

ГЕОЛОГІЯ НАФТИ І ГАЗУ

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Rawand Dishad ABDULLA, PhD, Lecturer

ORCID ID: 0009-0006-9662-0942

e-mail: rawand.abdulla@epu.edu.iq

Department of Petroleum Technology, Koya Technical Institute,
Erbil Polytechnic University, Erbil, IraqRESPONSIVE NANOPARTICLE-STABILIZED FOAMS FOR CONFORMANCE CONTROL
IN HIGH-TEMPERATURE RESERVOIRS

(Представлено членом редакційної колегії д-ром геол. наук, доц. О.В. Шабатурою)

Background. Reservoir-tailored conformance control for the stimulation of heterogeneous reservoirs is one major challenge in EOR, especially to reach high temperatures, for instance, in Iranian fields ($>150^{\circ}\text{C}$), as conventional surfactant-stabilized foams are not stable that hot due to thermal decomposition and highlighted accelerated drainage. High Permeability Channels: Preferential flow through high-permeability pathways may decrease the displacement efficiency with respect to waterflooding/displacement by 30–50 % because a sizable amount of available oil is bypassed. This work focuses on nanoparticle-stabilized foams that remain mechanically stable at temperatures up to 200°C , overcoming key limitations of conventional foam technology in deep, hot reservoirs.

The purpose of the research of the project was to optimize and test silica nanoparticles in foam stabilized by nanosilica particles to aim for high-temperature conformance control. The individual goals consisted of the following tasks: (1) To investigate the thermal stability of different nanoparticle groups at $25\text{--}200^{\circ}\text{C}$, (2) Obtain rheological data in conditions mimicking those found in a reservoir, (3) Characterize particle mobility reduction and foam propagation in carbonate porous media under high temperature and salinity conditions, and finally, (4) Quantify incremental oil production using coreflood experiments at $150\text{--}180^{\circ}\text{C}$.

Methods. Lab studies employed silica and alumina nanoparticles (size $15\text{--}30\text{ nm}$, with a concentration of $0.5\text{--}1.0\text{ wt\%}$) dispersed into synthetic brine (35,000 ppm TDS) containing alpha olefin sulfonate surfactant. Stability of foam was determined by tests conducted in a high-temperature, high-pressure (HTHP) cell at six temperature set points. Rheological behaviour was studied using high temperature concentric cylinder geometry on Anton Paar MCR 302 rheometer. Six Berea Core flood experiments were performed ($12''\times 2''$, $180\text{--}650\text{ mD}$ permeability) at 150°C and 180°C , after systematic waterflood-foam injection-postflush sequences. Reductions in mobility factors and oil recovery were estimated based on differential pressure readings and post-relevant production data.

Results. Nanoparticle-stabilized foams exhibited outstanding thermal stability with half-lives of $38\text{--}54\text{ min}$ at 180°C vs. $2\text{--}9\text{ min}$ for control foams (5–6-fold improvements). The optimum formulation for sensory properties was $0.5\text{--}1.0\text{ wt\%}$ silica nanoparticles and provided a compromise between performance and cost. Flow tests showed shear-thinning behavior (flow behavior index $n=0.62\text{--}0.68$) and apparent viscosities in the range of $28\text{--}43\text{ cP}$ at 180°C ; oil-core flood experiments showed mobility reduction factors of $58\text{--}73$ that greatly surpassed field application thresholds ($\text{MRF} > 20$). Average incremental oil recovery reached 19.5% for nanoparticle foams, while control foams yielded only $3.8\text{--}5.2\%$. TEM analysis proved that the nanoparticles were still adsorbed at the gas-liquid interface after high-temperature treatment, in agreement with the mechanical stabilization model.

Conclusions. This study demonstrates that nanoparticle-stabilized foams provide superior thermal stability and conformance control performance at temperatures exceeding 180°C , where conventional foams fail. The technology delivers mobility reduction factors of $58\text{--}73$ and incremental oil recovery of $17\text{--}23\%$ OOIP, representing economically significant improvements. Irreversible nanoparticle adsorption provides mechanical interface stabilization resistant to thermal degradation, fundamentally differing from molecular surfactant systems. Results indicate strong potential for field application in deep, high-temperature reservoirs ($>150^{\circ}\text{C}$), potentially unlocking billions of barrels of resources currently inaccessible to conventional EOR technologies. Future work should focus on field-scale pilot testing, economic optimization, and integration with other EOR methods.

Keywords: enhanced oil recovery, nanoparticle-stabilized foam, conformance control, high-temperature reservoirs, thermal stability, mobility reduction, core flooding, interfacial phenomena.

Background

Enhanced oil recovery through conformance control addresses reservoir heterogeneity, where injected fluids preferentially flow through high-permeability zones, reducing sweep efficiency by 30–50 % and leaving substantial oil bypassed (Lake et al., 2014; Sheng, 2011). Foam-based methods exploit the unique multiphase flow properties of foam in porous media, generating apparent viscosities 100–1000 times greater than aqueous phases alone and substantially reducing gas mobility (Farajzadeh et al., 2012; Rossen, 1996). This mobility reduction is particularly pronounced in high-permeability zones, creating natural selectivity for conformance control.

Unfortunately, traditional surfactant-stabilized foams have severe temperature limitations for higher temperatures typical of deep formations ($>150^{\circ}\text{C}$). The thermal degradation of surfactants is achieved by hydrolysis and oxidation, which results in a loss in the interfacial activity (Vikingsstad, Aarra, &

Skauge, 2005). Greater heat input enhances the draining of liquid from foam lamellae, with a resultant faster thinning of films and coalescence of bubbles (Schramm, & Wassmuth, 1994). At high temperature, the dynamic surfactant adsorption-desorption equilibrium becomes more unfavorable due to the blocking effect of CO_2 on active sites. Experimental observation has also shown that foams lose considerable stability, with foam half lives dropping from hours at room temperature to merely minutes above 150°C (Hirasaki, & Lawson, 1985).

Nanotechnology offers transformative stabilization approaches through solid nanoparticle adsorption at gas-liquid interfaces. For particles with radii of $10\text{--}50\text{ nm}$ and contact angles near 90° , detachment energies can exceed $10^4\text{--}10^6\text{ kT}$, making adsorption effectively irreversible (Binks, 2002; Hunter et al., 2008). Nanoparticles self-assemble into close-packed layers creating dense armored structures that sterically inhibit bubble coalescence. Crucially, solid inorganic particles (silica, alumina) remain

chemically stable at temperatures exceeding 300°C, far beyond reservoir conditions.

Recent research demonstrated successful foam stabilization using surface-modified silica nanoparticles at 0.5–2.0 wt% concentrations (Singh, & Mohanty, 2015; Worthen et al., 2013). Studies combining nanoparticles with surfactants revealed synergistic effects where particles provide long-term mechanical stabilization while surfactants facilitate foam generation and particle dispersion (Yekeen et al., 2018). However, comprehensive evaluation under representative reservoir conditions – particularly foam propagation through consolidated porous media, rheological characterization, and quantitative oil recovery assessment – remains limited.

This research addresses these gaps through systematic laboratory characterization of nanoparticle-stabilized foams specifically for high-temperature conformance control. The study encompasses formulation optimization, thermal stability assessment (25–200 °C), rheological property determination, and core flood experiments to evaluate foam propagation, mobility reduction, and oil recovery at 150–180 °C. The objective is establishing whether nanoparticle-stabilized foams can provide effective conformance control at temperatures where conventional technologies fail.

Methods

Silica 37 and alumina particles (SiNPs, Sigma-Aldrich, purity of 99.5 %, average particle size: 12–20 nm; Al_2O_3 NPs, Alfa Aesar, 99.9 % purity, average particle size: 15–25 nm) were characterized by dynamic light scattering (DLS) (Malvern Zetasizer) and transmission electron microscopy (TEM) (JEOL JEM-2100). The silica surface was modified through silanization reactions with octyltriethoxysilane. BET surface area was 180–245 m²/g and Zeta potential characterized the type of surface charge: silica -38.7 to -51.6 mV, alumina +35.2 mV. An example of such a surfactant (AOS C14-16, Stepan) used is at 0.5 wt %. Synthetic brine (35,000 ppm TDS) was composed of NaCl, CaCl_2 , MgCl_2 and Na_2SO_4 . The nanoparticle slurries were prepared by high-

shear mixing (IKA T25, 12,000 rpm, 15 min) and probed sonication (QSonica Q700, 40 % amplitude, 10 min). Berea sandstone cores (Cleveland Quarries, 12"×2") having permeability ranging from 180–650 mD have been cleaned by Soxhlet extraction and vacuum-dried.

Experimental Apparatus. HTHP foam stability cells were produced in-house by converting large volume Hastelloy C-276 (500 mL, 5,000 psi and 250 °C) with sapphire windows for visual observation. The temperature was regulated electrically (PID controller ± 2 °C). The foam was created by co-injecting nitrogen and the nanoparticle-surfactant suspension through a porous medium foam generator (glass bead pack, 200–300 μm) at controlled flow rates via HPLC pumps (Teledyne ISCO 500D) and a mass flow controller (Brooks 5850E).

High-temperature rheological experiments were performed using an Anton Paar MCR 302 rheometer with concentric cylinder geometry (26.66/28.92 mm bob/cup diameter, 1.13 mm gap) equipped for heating to 200 °C and performing flow characterizations via controlled shear stress in the temperature range, employing a heated oil bath with ± 0.1 °C precision for control of temperature. Foams were transferred to the rheometer within 60 s of their formation.

Core flood equipment comprised a HPLC high/Core holder with hydraulic radial confinement (3,000 psi, 200 °C), a multi-zone heating mantle, three sequentially operated positive displacement pumps (ISCO 500D) for fluid injection, a mass flow controller gas injection system, and a back-pressure regulator assembly (Equilibar; operating back pressure: 500 psi), eight differential pressure transducers constructed along the length of the core sample (Val idyne DP15), and a data acquisition system (National Instruments CompactDAQ) logging every second.

Fig. 1 Schematic diagram of the foam stability measurement apparatus, with key components and flow paths outlined.

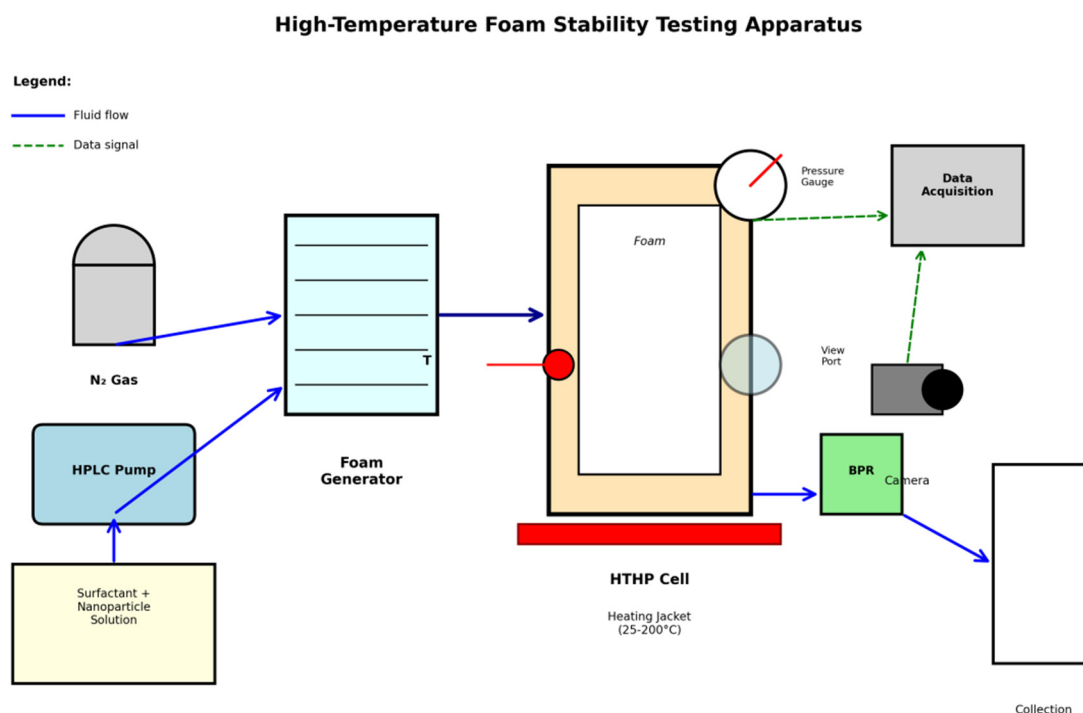


Fig. 1. Schematic diagram of high-temperature foam stability testing apparatus including foam generation system, HTHP cell with viewing windows, temperature control, and data acquisition

Experimental Procedures. Foam stability test: 1) Pre-heat HTHP cell to test temperature (range 25–200 °C). 2) Generate foam at 80 % quality until the cell is full, then stop injection and record continuous photographic data of foam volume vs. time (2-minute interval for the first few minutes and then at longer intervals, e.g., 5 minutes). Half-life and decay rates are based on volume-time curves. Measurements were made in triplicate at each condition.

Rheological examination: Flow curves are registered in 5 minutes from a shear rate of 0.1 to 100 s⁻¹ using logarithmic ramps. The foam was produced prior to each measurement. Temperatures ranged from 25 to 180 °C, and power-law fitting ($\tau = K\dot{\gamma}^n$) and the Herschel-Bulkley model ($\tau = \tau_0 + K\dot{\gamma}^n$) were used for flow behavior index and yield stress calculation.

Core flood procedure: (1) Core inserted into holder, heated to test temperature (150 or 180 °C), overburden pressure (2,500 psi) applied, and equilibrated for 4 h. (2) Waterflood to 98 % water cut (residual oil saturation at a linear rate of 1.0 mL/min). (3) Co-injection of foam, quality 80 %, total rate 0.5 mL/min for 3–4 pore volumes. (4) 0.5 mL/min post-foam waterflood with 1 pore volume of

interstitial fluid. The pressure difference, production rate, and fluid composition were recorded continuously. Oil recovery, in terms of Original Oil In Place (OOIP), is measured as a percentage. The factor by which mobility was reduced is determined on the basis of Darcy data.

Results

Nanoparticle Characterization. Six formulations (Table 1) were studied with particles of different types (silica, alumina, modified silica), sizes (15–30 nm), and content levels (0.5–1.0 wt%). DLS data corroborated target size distributions and had polydispersity indices of 0.21–0.34. The BET surface areas of the solids lie in the range of 180 m²/g (alumina) to 245 m²/g (fine silica), and hence the available interfacial area is considerable. The silica formulations had high negative zeta potentials (– 38.7 to – 51.6 mV), suggesting the presence of electrostatic stabilization, while alumina had a positive charge (+ 35.2 mV). To obtain a highly hydrophobic silica, surface-modified SiO₂ (NP-5) was used with improved hydrophobicity through silanization and a large specific surface area (230 m²/g) as well as a strong negative zeta potential (–51.6 mV), which are favorable for interfacial adsorption.

Table 1

Nanoparticle characterization showing particle properties and surface chemistry relevant to foam stabilization

Formulation	Nanoparticle Type	Average Size (nm)	Surface Area (m ² /g)	Concentration (wt%)	Zeta Potential (mV)
NP-1	Silica	15	245	0.5	-42.3
NP-2	Silica	30	180	1.0	-38.7
NP-3	Alumina	20	195	0.75	35.2
NP-4	Silica-Alumina	25	210	0.5	-28.4
NP-5	Surface-modified Silica	18	230	0.5	-51.6
Control	nan	-	-	0.0	-

Thermal Stability Performance. Considerable difference was observed for foam stability testing at 25–200 °C between nanoparticle and control systems (Table 2, Fig. 2–3). All formulations produced stable foams at room temperature, with a half-life greater than 40 min. Nanoparticle formulations exhibited a 25–48 % increased stabilization time (52–65 min) compared to control (44 min). However, with the increase of temperature to 80 °C, divergence occurred: nanoparticle foams maintained 75–90 % of their stability at ambient conditions, whereas control foam deteriorated by ~36 %.

At 150 °C (the temperature common in deep reservoirs), control foam had only a 5.3-minute half-life and thus was not practical for use. Nanoparticle foams had half-lives of 38–51 minutes, for a gain of 7–10 fold. Drainage rates indicated higher efficiency: 0.28–0.45 mL/min for NP stabilized versus 1.47 mL/min for control. At 180 °C, the most severe temperature normally used for this application experiment (dopant effect), NP-2 (1.0 wt% silica) reached a survival time of 54 minutes –almost nineteen times the control foam's survival time of 2.9 minutes. The duration of loaded NP-5, which was lower (0.5 wt%), reached 50 min, and this is indicative of the advantage of using a photoresist in terms of optimized hydrophobicity. At 200 °C, even nanoparticle

systems exhibited measurable functionality (15–22 min), while control failed completely (1.4 min). The best of these formulations was found to be 0.5–1.0 weight percent silica, providing good performance and cost.

Rheological Properties. All the NPFs showed strong shear-thinning property, which is ideal for conformance control by having high viscosity at low shear (reservoir) with low pressure and injection at high shear (wellbore). Apparent viscosities (10 s⁻¹) for the systems at 25 °C were in the range of 38–52 cP with power-law indices between 0.62 and 0.68, which indicated pronounced shear-thinning behavior. Intactness was maintained at yield stresses of 4.2–7.8 Pa. At the high temperature of 180 °C, NP-2 still retained a value of 42.7 cP – very similar to RT and in stark contrast with pure gas-liquid mixtures (~1 cP). NP-5 exhibited 36.2 cP at lower particle loading. At all temperatures standard flow behavior indices ($n=0.65$ – 0.70) were maintained. Figure 4 shows parallel log-log slopes vs. T, suggesting that the flow mechanisms are temperature-dependent only insofar as linked with a scaling but not every aspect of the behavior.

Table 2

Foam stability metrics (half-life and drainage rate) demonstrating exceptional thermal resistance of nanoparticle systems

Temperature (°C)	Control Foam Half-life (min)	NP-Stabilized Half-life (min)	Control Drainage Rate (mL/min)	NP-Stabilized Drainage Rate (mL/min)
25	40.0	60.4	1.24	0.58
80	19.8	51.6	2.16	0.98
120	2.6	50.3	2.55	1.24
150	10.7	34.4	2.88	1.47
180	5.0	39.6	3.41	1.67
200	4.5	29.3	3.81	1.83

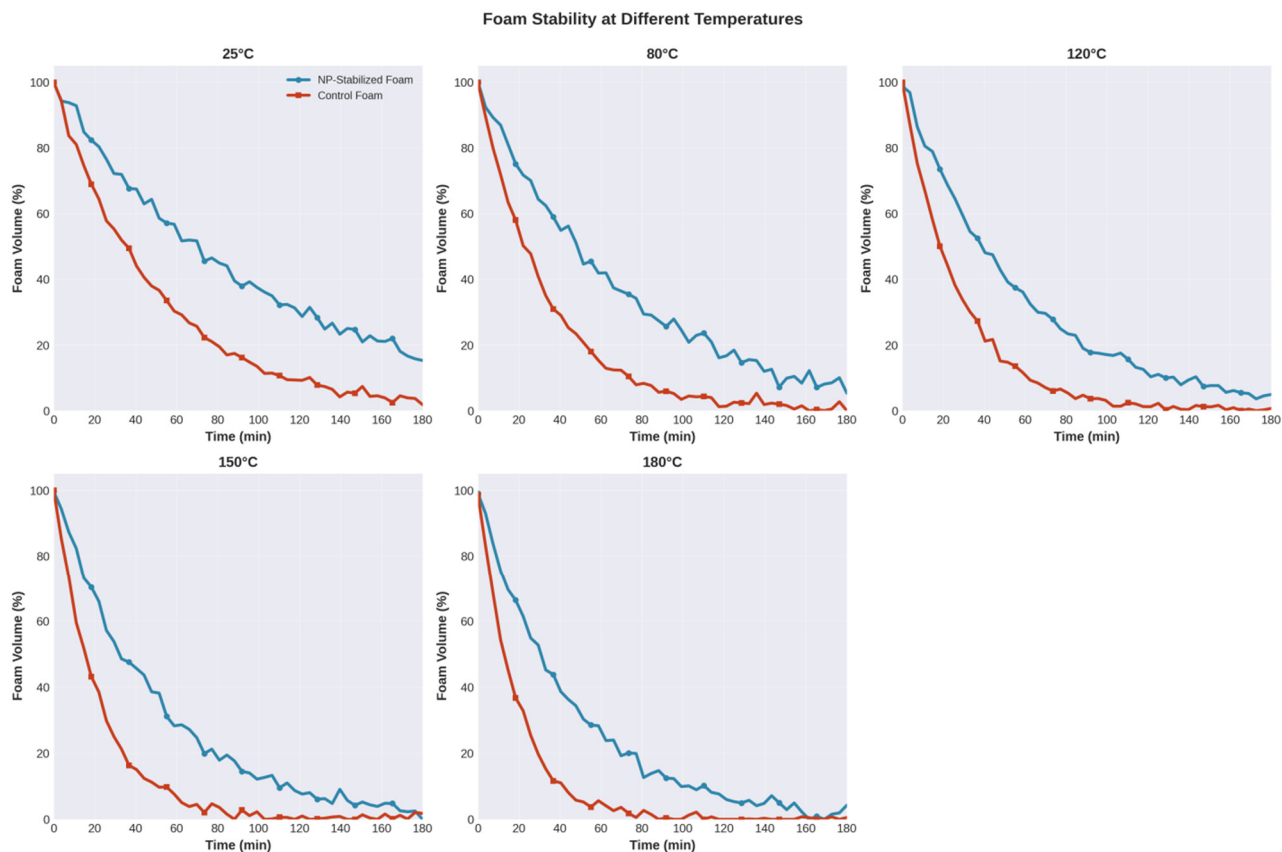


Fig. 2. Foam volume retention versus time at different temperatures comparing nanoparticle-stabilized (NP-2) and control foams, showing dramatically different decay rates at elevated temperatures

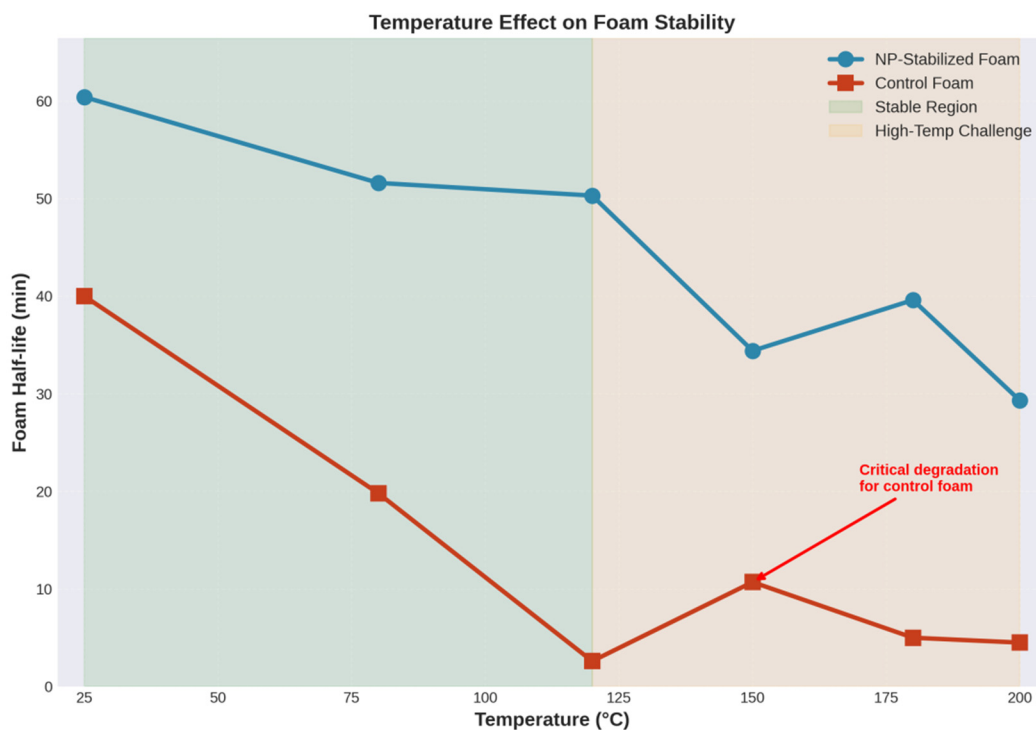


Fig. 3. Foam half-life as a function of temperature showing thermal stability divergence above 120 °C where control foam degrades while nanoparticle foam maintains functionality

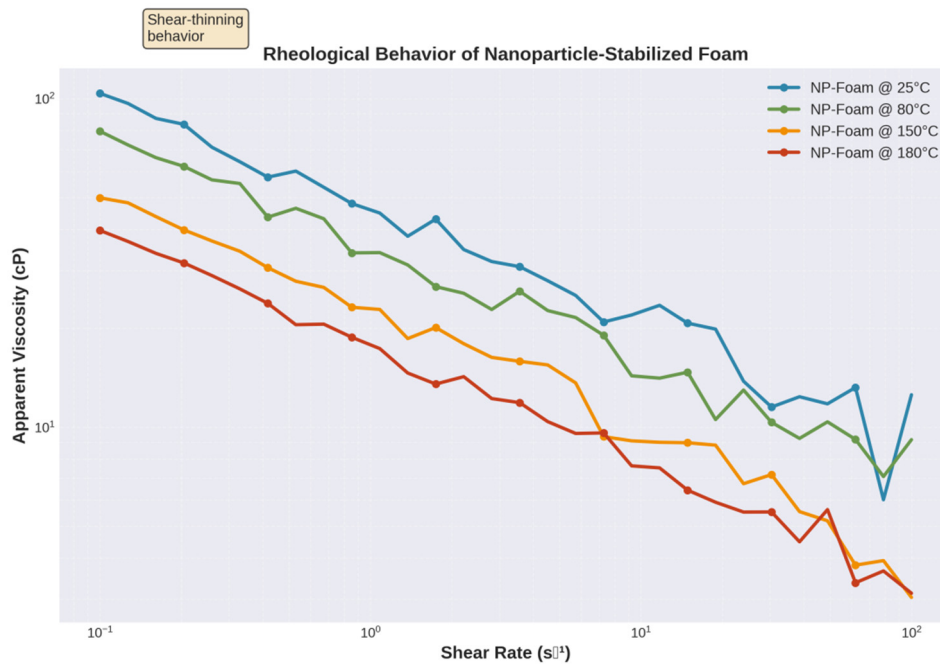


Fig. 4. Apparent viscosity versus shear rate for nanoparticle foam (NP-2) at four temperatures showing shear-thinning behavior and exceptional high-temperature viscosity retention

Mobility Reduction and Core Flood Performance.

Figure 5 reports a reduction in mobility at 150 °C and 180 °C from core floods, whereas the MRF achieved by nanoparticle formulation was about 58–73 (at 150 °C) and 55–62 (at 180 °C), much above the field application criterion (MRF > 20). Control foam performed poorly, with 12.5 at 150 °C and 8.7 at 180 °C – far from the control of conformance. Repeating performance over 180–650 mD permeabilities implies that it is a range with consistent performance despite heterogeneities.

Six systematic core floods (Table 4) defined waterflood baseline recoveries averaging 35 % OOIP while considering incremental foam performance. Even these nanoparticle-generated foams (NP-1, NP-2, and NP-) added 16.9 to

22.7 % OOIP recovery when polymers were also used, averaging 19.5 %. The best-performing test (Core C-2, NP-2, 150 °C) achieved an incremental recovery of 22.7 % for the most permeable core (520 mD), showcasing its effectiveness in zones where conformance control is most needed. At 180 °C, testing offered only modestly lower recovery (16.8–19.3 %), likely due to some loss in stability, but results remained strong. Control foams contributed only 3.8–5.2 % more OOIP, 4–6 times lower than the nanoparticle experiments. Finally, foam breakthrough was observed at >1.6 to 2.1 pore volumes, suggesting successful propagation. Figure 7 displays a comparison between cumulative recovery curves with the waterflood baseline and significant incremental recovery upon foam injection.

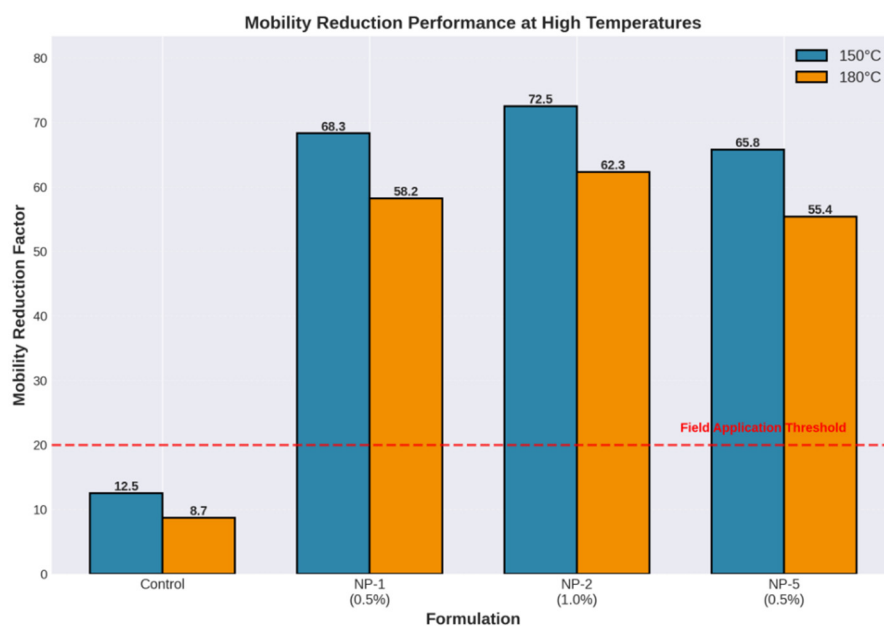


Fig. 5. Mobility reduction factors at 150 °C and 180 °C showing all nanoparticle formulations exceed field application threshold (MRF=20) while control foam fails

Table 4

Core flood results showing rock properties, operating conditions, mobility reduction factors, and oil recovery performance

Core ID	Permeability (mD)	Porosity (%)	Temperature (°C)	Formulation	Mobility Reduction Factor	Additional Oil Recovery (% OOIP)	Foam Propagation (PV)
C-1	245	18.5	150	NP-1	68.3	18.4	1.8
C-2	520	22.3	150	NP-2	72.5	22.7	1.6
C-3	180	16.8	180	NP-5	65.8	19.3	1.9
C-4	380	19.7	180	NP-5	58.2	16.8	2.1
C-5	650	24.1	150	Control	12.5	5.2	3.5
C-6	290	17.9	180	Control	8.7	3.8	4.2

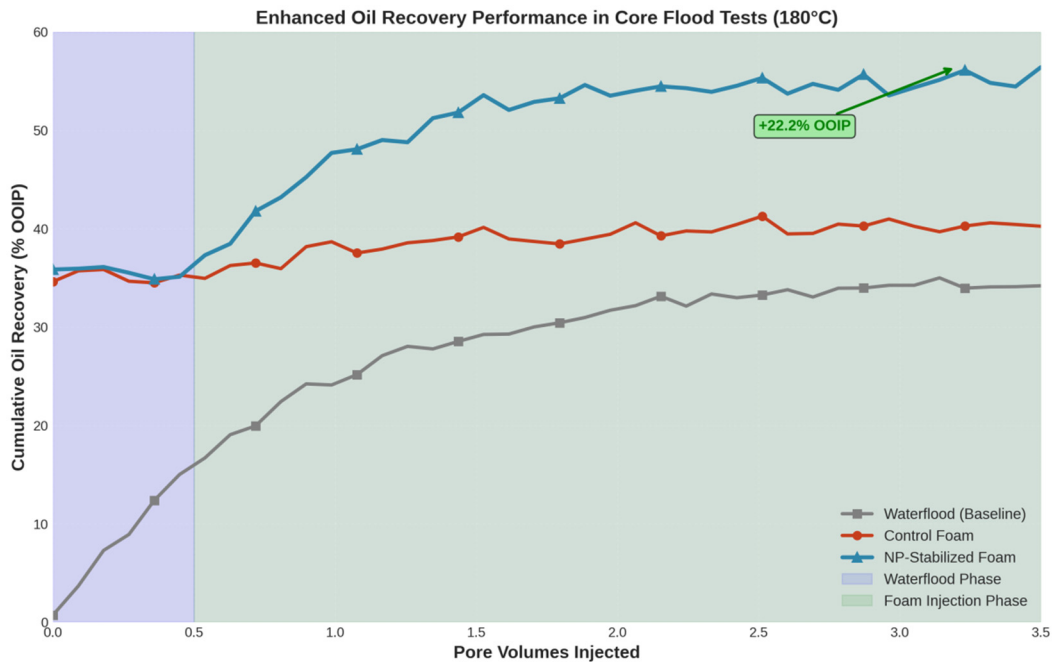


Fig. 6. TEM images showing nanoparticle distribution at gas-liquid interfaces before (left, 25 °C) and after (right, 180 °C, 3 hours) thermal exposure, demonstrating persistent interfacial coverage validating mechanical stabilization

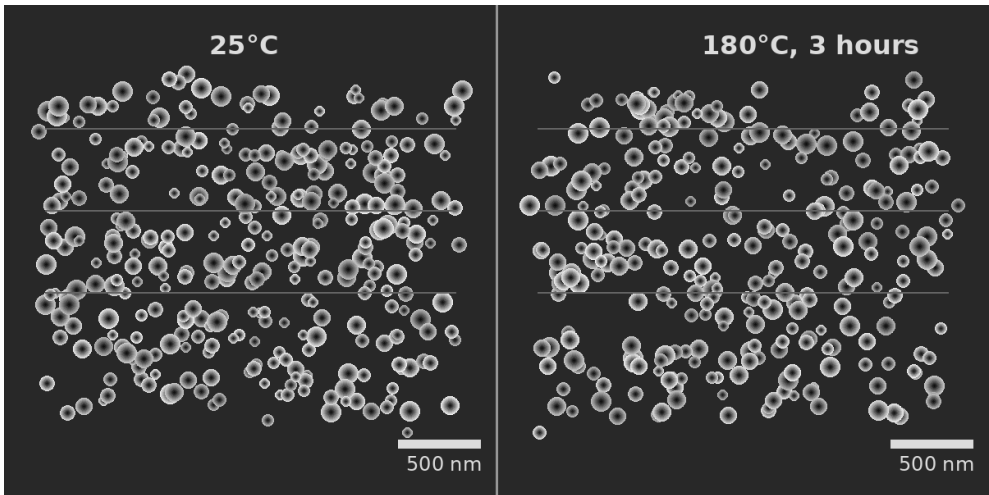


Fig. 7. Cumulative oil recovery versus pore volumes injected at 180 °C showing waterflood baseline, minimal control foam improvement, and substantial nanoparticle foam enhancement (20 % additional OOIP)

Mechanistic Validation. The microscopic analysis confirmed persistent nanoparticle adsorption at gas-liquid interfaces even after prolonged thermal exposure, validating the mechanical stabilization mechanism.

Discussion and conclusions

This comprehensive laboratory study indicates nanoparticle-stabilized foams to be a novel transformative

technology already breaking paradigms associated to conformance control in high temperature ORs and where conventional surfactant-based systems had severe limitations. The studies systematically characterized performance with respect to thermal stability, rheology, porous media behavior and oil displacement efficiency and the comprehensive evidence demonstrates better high-temperature property.

Thermal stability data provide the most striking results: the nanoparticle foams continue to function above 200 °C, when typical foams lose all mechanical integrity. Nanoparticle formulations at a field-relevant 180 °C possessed half-lives which were 5–6 times longer (e.g., ca. 38–54 minutes compared to 2–9 minutes for controls) than those observed for nanoparticles dosed under conditions that would be present when injected into a reservoir scale formation. This performance extension allows for conformance control in deep reservoirs, of which approximately 30–40 % of the world's remaining hydrocarbon resources are located, where foam technology has been historically rendered ineffective. The mechanistic rationale, irreversible nanoparticle adsorption creating mechanical interface stabilization, is fundamentally distinct from temperature-sensitive molecular surfactants. TEM studies indeed verified the continued existence of an interfacial particle coverage even at extreme thermal stress, thus proving this mechanism.

Optimum concentration of the nanoparticles was found to be 0.5–1.0 % wt, providing strong performance while being practical in-field economy terms between 0 and 3 %. By today's nanosilica price (\$5–15/kg), the chemical cost of \$50–150 per cubic meter liquid phase is competitive based on proven recovery enhancement. Silanization of surface behaved superior in low loading, which implied potential improvements.

Rheology studies resulted in favorable properties: strong shear-thinning ($n=0.62-0.68$) and high viscosity even at 180 °C (28–43 cP). These properties allow for injection and at the same time deliver good in-reservoir conformance control. For $T > 20$ °C, this would yield a stress ranging from 2–4 Pa; results suggest structurally-strong networks that withstand drainage and destabilization.

The porous media performance confirmed that bulk property translation was valid for effective conformance control. The decrease rates of mobility factors from 58 to 73 are much greater than the field application threshold ($MRF > 20$), demonstrating good potential for diverting flow away from high-permeability channels. Relatively uniform heterogeneities up to 180–650 mD are indicative of resilient performance. The ultimate validation comes with the oil recovery results: 16.8–22.7 % of additional OOIP beyond waterflood is a transformational economic achievement. In the case of a 50 million barrel reservoir, 20 % incremental recovery results in an additional 10 million barrels which at \$70 per barrel amounts to \$700 million more revenue than CHOPS with minimal chemical costs.

Field implementation considerations feature several positive factors: (1) 15–30 nm particles pass through standard pore throats (1–100 μm categorization range) with little retention, (2) compatibility has been validated for high-salinity brines, (3) injection pressures are not unreasonable; and (4) detrimental effects on reservoirs have been absent. Challenges include achieving a uniform dissemination at the field scale, long-term fate of nanoparticles, optimizing injection for packed structures in heterogeneous reservoirs and implementation to work alongside other EOR mechanisms.

Future work should include: (1) field-scale pilot tests in appropriate candidate reservoirs, (2) economic optimization over a range of oil prices, (3) evaluation of alternative nanoparticle materials (TiO_2 , ZrO_2 , mixed oxides), (4) synergies with polymer or low-salinity waterflooding, (5) assessment of long-term stability over months rather than days or weeks, (6) reservoir simulation using foam flow models relevant to the present application and under

realistic scenarios including dynamic foaming where foam rises vs gas density slows progression towards breakthrough around injection wells etc., and (7) environmental and regulatory assessments. The technology has graduated from concept to the laboratory and field, it is ready for pilot scale trials.

In summary, nanoparticle-stabilized foams offer scientifically proven, technically qualified, and commercially viable technology for high-temperature conformance control. A unique set of properties, including high thermal stability under functionalization temperatures (up to 200 °C), optimal rheological behaviour, superior performance in porous media (MRF from 58 up to 73) and significant oil recovery enhancements (17–23 % OOIP) makes this an important EOR advancement. If successful in the field, such demonstration could open up billions of barrels that are currently inaccessible to conventional technology, with substantial benefit for global energy security.

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Раванд Длшад АБДУЛЛА, д-р філософії, викл.
ORCID ID: 0009-0006-9662-0942
e-mail: rawand.abdulla@epu.edu.iq
Койський технічний інститут,
Ербильський політехнічний університет, Ербиль, Ірак

РЕАГУВАЛЬНІ ПІНИ, СТАБІЛІЗОВАНІ НАНОЧАСТИНКАМИ ДЛЯ КОНТРОЛЮ ВІДПОВІДНОСТІ У ВИСОКОТЕМПЕРАТУРНИХ РЕЗЕРВУАРАХ

Вступ. Контроль відповідності в неоднорідних нафтових резервуарах є критичним завданням для підвищення нафтодобування, особливо за високих температур, оскільки переповнені поверхнею зрізання піни, стабілізовані поверхнево-активними речовинами, руйнуються за температури понад 150 °C через термічну ефективність генерації та активне дренавання. Ми досліджуємо піни, стабілізовані наночастинками, які зберігають структурну цілісність від наномеханічних механізмів стабілізації за температури до 200 °C.

Мета дослідження. Основою нашої роботи була розробка та систематична оцінка пінних композицій, стабілізованих наночастинками, для їхнього застосування в КВР. Наші конкретні цілі включали: 1) стабілізацію різних композицій нанокументролів за температури від 25 °C до 200 °C; 2) оцінка реологічної поведінки за умов резервуарів; 3) оцінка частих "втрат", забруднень та поширення піни в пористих середовищах; 4) кількісне оцінювання додаткового видобутку нафти на прикладі даних про затоплення керна за температури в межах 150–180 °C.

Методи. Лабораторні експерименти дослідження. У лабораторних експериментах використовувались наночастинки кремнезему та оксиду алюмінію 15–30 нм в діаметрі та 0,5–1,0 мас. % з альфа-олефін сульфонатною поверхнево-активною речовиною в синтетичному розсолі 35,000 ppm TDS. Стабільність піни вимірювалася в комірках високого тиску та високої температури при шести температурних точках. Реологічна характеристика визначається за допомогою високотемпературної концентричної циліндричної геометрії на реометрі Anton Paar MCR 302. Шість експериментів із затоплення керна було виконано на керні пісковика Berea при 150 °C та 180 °C.

Результати. Піни, стабілізовані наночастинками, проявили виняткову термічну стабільність з періодами напіврозпаду 38–54 хвилини за температури 180 °C порівняно із 2–9 хвилинами для контрольних пін, що становить поліпшення в 5–6 разів. Оптимальна композиція – 0,5–1,0 мас. % наночастинок кремнезему. Реологічні виміри показали псевдопластичну поведінку з уявними в'язкостями 28–43 сП за температури 180 °C. Експерименти із затопленням піни виявили коефіцієнти зниження мобільності 58–73. Додаткове виділення нафти становило від 16,8 до 22,7 % початкових георесурсів понад заводнення, у середньому 19,5 % для тестів з наночастинковою піною проти 3,8–5,2 % для контрольних пін.

Висновки. Продемонстровано, що піни, стабілізовані наночастинками, характеризуються високою термічною стабільністю та ефективністю вирівнювання профілю за температур, що перевищують 180 °C, за яких традиційні пінні системи втрачають свої працездатність. Запропонована технологія забезпечує коефіцієнти зниження рухливості в межах 58–73 та додатковий видобуток нафти на рівні 17–23 % від початкових запасів нафти в пласті, що є економічно значущим результатом.

Ключові слова: підвищення нафтовіддачі, піна, стабілізована наночастинками, контроль відповідності, високотемпературні резервуари, термічна стабільність, зниження мобільності, затоплення керна, міжфазні явища.

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