C A P Í T U L O 6

PERFORMANCE EVALUATION OF NANOTREATMENTS FOR INJECTIVITY ENHANCEMENT: A COMBINED LABORATORY AND FIELD STUDY IN WATER DISPOSAL WELLS

Daniel F. Gómez
National University of Colombia, Medellin, Colombia

Lady J. Girlado
National University of Colombia, Medellin, Colombia

Camilo A. Franco
National University of Colombia, Medellin, Colombia

Farid B. Cortes
National University of Colombia, Medellin, Colombia

Carlos A. Franco
Ecopetrol S.A, Colombia

ABSTRACT: Handling large volumes of produced water often results in poor quality water with significant suspended solids, inorganic scale, and fats and oils (F&O). These contaminants clog injection/disposal wells, increasing energy consumption and greenhouse gas emissions. This study focused on the development and optimization of nanotechnology-based treatments to cost-effectively remediate and inhibit formation damage.Injection water from a Colombian oil field high in F&O and suspended solids was analyzed. Physicochemical tests, filter press tests, and SEM-EDS identified the damage-causing materials. A design of experiments optimized a treatment to remove over 95% of F&O (60-1000 mg/L). Three nano-treatments were evaluated for concentrations below 60 mg/L through water quality, injectivity, and high-pressure, high-temperature (HP-HT) remediation tests. A field test demonstrated the effectiveness of the nanofluid in reducing formation damage, injection pressure, energy consumption (6.08 GWh/year), and GHG emissions (4,029 tCO2e/year), with an OPEX savings of $0.49 MUSD/year. The longevity and adaptability of the treatment allows for a phased expansion, which is expected to have a significant positive impact and contribute to a cleaner oil and gas sector.

KEYWORDS: Water disposal, wells injection, Reservoir formation damage, nanotechnology, energy consumption analysis

INTRODUCCTION

During reservoir production, surface fluids include hydrocarbons (gas and oil) and an aqueous phase, with water-to-hydrocarbon ratios typically ranging from 3-10:1 (Al-Ghouti et al., 2019; Nonato et al., 2018). This ratio often escalates with well age and secondary recovery methods like water injection, reaching water cuts of 98-99% (Al-Ghouti et al., 2019). In Colombia, ECOPETROL S.A. reported 12 water barrels per oil barrel in 2016 (Suarez et al., 2016), and in the Eastern Llanos basin, approximately 4 million water barrels were produced per 170,000 oil barrels (Villegas et al., 2017) the Oil & Gas industry employs three produced water disposal methods: reservoir reinjection, effluent discharge, and surface uses. Reinjection, for pressure maintenance or enhanced recovery, is the most common due to environmental concerns (Amakiri et al., 2022). Produced water's composition varies, containing inorganic contaminants (salts, fine particles, heavy metals) and organic fractions (crude oil traces, bacteria, dissolved gases) (Klemz et al., 2021; Patni & Ragunathan, 2023). Treatment is crucial to meet disposal regulations, but high water volumes often result in inadequate contaminant removal, yielding low-quality water. Injecting this water can cause formation damage, reducing flow capacity and injectivity, and increasing injection pressures and energy costs (Bennion et al., 1998).

Specialized literature identifies suspended solids and inorganic scale precipitation as major contributors to reduced reservoir injectivity. However, the presence of fats and oils (F&O) significantly amplifies damage, as these organic fractions bind and aggregate solids, forming cakes at the formation face and within the reservoir (Khatib, 1994; Meyer, 1988; Nabzar et al., 1997; Nasr-El-Din, 1996; Rossini et al., 2020). Traditionally, chemical stimulation methods, employing acids, corrosion inhibitors, surfactants, solvents, and other additives, have been used to dissolve these cakes and plugs (Nasr-El-Din et al., 2000; Nasr-El-Din et al., 2004). However, reducing the chemical load and stimulation frequency is a significant challenge.Recent studies explore nanoparticle benefits for stabilizing solid particles and fines (Carpenter, 2021; Cheraghian & Hendraningrat, 2016; Ju & Fan, 2009; Madadizadeh et al., 2022). This study's objective is to design and optimize nanotechnology-based treatments for cost-effective remediation and inhibition of formation damage, leveraging nano-treatment interactions with injection fluids. The optimized nano-treatment was initially evaluated in the laboratory and subsequently pilot-tested in the field. Results demonstrated improved injectivity, reduced energy and economic costs, and decreased CO2e emissions, confirming the treatment's effectiveness in mitigating injection process damage.

METHODOLOGY

This work followed a structured experimental design consisting of: (a) initial characterization of field water samples to assess damage potential; (b) laboratory-based performance evaluation of nanotreatments using water quality and flow tests; (c) mixture design optimization of nanotreatment formulations validated under high-pressure, high-temperature conditions; and (d) field application and performance evaluation (Figure 1).

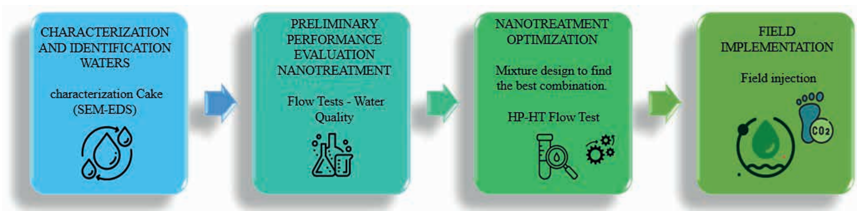


Figure 1. Outline Methodology carried out. (produced by the author)

Materials

Injection water from a Colombian field of interest supplied by Ecopetrol S.A. was used. The nanotreatments to be evaluated were of commercial origin, supplied by the national company based on previous experience. Initially, A1 and B1 nanotreatments were used in a preliminary performance evaluation. However, a third nanotreatment, B2, was then added to perform treatment optimization based on the type of damage to be addressed. For the development of the low pressure/low temperature (LP/LT) flow tests, a 3-1/2 (9.0 cm) diameter BX/100, grade 50 filter paper was used under static conditions. For high pressure/high temperature (HP/HT) conditions, an allozite filter with a pore size of 10 microns was used.

Methods

Initial characterization of the injection water is performed, including measurement of pH, density, conductivity, salinity, and dissolved solids, among other parameters, according to standardized analytical methods. Then, initial flow tests are performed to evaluate the damage potential of the injected water and the preliminary performance of the nano-treatments considered. This test will be carried out using a filter paper and a low pressure and temperature press according to API 13B-1 protocols, and the results will be characterized by SEM and EDS. First, the performance of A1 and B1 nano-treatments is evaluated and then the simplex centroid design of experiments is used to perform an optimization of the nano-treatment, including the B2 nano-treatment, evaluating the response of the system in terms of dissolution of organic fractions (evaluated by spectrophotometric tests) by varying the concentrations of the nano-treatments and the combinations between them, seeking the efficiency and the minimum number of tests required. The collected data are analyzed with STATGRAPHICS to optimize the performance of the process, using the results of previous G&A dissolution tests.

Following optimization of the nano-treatment through mixture design, the performance of the optimized nano-treatment is evaluated through flow tests at high pressure and temperature conditions to assess remediation and inhibition scenarios. Water is injected until loss of injectivity is achieved, followed by a soak time with the nano-treatment focused on cake dissolution and a post-flow test with water spiked with the inhibition nano-treatment. The HP-HT filter press operates at 400 psi and 130°F.

RESULTS AND DISCUSSION

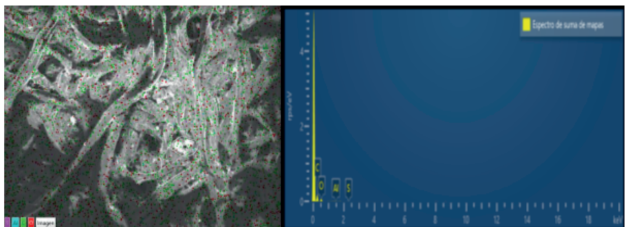
Injection Water Characterization and Damage Identification

Injection water characterization and damage identification Table 1 shows the results of the basic characterization of the injection water, highlighting the values of suspended solids and oils with values of 54.6 and 60.9 mg/L, respectively. On the other hand, there is evidence of high electrical conductivity, which reaches a value of 1519.6 mg/L.

Parameter	**Units**	**Injection Water**
ELECTRICAL CONDUCTIVITY	µS/cm	1519.56
TOTAL HARDNESS	mg $CaCO_3$/L	20.697
TOTAL SUSPENDED SOLIDS	mg TSS/L	54.6
OILS AND/OR GREASES	mg O&G/L	60.9
pH	pH Units	8.039
TURBIDITY	NTU	95.2

Table 1. Basic characterization of injection water.

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were used to characterize the solids retained on the filter paper from the water quality tests. The analysis revealed that the retained solids lack a well-defined morphology and exhibit an agglomeration pattern around the filter fibers, indicating a high carbon content. In addition, the presence of elements such as silicon, aluminum and sulfur was detected, indicating the formation of aluminosilicate-type precipitates. Carbon and oxygen were also identified, which may be associated with organic fractions or degradation by-products. These results provide valuable insights into the composition and potential sources of suspended solids in the water samples, and contribute to a better understanding of the physicochemical processes involved in their formation and deposition.



Espectro de suma de mapas							
Elemento	Tipo de línea	% peso	Sigma % peso	% atómico	Óxido	% óxido	Sigma % óxido
O	Serie K	72.59	0.92	66.66			
C	Serie K	27.14	0.91	33.20	CO2	99.46	3.34
Al	Serie K	0.20	0.07	0.11	Al2O3	0.38	0.12
S	Serie K	0.06	0.05	0.03	SO3	0.16	0.13
Total		100.00		100.00		100.00	

Figure 2. SEM and EDS analysis of solids retained on the filter paper of the injection water. (produced by the author)

Nano-Treatment Performance Evaluation

In order to evaluate the potential for damage to the injection water and its subsequent remediation by the incorporation of nano-treatments, flow tests through a filter paper were performed. Figure 3 illustrates the effect of nano-treatments A1 and B1, which were designed to control solids and promote the dissolution of organic fractions, respectively. The results show that these treatments significantly improved the volume of filtered water by 164% and 195% compared to the untreated injection water.

The graph shows that the normalized water flow rate decreases more rapidly in the base damage condition, while the systems with nano treatments maintain a more sustained flow rate throughout the experiment. In particular, the B1 treatment at 100 ppm shows the best performance, allowing a higher volume of filtered water.

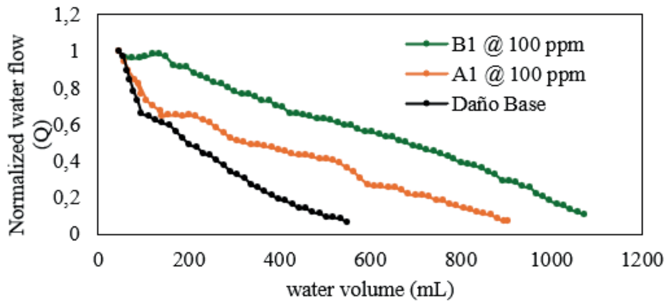


Figure 3. flow curves with injection water and with systems armed with A1 and B1 nanofluids at 100 ppm.(produced by the author)

Nano-treatment optimization with focus on dissolution of organic fractions

According to the results obtained in preliminary sections, a large part of the damage generated is related to the organic load in the injection water, so an improvement and optimization of a nanotreatment based on the addition of a preliminary stage of cake dissolution is proposed, so a simplex centroid type design of experiments is carried out with three nanotreatments focused on the dissolution of fats and oils. Nanotreatment B2 is included, which has a composition focused on the dissolution of organics enhanced with nanomaterials for it.

Figure 4 shows the response surface relating absorbance (as a measure of the dissolution capacity of organic fractions) to a color map. The results indicate that the optimal combination for the dissolution of fats and oils is 90% B2 and 10% of the B1 nanotreatment.

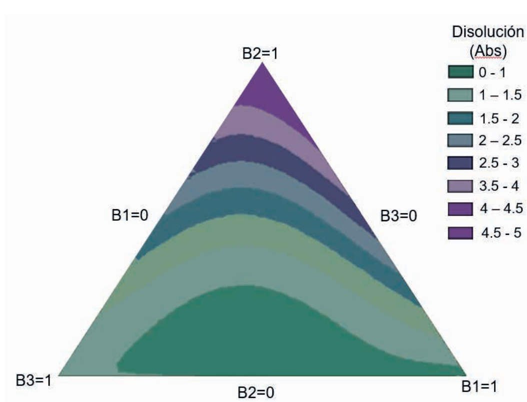


Figure 4. Design of simplex centroid experiments for remediation treatment optimization.(produced by the author).

Subsequently, the efficiency of the optimized nano-treatment (90/10 - B2/B1) was evaluated under high pressure and high temperature (HP-HT) conditions. Figure 5 shows that the optimized nano-treatment recovers 72% of the injectivity after soaking (remediation stage - cake removal). On the other hand, the B1 nano-treatment maintains a 66% increase in the volume of water passing through the disk after soaking, indicating a good damage inhibition capacity. A color change in the disc is also observed, which is evidence of dissolution of the cake formed.

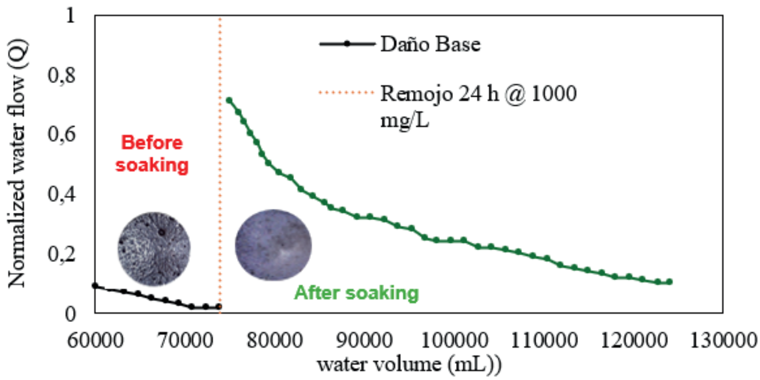


Figure 5. HP-HT test with soaking of 1000 mg/L of the 90/10 -B2/B1 mixture and postflow of 60 mg/L of B1 in the injection water.(produced by the author)

The results obtained in the evaluation of nanofluids are consistent with existing literature on the benefits of nanotechnology in remediation and reservoir damage control. Nanofluids demonstrated remarkable efficacy in solids control and organic fraction disaggregation, as evidenced from laboratory testing to field implementation of the technology.

Field Implementation

Based on the results obtained in laboratory under high pressure conditions, where the potential of nano-treatment for remediation and damage inhibition has been demonstrated, its implementation at field level in a well of interest located in the eastern basin of colombia has been considered. The selected well has experienced a progressive decline in its injection capacity since 2018, which has been attributed to the accumulation of schmoo. This material accumulates in the injection lines over time, reducing the available volumes and affecting the efficiency of chemical treatments. In addition, its entrainment by the water flow has caused clogging in the pore throats, leading to a loss of injectivity in the wells.

To mitigate these effects, a two-phase remediation nanofluid injection program was implemented (08/06 - 04/08/2022 and 01/11/2022 - 03/01/2023), injecting a total of 17,858 gallons into the injector well flow over a 60-day period. The results demonstrated a sustained recovery of injection capacity and a reduction in PAD injection pressure. In addition, the treatment restored the operational and energetic conditions of the PAD, achieving a longevity of effect of 16 months post intervention, as shown in Figure 6.

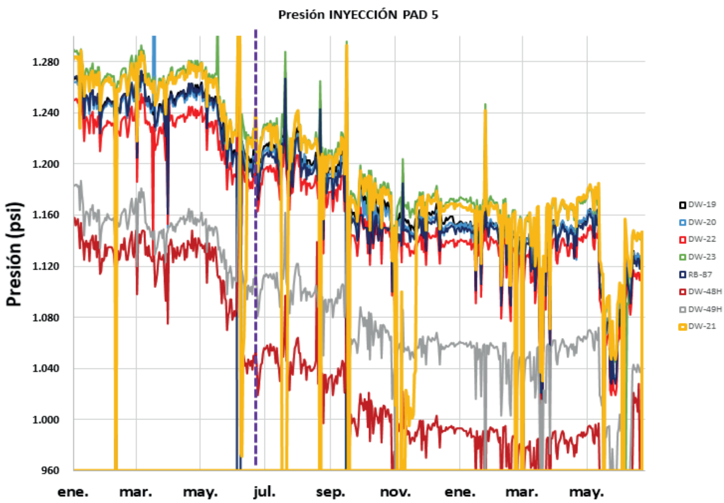


Figure 6. Injection pressure profiles of the different injection wells of the PAD under evaluation.(produced by the author)

With the injection of the nanofluid it has been evidenced that first there is a dissolution of the plugging that is generated in the injector wells, second it inhibits the solids-suspended mixture, grease and oil to be generated at some point of the injection system in the estimated time, and third with the restoration it improves the injectivity of the PAD as a whole allowing the dilution of the precipitated material and reducing the damage due to plugging in the pore throats. All this is evidenced by a significant reduction in the PAD during and after injection (up to 100 psi), reducing the skin of 25 to a value of 0, consequently restoring and mitigating formation damage.

CONCLUSIONS

The results indicate that the injection water carries an organic load that can contribute to clogging of the rock pores. However, nanotechnology has demonstrated significant benefits in stabilizing solid particles and enhancing the dissolution of organic fractions through surface interaction processes.

An optimized system has been developed to improve the dissolution efficiency of organic fractions at low concentrations, with positive results in both laboratory tests and field applications. In addition, this optimized system was found to be cost effective, resulting in a reduction in energy consumption of 6.08 GWh and a reduction in GHG emissions of 4.029 tCO_2e. These results highlight nanotechnology as a promising, efficient and sustainable solution for mitigating damage in water injection systems.

BIBLIOGRAPHIC REFERENCE

Carpenter, C. (2021). Nanotechnology Helps Decrease Pressure, Increase Injection in Offshore China Oil Field. Journal of Petroleum Technology, 73(09), 58-59.

Cheraghian, G., & Hendraningrat, L. (2016). A review on applications of nanotechnology in the enhanced oil recovery part A: effects of nanoparticles on interfacial tension. International Nano Letters, 6, 129-138.

Ju, B., & Fan, T. (2009). Experimental study and mathematical model of nanoparticle transport in porous media. Powder technology, 192(2), 195-202.

Khatib, Z. (1994). Prediction of formation damage due to suspended solids: modeling approach of filter cake buildup in injectors. SPE Annual Technical Conference and Exhibition?,

Madadizadeh, A., Sadeghein, A., & Riahi, S. (2022). The use of nanotechnology to prevent and mitigate fine migration: a comprehensive review. Reviews in Chemical Engineering, 38(1), 1-16.

Meyer, D. R. (1988). The water quality control station: a new monitoring tool for injection water. SPE Rocky Mountain Petroleum Technology Conference/Low-Permeability Reservoirs Symposium,

Nabzar, L., Coste, J.-P., & Chauveteau, G. (1997). Water quality and well injectivity. IOR 1997-9th European Symposium on Improved Oil Recovery,

Nasr-El-Din, H. (1996). Permeability Decline Due to Flow of Dilute Suspensions Through Porous Media. In. ACS Publications.

Nasr-El-Din, H., Al-Anazi, H., & Mohamed, S. (2000). Stimulation of water-disposal wells using acid-in-diesel emulsions: Case histories. SPE Production & Facilities, 15(03), 176-182.

Nasr-El-Din, H., Al-Mohammad, A., Al-Shurei, A., Merwat, N., Erbil, M., & Samuel, M. (2004). Matrix stimulation of water disposal wells using viscoelastic surfactant-based acid. SPE Asia Pacific Oil and Gas Conference and Exhibition,

Rossini, S., Roppoli, G., Mariotti, P., Renna, S., Manotti, M., Viareggio, A., & Biassoni, L. (2020). Produced Water Quality impact on injection performance: predicting injectivity decline for waterflood design. International Petroleum Technology Conference,

Suarez, A., Jaramillo, M. d., Gonzaléz, A., Londoño, J., & Pacavita, J. (2016). Gestión Integral de Recursos Hídricos. Bogotá: Ecopetrol.

Villegas, J. P., Arcila, N., Ortega, D., Franco, C. A., & Cortés, F. B. (2017). Remoción de hidrocarburos de aguas de producción de la industria petrolera utilizando nanointermedios compuestos por SiO2 funcionalizados con nanopartículas magnéticas. Dyna, 84(202), 65-74.

ACKNOWLEDGMENTS

The authors thank Ecopetrol S.A. for guaranteeing the successful application under real field conditions. The authors also thank the Universidad Nacional de Colombia for logistical support.