies and powers.

with calcium carbonate paste (dried to a metal surface) showed very little adhesion properties and could be removed with very little applied pressure. Of the methods tested, the electrochemical method provided the most adhesive layer and is based on the solubility of calcium carbonate decreasing with pH (Gabrielli et al., 1999). Here, CO_2 is bubbled through water to reduce the pH and allowing calcium carbonate powder to be dissolved – giving calcium carbonate solution. Then, the calcium carbonate solution fills a pipe section, and an electrode inside the pipe is switched on. This causes electrons to form hydroxide ions (at the cathode – the inner pipe surface) and a localised increase in pH at that region. Hence, the calcium carbonate precipitates onto the inner wall of the pipe.

A simple method was developed further into the project with the use of gypsum (calcium sulphate dihydrate). Calcium sulphate scale is another problematic scale formed during oil production. To test the adhesive properties of calcium sulphate dihydrate, gypsum was acquired, and some preliminary tests run to determine a water gypsum mixture that would produce a solid layer. It was found that for a ratio of around 3:5 (Water/Gypsum) a more hardened layer was formed, as approximately given by the gypsum supplier and somewhat in line with theory (Çolak, 2001). The mixture was allowed to dry overnight on the inner wall of the test pipe to ensure full adhesion.

3.2. Scale strength tests

To assess the representativeness of the laboratory scale production, we conducted tests to assess the adhesive strength of the gypsum scale layers, considering variations in drying conditions. For this purpose, a push piston-bore type device, i.e. a cylindrical stainless-steel tube, that allows a smaller rod to go through it was fabricated, as shown in Fig. 6. The inner tube is then placed into the scale layered cylinder and a force applied via Hounsfield benchtop tensile and compression test apparatus, as illustrated in Fig. 7. The tests were replicated with five different samples in each drying time mode (1–2 h oven-dried, 24–48 h, and 48 h+) to ensure repeatability and enhance our understanding of uncertainty.

The results indicate the significant influence of the drying process on the strength of the gypsum scale layer. Oven-dried layers exhibited lower strength compared to those dried naturally over a period of 24–48 h, with longer drying time showing the higher strength. Fig. 8 shows the results. It is seen that for scale layers dried between 1 and 2 h (oven-dried), the average strength is 0.17 kN. The naturally dried layers, particularly those left for 48+ hours, exhibit higher strength, requiring forces of up to approximately 2.32 kN for removal.

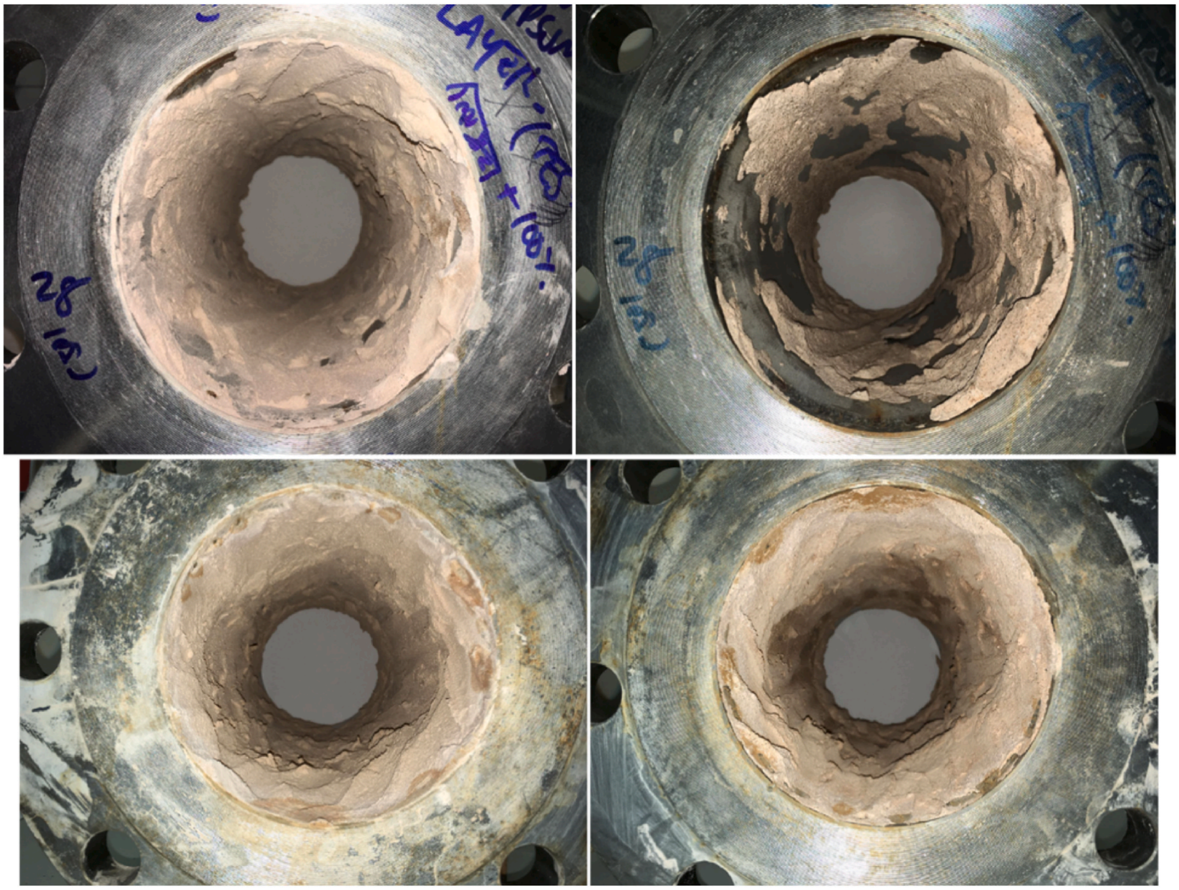


Fig. 15. Top-left and right, Gypsum scale layer before and after removal with 20 kHz 100 W transducer. Bottom-left and right, before and after removal with no ultrasound.

3.3. Scale removal quantification

In order to quantify both $CaCO_3$ and gypsum scale layer removal from the inner wall of the pipe, ImageJ was utilized. Considering that the color of $CaCO_3$ scale layer is white, the mean intensity of each image in the region of the removal area reflects the relative quantity of removal, i.e. the greater the mean intensity the more scale present. Both hue filters and image invert were used to achieve the desired effect and to improve the quantification accuracy. Fig. 9 depicts an example of the scale quantification using ImageJ.

To validate the scale quantification accuracy, the weight of the original layered scale has been compared with the sum of the removed scales and those that remained after the cleaning process. Furthermore, the weight of the removed scales, captures in the filters, is measured (using an accurate weighting scale) and compared with the weight calculated using ImageJ. This validation procedure has been conducted for several test cases and the results indicate that the error was consistently less than 5% for all test cases.

An overview of the methodology is illustrated as a flowchart in Fig. 10, summarizing the key steps undertaken in this experimental study.

4. Experimental results and discussions

4.1. Removal of scales using permanent transducers

4.1.1. Initial testing and impedance matching

Experiments were conducted on the removal of calcium carbonate ($CaCO_3$) and gypsum scales within the flow loop system with transducers operating at 28 kHz and powers 50 W and 100 W. The treatment time for each frequency was 1 h. It was noticed that the impedance of the system when operating at the nominal frequency of 28 kHz was poorly matched resulted in giving high reflected power (RP), implying that the operating frequency should be tuned to lower the RP to around or less than 5% of the Load Power (LP). The operating frequency was continuously adjusted during the experiment to keep the best transducer's impedance at its best value to maximize the efficiency and prevent the transducer overheating. The initial test results, as depicted in Fig. 11, showed the area of cleaning is much enhanced at 100 W in comparison to 50 W. The actual applied operating frequency for the 28 kHz 50 W and 100 W was set to 30.78 kHz and 31.96 kHz to minimize the reflected power impedance mismatching. A surface stabilizer (SS) was then added to the test with the 50 W transducer to observe how a closed pipe may also behave. It is seen that the area of cleaning was reduced, indicating the possibility of dampening of the pipe vibration. Higher frequencies were also initially tested but showed little or no scale removal on the test section. The results imply that the lower operating frequencies and higher powers increase the cleaning efficiency.

4.1.2. Impact of frequency, power, flow, and time on the removal rate

The effect of flow rate on the ultrasound removal process was investigated. Using a single transducer at different frequencies and flow rates, the percentage scale removal was determined through image analysis. Fig. 12 presents the comparative results for two operating frequencies 20 kHz and 28 kHz and three flow rates 0%, 50% and 100%. It is seen that the higher flow rate increases the scale removal, implying that flow rate works in synergy with the ultrasound effects of the attached transducer. Therefore, for the remainder of experiments flow was kept at its maximum. It is also noticed that the transducer with operating frequency 28 kHz gives a better cleaning performance.

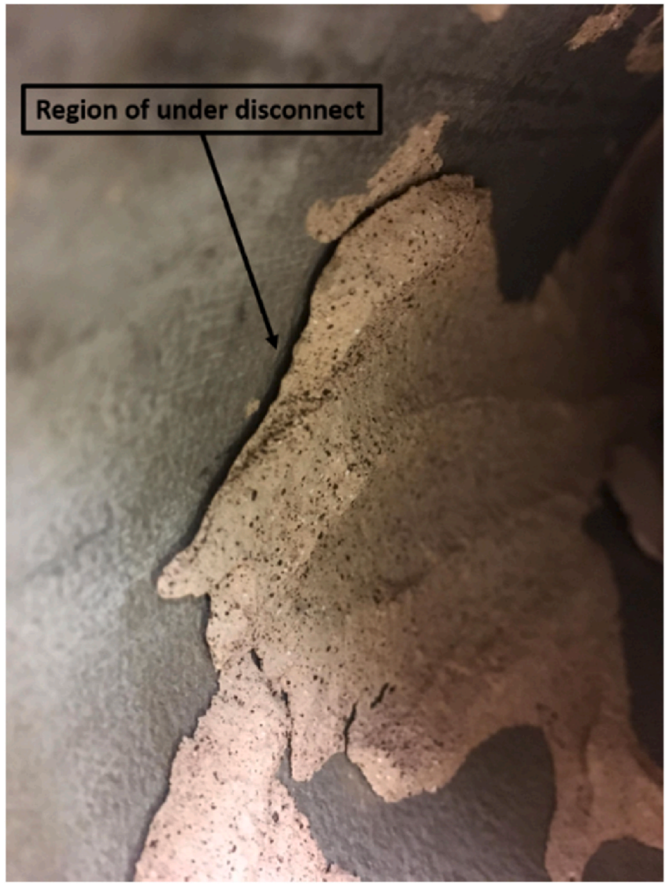


Fig. 16. Layer of gypsum scale disconnected from the inner pipe wall at the edge.

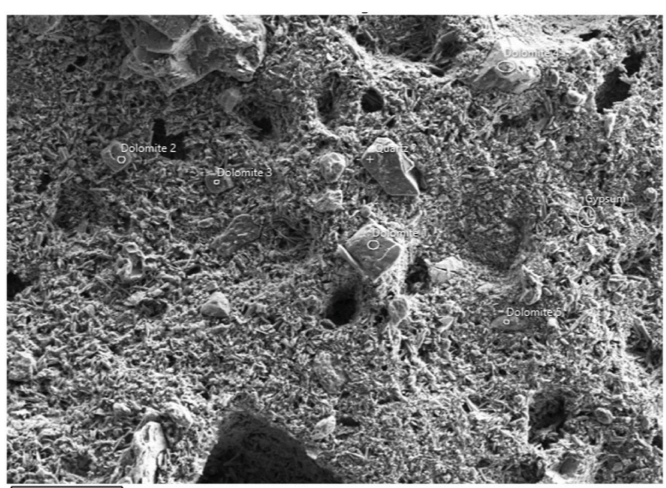


Fig. 17. Gypsum layer under SEM with 100 μm scale.

Notably, the 28 kHz, 100 W setup achieved approximately 25% removal in the proximity of the transducer. Higher frequencies including 40 kHz, 68 kHz and 120 kHz were also tested with 100% flow rate. However, the scale removal was very low for these higher frequencies which made the quantification very difficult and with low certainty. Therefore, these results for higher frequencies could not be validated and hence are not reported here.

Fig. 13 shows the removal of the $CaCO_3$ layer after 1 h of cleaning in the flow loop system with the transducers operating at frequencies of 20 kHz and 28 kHz. Again the 28 kHz 100 W transducer demonstrates the greatest amount of cleaning followed by 20 kHz 100 W and then 28 kHz 50 W.

To examine the impact of time on scale removal, the cleaning processes have been conducted using a single transducer with various operating frequencies and powers over an extended duration. Fig. 14 displays the results for the test cases at different times, along with a fitted curve for each case. It is seen that the relationship between the scale removal and time is logarithmic for all test cases. This implies that

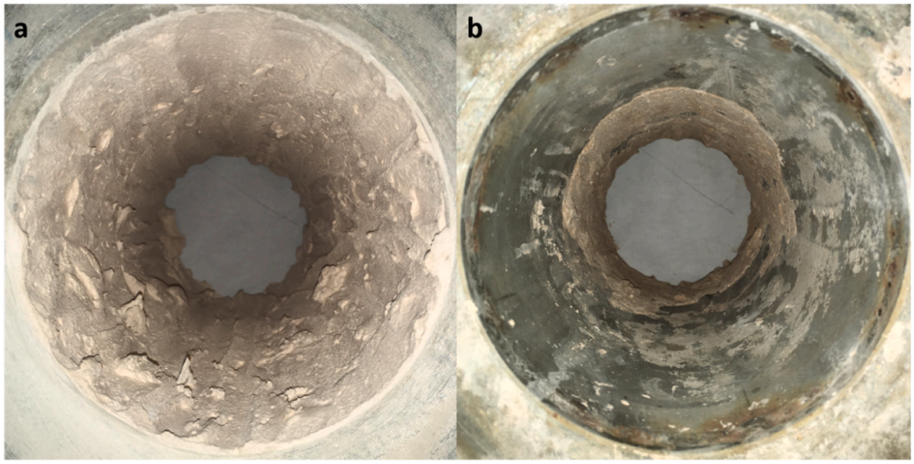


Fig. 18. Cleaning of the gypsum layer (weaker layer with oven drying) with 4 transducers configuration, 1 h per each side (a – before cleaning, b – after cleaning).

the scale removal increases with time but tends to saturate after approximately 2–3 h. Consequently, the optimal cleaning time is estimated to be around 2 h.

A gypsum layer was then applied to the inner side of two pipe sections and allowed to dry overnight. It was then placed in an oven for further drying. Then, the sections were placed in the flow loop and tested for removal with 20 kHz 100 W and 28 kHz 100 W transducers at 100% flow rate. The removal results are shown in Fig. 15 (top). To show the ultrasound effects, the same test was undertaken with the similar gypsum scaled pipe section with only flow (1 h–100% flow rate) and without ultrasound. Fig. 15 (bottom) shows the results. It is seen that ultrasound and flow together significantly increase removal in comparison to flow alone. A characteristic of the remaining scale is that the layer seems to have become detached from the pipe surface. There is a region of outer under disconnection, as shown in Fig. 16. Also, note the pitting in the remaining layer, possibly indicating some scale layer surface removal by collapsing cavities/shockwaves.

After removal of the gypsum layer with 28 kHz transducer, a SEM analysis was made on the layer fragments caught in the particle filters. Fig. 17 shows the Sem image. The gypsum layer before and after ultrasound treatment consisted of primarily gypsum and some small amounts of dolomite (*the cuboid shape in the image*). There was little evidence to suggest that the composition of the material had changed, potentially indicating that removal is not a heating effect but simply breaks the bonds due to vibrations. Furthermore, this would seem to suggest that cavitation effects are low since the heating caused by collapsing cavities may also induce structural changes.

The final test reported here involved attaching 4 transducers to the tubing section, with one transducer on each side. However, only one of the transducers is powered at a time, using the proposed configuration outlined in Fig. 5. The average operating time for each transducer was 1 h. Fig. 18 shows the gypsum removal at 42.56 kHz 100 W. It is shown that the gypsum layer could be almost fully removed at the transducer positions and towards the top of the pipe. However, there is some gypsum remaining on the lower section. In general, localised cleaning is very good with some removal away from the transducer position. These results indicate that the transducers are most suited to remove the thicker gypsum layers. For $CaCO_3$, the layer was not well removed, indicating that a lower frequency around 20 kHz and a longer cleaning period than 1 h should be utilized.

4.2. Removal of scales using in-pipe ultrasonic rod

The ultrasonic rod (depicted in Fig. 3-right) has only one operational frequency of approximately 26 kHz, which is a limitation of the ultrasonic rod. However, it has been demonstrated in the previous section that a frequency in this range gives the best cleaning performance.

Another limitation of working with the ultrasonic rod is its outer diameter (approximately 7 cm), which significantly reduces the volume of water around the rod in the pipe. This causes the rod temperature to rise, operating at much higher temperature than advised by the manufacturer. To maintain the ultrasonic rod temperature below the recommended 40 °C, a pulsed treatment technique was investigated. The ultrasonic rod was turned ON for duration T_{ON} and OFF for duration T_{OFF} continuously during the whole cleaning process.

Fig. 19 shows the 'pulsed' ultrasound treatment imagery for $CaCO_3$ before and after the treatments within the flow loop system (100% flow rate) at different pipe positions with different interval times 5s, 15s, 60s, 120s, and 150s. Here, the interval time is the time the ultrasonic rod is on, which is equal to its off time; i.e. Interval time = T_{ON} = T_{OFF}. The treatment time is 2 h, so the ultrasound rod average operating time is half of that, i.e. 1 h. For example, for an interval time of 5 s, the ultrasonic rod is on for 5 s, then switches off for 5 s, this is repeated over the 2 h. The test has been repeated with the scale inside the top, middle and bottom pipe section of the reactor (See Fig. 3), and the imagery results are provided in parts a, b, and c of Fig. 19.

The results shown in Fig. 19 are quantified and illustrated in Fig. 20. It is seen that the results are quite varied, which is typical of cavitation activity dependence on so many different parameters. According to the results, the $CaCO_3$ cleaning depends on the position in the flow loop and on the interval of the treatment time. For the bottom and top pipe positions there is a general trend of decrease in $CaCO_3$ removal with interval time, here the shortest interval time (5s) shows relative removal of 72% and 51% respectively (Fig. 20). For the middle pipe position, the removal rate is slightly higher (around 75% for the interval time of 5 s) and is less dependent upon the interval time. In terms of consistency, an interval period of 5 s provides the most $CaCO_3$ removal in each pipe, this is also the interval time that causes the highest heating in the pipe. This may be due to a decrease in cavitation threshold (with temperature) that produces more cleaning bubbles. For the decreases in removal, it may be the case that cavitation bubbles are being removed by the 100% flow rate.

A similar test was then undertaken for the gypsum scale layer, utilizing two types of gypsum scales, positioned only on the middle pipe. Fig. 21 a depicts the imagery results for a naturally dried scale layer, while the results for an oven-dried scale layer are presented in Fig. 21 b. The images show the pipes before starting the cleaning treatment, after 1 h of treatment, and after 2 h of treatment. The results show that the oven dried scale layer was almost completely removed at both 1 and 2 h. For the naturally dried scale the maximum removal was for treatment interval of 5 s ON and 5 s OFF for 2 h.

Fig. 22 presents the quantified results. It is seen that the results for

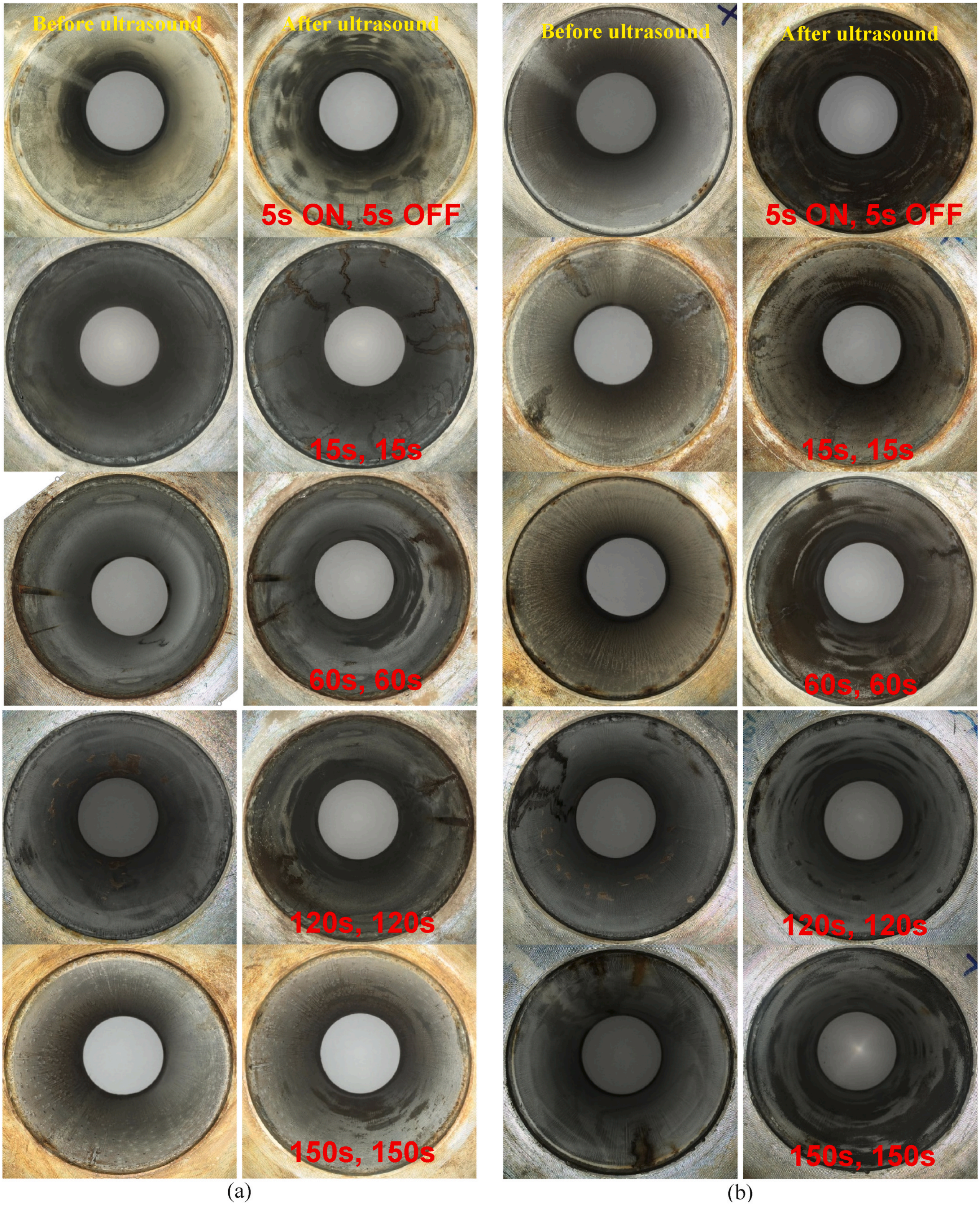
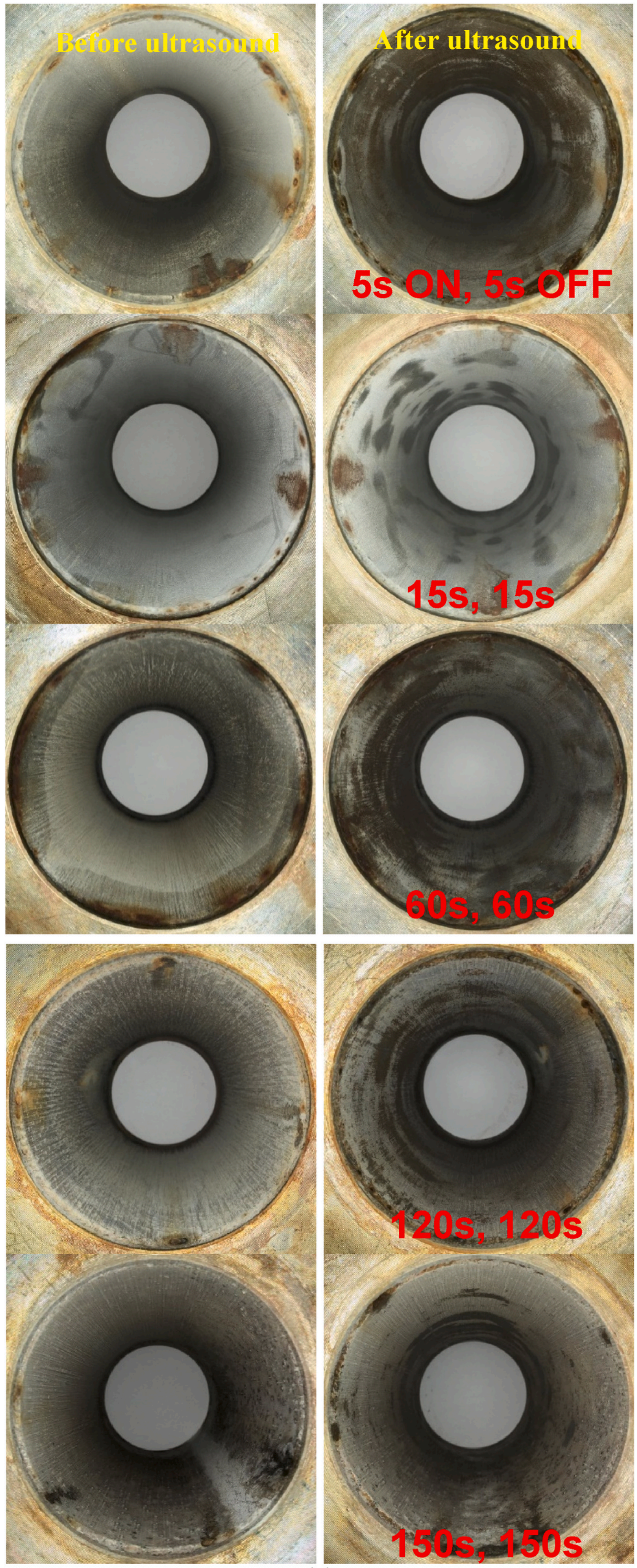


Fig. 19. Ultrasonic rod $CaCO_3$ removal for various pipe section positions: (a) top, (b) middle, and (c) bottom with different interval times of 5s, 15s, 60s, 120s, and 150s.



(c)

Fig. 19. (*continued*).

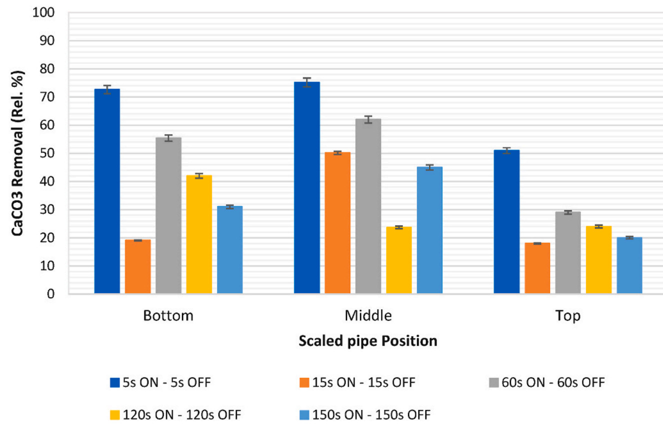


Fig. 20. The $CaCO_3$ removal after 2 h of treatment time (equivalently 1 h on) for different pipe positions and interval times.

the oven-dried scale are consistent across the 4 interval times, with removal rates of more than 90% and reaching 100% after 1 h and 2 h, respectively. In contrast, for the naturally dried scale, the maximum removal was achieved with the interval time of 5 s, yielding approximately 43% and 83% after 1 h and 2 h, respectively. This implies that the strength of the gypsum scale layer is critical to the success of ultrasonic removal with the ultrasonic rod treatment.

After the cleaning treatment, the pitted scale exhibited a noticeable transformation into a 'mush,' indicating a significant softening of the scale surface due to the ultrasonic rod treatment. This presents a potential novel treatment approach, wherein the scale layer could be systematically attacked and pitted by the cavities, followed by its gradual removal through a mechanical device, layer by layer. SEM images of the surface, as depicted in Fig. 23, illustrate the impact of cavitation attacks on the gypsum layer. Fig. 23 a provides an overview with a 1 mm scale, while the subsequent three images are presented with a scale of 100 μm, revealing holes ranging in size from 10 μm to 100 μm. Following the initial pit formation, both shockwave fluid turbulence and subsequent jet attacks may persist, contributing to the continued growth of the pit.

5. Conclusions and recommendations

Two experimental ultrasound setups, incorporating a controlled flow loop system, were developed to investigate the effectiveness of ultrasound-based technology in removing scale from pre-scaled downhole production tubing. In the first setup, multiple ultrasound transducers are attached to the outer side of the tubing, while in the second setup, an in-pipe ultrasonic rod is employed. The electrochemical method, along with applying the paste, was utilized to create two types of scale, calcium carbonate ($CaCO_3$) and gypsum, inside the tubing before initiating the removal process. The experimental findings indicate that both ultrasound-based techniques exhibit efficacy in scale removal at various levels. The effectiveness of the techniques depends on the scale type and operating conditions. The findings are summarized as below.

- The outer ultrasound transducers are more effective in cleaning the scale at their attached position. This efficacy diminishes at the adjacent positions, utilizing a vibrational removal mechanism without cavitation effects.
- Lower frequencies generally prove more effective in removing both $CaCO_3$ and gypsum scale layers. Notably, the 28 kHz transducer demonstrates better performance than 20 kHz transducer, possibly because of better impedance matching.
- The removal of thinner layers (0.5 mm) of $CaCO_3$ was found to be easier compared to the removal of thicker layers (1 mm).
- Fluid flow, in synergy with ultrasound, improves the cleaning efficiency for both types of scales and technologies.
- Longer operation time increases the overall cleaning efficiency for both technologies. However, the relationship between the scale removal and time shows a logarithmic curve, with almost no further removal after approximately 150 min.
- A configuration of 4 transducers, with one on each side and operating them in a time sequence, enhances the quality of the cleaning.
- Visual examination of images revealed the detachment of larger sections of the gypsum layer and sporadic removal of thinner scales, indicating a cracking effect on thicker layers and rubbing away of the remaining thinner layer. SEM analysis supports this hypothesis by indicating smaller crystal sizes.
- The in-pipe ultrasonic could remove approximately 75% of the $CaCO_3$ scale, and around 83% and almost 100% of the naturally dried and oven-dried gypsum scales, all with the interval time of 5 s and after 2 h of cleaning treatment.

From an implementation perspective, the permanent ultrasound transducers are most suitable for new wells, as embedding them in existing wells may not be practically recommended. Potential limitations in size may restrict their placement within the available space between the well and tubing, and the overall number of transducers, along with the required wiring, could present financial challenges. The power requirements for operating all transducers simultaneously may also be a challenge, but this could potentially be mitigated by activating the transducers in a time sequence. On the other hand, the ultrasonic rod demonstrates potential for application in both existing and new wells. However, a potential challenge with the ultrasonic rod lies in the limited space between the rod and tubing, which could potentially impact production efficiency.

The next phase of this research involves developing a pilot system to study the practical challenges of the technology and propose suitable solutions to mitigate them. The current Technology Readiness Level (TRL) of the proposed technology is 4, and it is anticipated to increase to TRL 6 upon the successful completion of the pilot system.

CRediT authorship contribution statement

Richard James Wood: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Hossein Hamidi:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Aliakbar Jamshidi Far:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

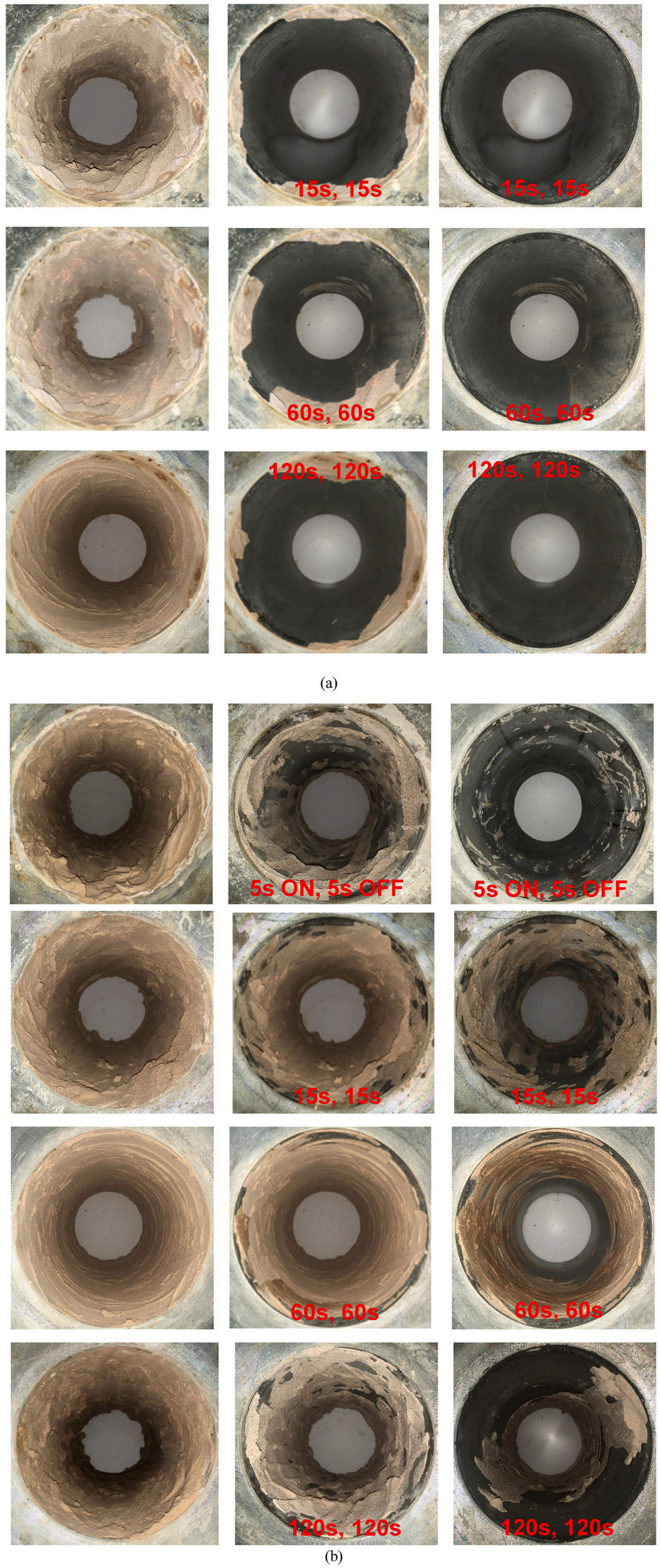


Fig. 21. Ultrasonic rod treatment of gypsum scale with 100% flow rate and various interval times: a) naturally dried scale, b) oven dried scale.

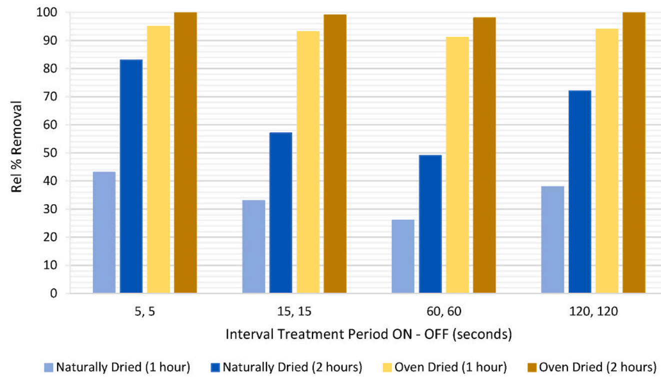


Fig. 22. Quantified results of the images presented in Fig. 21.

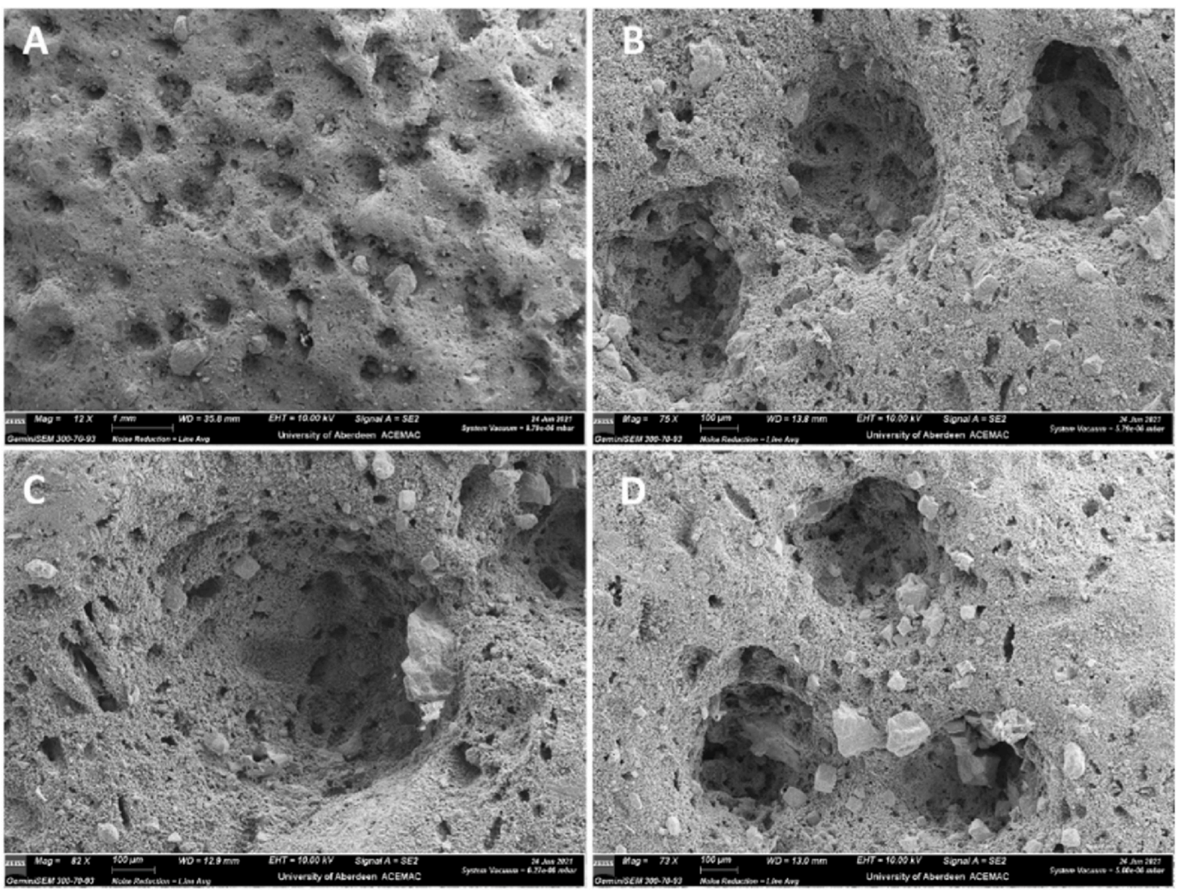


Fig. 23. *SEM images of the pitted scale, (A)* 1 mm *scale, (B – D)* 100 µm *scale.*

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Awad, S.B., Nagarajan, R., 2010. Developments in Surface Contamination and Cleaning: Chapter 6 - Ultrasonic Cleaning. Elsevier, pp. 225–280. https://doi.org/10.1016/C2009-0-61579-8.

Banakar, V.V., Gogate, P.R., Raha, A., Saurabh, 2023. Application of ultrasound in heat exchanger handling supersaturated CaSO4 solution for reduction of scaling by induced precipitation and in-situ cleaning. Chem. Eng. Sci. 276, 118814.

Cenegy, L.M., McAfee, C.A., Kalfayan, L.J., 2012. Field study of the physical and chemical factors affecting downhole scale deposition in the North Dakota bakken formation. SPE Prod. Oper. 28 (1), 67–76.

Çolak, A., 2001. Characteristics of acrylic latex-modified and partially epoxy-impregnated gypsum. Cement Concr. Res. 31 (11), 1539–1547.

Crabtree, M., Eslinger, D., Fletcher, P., Miller, M., Johnson, A., King, G., 1999. Fighting scale—removal and prevention. Oilfield Rev. 11 (3), 30–45.

Enyi, G.C., Nasr, G.G., Nourian, A., El Kamkhi, M.A., Burby, M.L., 2012. Removal of Scales in Petroleum Production Tubing Utilising High Pressure Atomisers. Institute for Liquid Atomization and Spray Systems - Europe, Heidelberg, Germany.

Gabrielli, C., Maurin, G., Poindessous, G., Rosset, R., 1999. Nucleation and growth of calcium carbonate by an electrochemical scaling process. J. Cryst. Growth 200 (1), 236–250.

Hamidi, H., Sharifi Haddad, A., Otumudia, E.W., Rafati, R., Mohammadian, E., Azdarpour, A., Pilcher, W.G., Fuehrmann, P.W., Sosa, L.R., Cota, N., Garcia, D.C., Ibrahim, R.M., Damiev, M., Tanujaya, E., 2021. Recent applications of ultrasonic waves in improved oil recovery: a review of techniques and results. Ultrasonics 110 (13), 106288.

Hamidi, H., Sharifi Haddad, A., Mohammadian, E., Rafati, R., Azdarpour, A., Ghahri, P., Ombewa, P., Neuert, T., Zink, A., 2017. Ultrasound-assisted CO2 flooding to improve oil recovery. Ultrason. Sonochem. 35 (Part A), 243–250 8.

Hasson, D., Shemer, H., Sher, A., 2011. State of the art of friendly "green" scale control inhibitors: a review article. Ind. Eng. Chem. Res. 50 (12), 7601–7607.

Heath, D., Brane, Š., Marko, H., Boštjan, P., 2013. The use of the cavitation effect in the mitigation of $CaCO_3$ deposits. J. Inst. Eng. Bangladesh 59 (4).

Jalili, P., Ganji, D.D., Nourazar, S.S., 2018a. Investigation of convective-conductive heat transfer in geothermal system. Results Phys. 10, 568–587.

Jalili, P., Ganji, D.D., Nourazar, S.S., 2018b. Hybrid semi analytical method for geothermal U shaped heat exchanger. Case Stud. Therm. Eng. 12, 578–586.

Kodel, K.A., Andrade, P.F., Valença, J.V.B., Souza, D.d.N., 2012. Study on the composition of mineral scales in oil wells. J. Petrol. Sci. Eng. 81, 1–6.

Kunanz, H., Wölfel, S. May 14, 2014. Scale Removal with Ultrasonic Waves. OnePetro, Aberdeen, Scotland.

Lais, H., Lowe, P.S., Gan, T., Wrobel, L.C., Kanfoud, J., 2018. Characterization of the use of low frequency ultrasonic guided waves to detect fouling deposition in pipelines. Sensors 18 (7), 2122.

Lais, H., Lowe, P.S., Kanfoud, J., Gan, T.-., 2017. Advancements in Fouling Removal Using High Power Ultrasonics for Industrial Applications, p. 1.

Merdhah, A.B., Mohd Yassin, A.A., 2008. Study of scale formation due to incompatible water. Jurnal Teknologi F (49F), 9–26.

Muryanto, S., Bayuseno, A.P., Sediono, W., Mangestiyono, W., 2012. Development of a versatile laboratory project for scale formation and control. Educ. Chem. Eng. 7 (3), e78–e84.

Mwaba, M.G., Rindt, C.C.M., Steenhoven, A.A.V., Vorstman, M.A.G., 2006. Experimental investigation of CaSO4 crystallization on a flat plate. Heat Tran. Eng. 27 (3), 42–54.

Oil & Gas Authority, 2018. OGA Wells Insight Report.

Otumudia, E., Hamidi, H., Jadhawar, P., Wu, K., 2023. Effects of ultrasound on the removal of emulsion plugging in oil reservoirs. Colloids Surf. A Physicochem. Eng. Asp. 676 (Part B), 132289.

Otumudia, E., Hamidi, H., Jadhawar, P., Wu, K., 2022. Effects of reservoir rock pore geometries and ultrasonic parameters on the removal of asphaltene deposition under ultrasonic waves. Ultrason. Sonochem. 83 (13), 105949.

Paipetis, A.S., Matikas, T.E., Aggelis, D.G., Hemelrijck, D.V., 2012. Emerging Technologies in Non-destructive Testing V, first ed. CRC Press.

Pečnik, B., Hočevar, M., Širok, B., Bizjan, B., 2016. Scale deposit removal by means of ultrasonic cavitation. Wear 356–357, 45–52.

Taheri-Shakib, J., Naderi, H., Salimidelshad, Y., Kazemzadeh, E., Shekarifard, A., 2018. Application of ultrasonic as a novel technology for removal of inorganic scales (KCl) in hydrocarbon reservoirs: an experimental approach. Ultrason. Sonochem. 40, 249–259.

Turbyne, R., 2019. Ultrasound project aims to tackle multi-million pound scale problem in oil and gas production. https://www.abdn.ac.uk/news/13304/.

Wylde, J.J., Williams, G.D.M., Careil, F., Webb, P., Morris, A., 2006. Deep downhole chemical injection on BP-operated miller: experience and learning. SPE Prod. Oper. 21 (2), 188–193.

Yuan, M., 1996. Water Scaling in North Sea Oil Fields and Scale Prediction–An Overview. Geilo, Norway.

Yusof, N.S.M., Babgi, B., Alghamdi, Y., Aksu, M., Madhavan, J., Ashokkumar, M., 2016. Physical and chemical effects of acoustic cavitation in selected ultrasonic cleaning applications. Ultrason. Sonochem. 29, 568–576.