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Non-intrusive power ultrasonic approach for calcium carbonate scale reduction in industrial pipelines

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Abstract: This study investigates the use of ultrasound to mitigate scale formation in pipelines within the iron ore filtration process. The formation of calcium carbonate scale, caused by the addition of lime and carbon dioxide, results in blockages, increased pressure, and equipment wear. Experimental tests for characterize and reduce the fouling were performed. The results suggest that while ultrasound may not be feasible for large-scale removal, it holds promise for scale prevention in mining pipelines.

Keywords: Calcium carbonate, Langevin transducer, acoustic cavitation, pipeline fouling, scale formation.

Background, Motivation and Objective

Fouling in pipelines is a critical operational challenge in mineral processing plants, especially during the filtration stage of iron ore slurries [1, 2, 3, 4]. The use of chemical additives like calcium oxide (CaO) facilitates the process, but also leads to the formation of calcium carbonate ($CaCO_3$) as a by-product of subsequent pH control with CO_2. The deposition of $CaCO_3$ scales along the inner surfaces of pipes and equipment can cause significant disruptions, including reduced flow rates and increased pressure drops. Recent studies have explored non-invasive techniques such as high-power ultrasound to mitigate these issues [5, 6, 7]. Ultrasonic waves, when applied via transducers like those of the Langevin type, induce cavitation and microstreaming, which can weaken or dislodge scale layers, potentially reducing the rate of fouling without the need for harsh chemicals or frequent mechanical interventions. Recent studies have demonstrated the feasibility and effectiveness of inducing cavitation using high-power ultrasonic transducers in pressurized environments, such as vessels and pipelines [8]. Cavitation effects are known to enhance scale removal particularly at rough interfaces, as demonstrated for $CaCO_3$-coated metallic surfaces under ultrasonic exposure [9].

In this study, the application of high-power ultrasound transducers as an alternative strategy to reduce pipeline fouling in real iron ore filtration processes is investigated. Furthermore, the fouling samples were acoustically characterized. Propagation velocity, density, attenuation, porosity and acoustic impedance were measured. By introducing ultrasonic waves into critical segments of the pipeline system, we aim to disrupt the early formation of $CaCO_3$ deposits through mechanisms such as acoustic cavitation and surface vibration. The study is conducted under representative operating conditions of an industrial mineral processing unit, enabling a realistic evaluation of ultrasound's potential to reduce maintenance demands, improve process stability, and lower chemical consumption. The findings may contribute to more efficient, safer, and environmentally friendly scale control strategies in large-scale ore beneficiation operations.

Methodology

The ultrasonic system employed in this study was initially designed, fabricated, and experimentally characterized to ensure its applicability for fouling control in iron ore filtration pipelines. The design process focused on developing a high-power Langevin-type transducer to operate at a nominal frequency of 21 kHz.

The transducer design was carried out using finite element analysis (FEA) with the COMSOL Multiphysics software. A 2D axisymmetric geometry was employed to model the transducer configuration. The Solid Mechanics and Electrostatics modules were coupled and solved in the frequency domain, allowing the prediction of the electrical impedance response of the device.

Following the simulation model, the individual mechanical components of the transducer were machined based on the optimized geometry obtained from the numerical model. To validate the numerical model, the electrical impedance spectrum of the constructed transducer was measured using an impedance analyzer. Figure 1 presents a photograph of the built transducers.

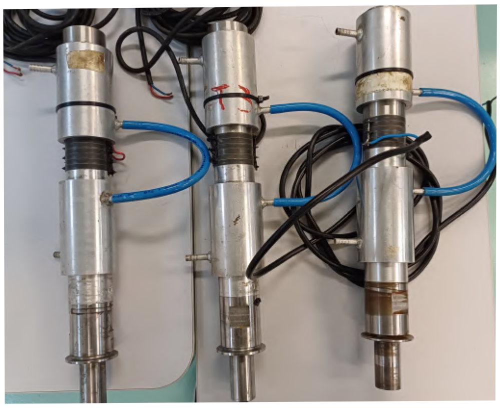

Fig. 1: Photograph of the build transducers.

The characterization of the fouling samples was carried out by means of transmission-reception tests in water. Two 1 MHz narrowband transducers were used for signal transmission and reception. By means of the acoustic signals that pass through the sample, it is possible to obtain important quantities such as sound propagation speed, attenuation, and acoustic impedance. Measurements of the density of the samples, as well as the level of porosity, were also carried out. These quantities are essential to understand the propagation of sound as it passes through the samples and thus design the appropriate ultrasound reduction system.

To validate the analysis regarding the effectiveness of ultrasound in reducing calcium carbonate ($CaCO_3$) fouling in pipelines, a closed-loop experimental circuit was constructed incorporating a 500 mm long section of 12-inch diameter carbon steel pipe. The pipe segment was sourced directly from an operational mineral processing plant. The pipeline was modified by welding two flanges to its ends. This allowed the system to be sealed using 12 mm thick acrylic covers, bolted to the flanges with screws and nuts. Additionally, five threaded studs were installed along the length of the pipeline to allow for the mounting of the ultrasonic transducers.

Five Langevin-type ultrasonic transducers were strategically mounted onto the pipe via custom-designed fixation points to ensure optimal acoustic coupling and spatial coverage of the inner wall. This setup was integrated into a recirculating fluid loop equipped with a centrifugal pump to maintain continuous flow, as illustrated in Figure 2. To prevent thermal degradation and ensure operational stability of the transducers during prolonged use, an individual heat exchanger was implemented for each unit, enabling effective thermal management throughout the experiments.

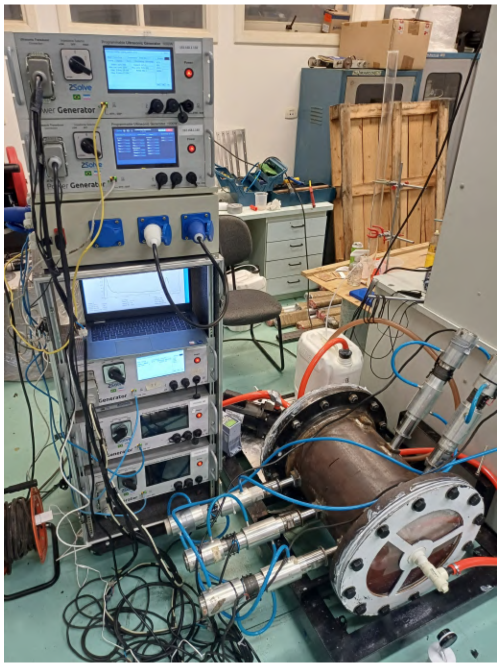

Fig. 2: Photograph of the experimental setup.

The fouling reduction laboratory experiments were conducted in four main steps to evaluate the effectiveness of power ultrasound in reducing mineral scale deposits in iron ore filtration pipelines sample. Initially, hot water circulation tests were performed, followed by tests using a 5% acetic acid solution and in both cases tests were performed with and without ultrasound. In the first step, only hot water at approximately $50\,^{\circ}\mathrm{C}$ was circulated through the encrusted pipeline for 3 hours without the application of ultrasound. In the second step, the procedure of the first step was repeated, with the addition of ultrasound effects. The five transducers were powered with an average power of 250 W. In the third step, a 5% acetic acid solution was used as the circulating fluid for a period of 180 min without the use of ultrasound, and in the last step, ultrasound effects were added together with the acid solution.

Results

Before conducting the scale reduction experiments using ultrasound high-power transducers, the fouling material inside the pipeline was characterized. Since the sample was collected from a real iron ore filtration plant, the incrustation contained not only calcium carbonate but also impurities such as iron oxide. To this end, fragments of the incrustation were carefully removed and subjected to ultrasonic characterization using the pulse-transmission technique. The setup employed two 1 MHz ultrasonic transducers. A total of five physical quantities were measured. Table 1 presents all quantities that were ultrasonically characterized.

Tab. 1: Ultrasonic characterization of incrustation material

Measurements	Values
Density [g/cm^3]	1.71
Speed of sound [m/s]	1022
Attenuation [dB/cm]	27.85
Impedance [MRayl]	2
Porosity [%]	13
Dry mass [g]	11.6
1 hour Wet mass [g]	13.8

Figure 3 presents the ultrasonic signals obtained during the characterization tests using the pulse-transmission setup with 1 MHz transducers. The graph shows two waveforms: one acquired with the incrustation sample positioned between the transducers, and another acquired in the absence of the sample, representing the reference signal. A significant reduction in amplitude and a delay in the arrival time can be observed in the presence of the fouling material.

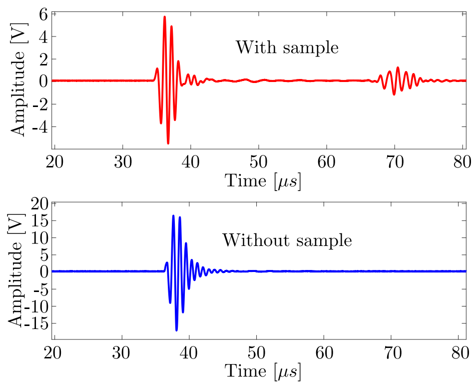

Fig. 3: Ultrasonic signals recorded during the pulse-transmission test with and without the incrustation sample between the transducers.

Following sample characterization, the fouling reduction experiments were conducted. Initially, hot water at 50 °C was circulated through the system for a period of 180 minutes without the use of ultrasound. This process resulted in the removal of 11 g of scale. Next, five Langevin-type transducers (each operating at approximately 200 W) were activated, and hot water was recirculated for the same duration of 180 minutes. A slightly higher amount of residue (19 g) was collected. However, the overall removal efficiency with hot water alone remained low, suggesting limited physical disaggregation of the deposits by ultrasound under these conditions. This behavior aligns with results from FEM-assisted ultrasonic descaling tests in industrial pipelines, which showed modest removal efficiency in the absence of chemical assistance [10].

The 5% acetic acid solution was prepared by mixing 1L of 100% acetic acid with 19L of pre-heated water at 50 °C. Each test lasted 40 minutes. As with the tests using water, the first experiment involved circulating only the acid solution without ultrasound activation, resulting in the extraction of 140 g of solid residue.

Subsequent tests were performed with ultrasound applied during the acid circulation. For this condition, three independent test batches were carried out, each lasting 40 minutes. The amounts of residue removed in these tests were 227 g, 169 g, and 175 g, respectively. All solid residues collected from each experiment were separated by decantation, dried, and weighed, confirming that the use of ultrasound significantly enhanced the descaling efficiency of the acid solution. Similar enhancement effects have been reported in other contexts, such as the ultrasonic cleaning of compact heat exchanger surfaces using high-power transducers [11].

Table 2 summarizes the amount of residue collected in each experimental test. The results indicate that the experiments using ultrasound were more effective than those performed with circulating acid alone. At the end of the test campaign, a total of 741.86 g of detached scale was collected. Compared to the estimated total mass of encrusted material prior to the tests (55 kg), the amount of residue removed corresponds to approximately 0.02% for the test with heated water alone, 0.034% for water with ultrasound, 0.22% for the test using acetic acid without ultrasound, and approximately 0.37% for each test using acetic acid combined with ultrasound.

Tab. 2: Mass of scale removed in each experimental test

Tests	Time	Reduction [g]
Water	180	11
Water and ultrasound	180	19
Acetic acid (AA)	40	140
AA and ultrasound	40	227
AA and ultrasound	40	169
AA and ultrasound	40	175

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Additionally, visual inspection revealed further reduction of incrustation due to the chemical reaction of acetic acid with calcium carbonate, which produces CO_2 and facilitates scale dissolution. Notably, increased degradation was observed in the region aligned with the position of the ultrasonic transducers. Figure 4 presents photographic records of the inner surface of the pipeline: (a) before the treatment, (b) a magnified view of the encrusted region, and (c) after ultrasonic application. A clear degradation of the scale layer is visible within the red dashed rectangle, which corresponds to the area directly aligned with the transducer installation.

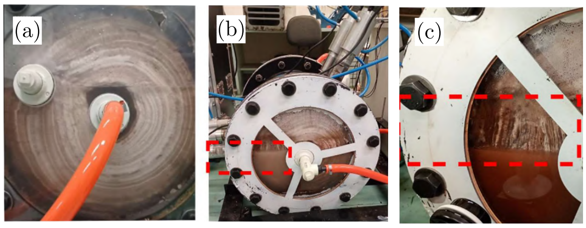

Fig. 4: Photographs of the pipeline's internal surface before and after ultrasonic treatment: (a) fouling surface before ultrasonic treatment, (b) a general view of the structure after the treatment, and (c) surface condition after ultrasonic application. The red dashed rectangle highlights the region aligned with the ultrasonic transducer, where more pronounced degradation of the scale was observed.

Conclusion and perspective

A detailed characterization of scale samples collected from the filtration process of an iron ore processing plant was conducted. The incrustation material exhibited high acoustic attenuation, which significantly limits the penetration of ultrasonic waves and prevents the occurrence of acoustic cavitation within the interior of the pipeline. As a result, the effective reduction of scale through ultrasonic treatment is severely hindered. Despite the modest descaling performance observed using power ultrasound, particularly in the removal of calcium carbonate deposits from the pipeline walls, the proposed system demonstrates potential as a preventive solution. Its application in continuous operation could inhibit early-stage scale formation, thereby reducing the frequency and intensity of required chemical or mechanical cleaning interventions.

References

[1] Z. Qu et al. "Influence of water flow velocity on fouling removal for pipeline based on eco-friendly ultrasonic guided wave technology". In: *Journal of Cleaner Production* 240 (2019), p. 118173.

[2] W. Ma et al. "Study on fouling characteristics of $CaCO_3$ at low reynolds number". In: *Environ Prog Sustainable Energy* 38 (2019), p. 13163.

[3] L. Zhang et al. "Corrosion-induced $CaCO_3$ fouling in steel tube of oilfield wastewater treatment and the interfacial bonding mechanism: An experimental and theoretical investigation". In: *Journal of Petroleum Science and Engineering* 205 (2021).

[4] J. B. R. Loureiro et al. "Large-Scale Pipe Flow Experiments for the Evaluation of Nonchemical Solutions for Calcium Carbonate Scaling Inhibition and Control". In: *SPE Journal* 28 (2023), pp. 201–214.

[5] Z. Qu et al. "Methodology for removing fouling within liquid-filled pipelines based on ultrasonic guided waves cavitation effect". In: *Applied Acoustics* 157 (2020).

[6] N. Kamar. "Scaling control by using ultrasonic guided waves". In: *Chemical Engineering and Processing - Process Intensification* 176 (2022).

[7] C. E. T. da Silva et al. "A New Ultrasonic Reactor for $CaCO_3$ Antiscaling in Pipelines and Equipment". In: *SPE Journaul* 28 (2023), pp. 215–225.

[8] N. Tanabi et al. "Fluid Cavitation Analysis in Pressurized Vessels Using High-Power Ultrasonic Transducers". In: *Proceedings of the 2024 IEEE UFFC Latin America Ultrasonics Symposium (LAUS)*. Montevideo, Uruguay: IEEE, 2024, p. 1.

[9] B. Pečnik et al. "Scale deposit removal by means of ultrasonic cavitation". In: *Ultrasonics Sonochemistry* 45 (2018), pp. 28–36.

[10] A. Mohammadi et al. "Improving the Descaling Rate of an In-Situ Ultrasonic Fouling Removal Method for Industrial Water-Filled Pipelines". In: *Preprint* (2023). arXiv/Research Square preprint. DOI: 10.21203/rs.3.rs-3281577/v1.

[11] H. Nasiri et al. "Cleaning of Printed Circuit Heat Exchangers (PCHE) Using High-Power Ultrasonic Transducers". In: *Proceedings of the 2024 IEEE UFFC Latin America Ultrasonics Symposium (LAUS)*. Montevideo, Uruguay: IEEE, 2024, p. 1.