Development of multifunctional nanomaterials for the co-production of upgraded heavy crude oil and hydrogen at different pressures and temperatures

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Objective and Novelty

This thesis explores the development of multifunctional nanomaterials tailored to simultaneously improve the quality of heavy and extra-heavy crude oil and produce hydrogen at various pressures and temperatures. The novelty lies in the synthesis of advanced nanomaterials derived from lanthanide oxides, transition metal oxides, aluminosilicates, carbon-based materials, and composite structures, designed specifically for catalytic degradation of hydrocarbon macromolecules, heteroatoms, and crude oil under oxidation, gasification, and pyrolysis conditions. This dual-purpose approach not only addresses the need for more efficient crude oil upgrading but also supports the transition toward cleaner energy sources by enhancing hydrogen production as a complementary energy vector. These nanomaterials were designed to improve crude oil reactivity, reduce asphaltene aggregation, and increase hydrogen yield, all while operating at relatively low temperatures (<230 °C) and pressures up to 6.0 MPa. Additionally, the research investigates the integration of nanofluids into cyclic steam stimulation processes, demonstrating their potential to enhance oil recovery, improve crude quality, and increase hydrogen generation within the reservoir. This study highlights the successful scale-up and field implementation of synthesized nanoparticles into a cyclic steam stimulation process during field trials demonstrating their potential to enhance oil recovery, improve crude quality, and increase hydrogen generation within the reservoir. Additionally, the study confirmed that nanomaterials could capture and catalytically convert CO_2 into valuable gases, contributing to emission reduction and sustainable energy production.

Results

The results of this study encompass several key areas, including the thermal oxidation and reactivity of crude oil fractions, the catalytic performance of nanomaterials, hydrogen production, enhanced oil recovery, CO_2 capture and conversion, and sulfur removal. The catalytic performance of nanomaterials was evaluated using carbon xerogels and CeO_2 nanoparticles doped with Ni, Co, Fe, and Pd. Among the tested combinations, Ni-Pd-CeO_2 exhibited the highest catalytic efficiency, achieving 100% asphaltene conversion within 90 minutes at 220 °C while reducing activation energy by 80%. Morphological modifications further enhanced performance, with cubic Ni-Pd-CeO_2 demonstrating the best results due to its increased oxygen chemisorption capacity and lower decomposition temperatures. Hydrogen production was assessed during the catalytic steam gasification of asphaltenes and resins at low temperatures (<230 °C). The $CeNi_1Pd_1$ nanomaterial exhibited the highest hydrogen yield, achieving up to 55 vol% H_2 in the effluent gas, representing a 70% increase compared to non-catalytic systems. The integration of nanofluids into cyclic steam stimulation processes demonstrated significant improvements in oil recovery and crude quality. Injecting nanofluids dispersed in steam increased oil recovery by 25% during dynamic tests, with an additional 42% increase observed after a 12-hour soaking period compared to steam-only injection. Crude oil quality improved substantially, with API gravity increasing by 9.0° units (from 6.9° to 15.9°), representing a 130% increase. The study also demonstrated the potential of nanomaterials for CO_2 capture and catalytic conversion. Nanoparticles with adsorbed asphaltenes showed a higher tendency to capture CO_2, facilitating its catalytic conversion into valuable gases such as CO, CH_4, H_2, and light hydrocarbons. The most significant outcome of this study was the successful field application of the developed nanotechnology in a Colombian reservoir using cyclic steam stimulation (CSS). The field implementation of nanofluids in wells affected by steam injection demonstrated substantial improvements in oil production and quality. In Well A, treated between June and July 2022, the application of functionalized nanoparticles at a concentration of 500 $mg \cdot L^{-1}$ in a commercial carrier fluid resulted in an incremental production of 9,164 barrels of oil. Encouraged by these results, a second field trial was conducted in Well B between November and December 2022, leading to an additional production of 6,652 barrels. Both trials confirmed that nanofluids effectively enhanced oil mobility, reduced viscosity, and sustained improved oil quality over several months, validating the technology's scalability and broad applicability in enhanced oil recovery (EOR) operations. Hydrogen generation within the reservoir enhanced oil mobility, while CO_2 capture and conversion into CO, CH_4, and H_2 minimized emissions. The nanocatalysts maintained performance over multiple injection cycles, demonstrating their regenerative capacity, long-term efficiency, and industrial feasibility.

Conclusions

This study successfully advanced the nanofluid technology from TRL 3 to TRL 7, validating its effectiveness from laboratory experiments to field trials. The developed nanofluid significantly improved thermal enhanced oil recovery (TEOR) by enhancing oil production, asphaltene decomposition, in situ crude upgrading, hydrogen generation, and CO_2 capture and conversion. Field trials demonstrated increased oil recovery and API gravity, confirming improved crude quality and reservoir conditions. The nanofluid optimized hydrogen fugacity, promoting in situ upgrading while reducing hydrogen diffusion losses. Additionally, CO_2 capture and its catalytic conversion into valuable gases supported emission reduction and sustainable energy production. These findings confirm the scalability and industrial feasibility of nanofluid-assisted TEOR, positioning this technology as a promising solution for improving hydrocarbon recovery while supporting the transition to cleaner energy processes.

Related publications

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