Experimental Investigation of the Effect of Temperature on the Stability of Hybrid Nanofluids for Enhanced Oil Recovery

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ABSTRACT

Due to the ever-growing demand for energy and the continuous depletion of conventional oil reserves, the petroleum industry is faced with the challenge of recovering more hydrocarbons from existing reservoirs. Enhanced Oil Recovery (EOR) technologies have emerged as effective methods to increase oil production beyond primary and secondary recovery stages. Among the various EOR techniques, the use of nanofluids—especially those containing silica (SiO_2) and alumina (Al_2O_3) nanoparticles—has shown great promise. These nanofluids improve oil recovery by altering rock wettability, decreasing interfacial tension (IFT), and improving fluid mobility. This study focuses on assessing how temperature variations affect the stability of hybrid nanofluids and their subsequent impact on oil recovery performance. Through comprehensive visual testing and injection into 2D micromodels saturated with crude oil, results demonstrate that elevated temperatures enhance nanoparticle stability, leading to more efficient oil displacement. The findings suggest that hybrid nanofluids could provide a superior EOR strategy for high-temperature reservoir environments.

Keywords: *Nanofluids, Enhanced Oil Recovery, Temperature, Stability, Silica Nanoparticles, Alumina Nanoparticles, Wettability, Interfacial Tension, Hybrid Systems, Micromodel*

1. *INTRODUCTION*

With the global energy consumption on a steep rise, primarily driven by population growth and industrial expansion, oil remains a key resource. While new exploration continues, the focus has shifted towards maximizing extraction from existing oil fields. Typically, oil production occurs in three stages: primary (natural reservoir pressure), secondary (water/gas injection), and tertiary or enhanced oil recovery (EOR). EOR aims to extract residual oil left behind after conventional recovery methods.

In recent years, advancements in nanotechnology have introduced novel approaches to EOR. Nanoparticles, due to their ultra-small size and surface properties, interact with reservoir rock and fluids in unique ways. Silica and alumina nanoparticles, in particular, are recognized for their ability to reduce interfacial tension (IFT), change the wettability of rock surfaces, and improve sweep efficiency during flooding operations.

However, the performance of nanofluids in subsurface environments is strongly influenced by their stability under reservoir conditions, especially temperature. Stability determines the degree to which nanoparticles remain dispersed in a fluid without aggregating or sediment Ing. Aggregation negatively impacts pore-scale flow, permeability, and injectivity. Therefore, understanding how temperature affects nanofluid stability is crucial for real-world application.

This research investigates hybrid nanofluids composed of silica and alumina nanoparticles—delivered simultaneously—to evaluate their synergistic behavior. By examining how these fluids perform at different temperatures in micromodels representing carbonate reservoirs, this study aims to offer insight into optimizing EOR strategies using hybrid nanotechnology.

1.1 Material and Methods

Recent advancements in nanotechnology have introduced a variety of nanoparticle types into the field of enhanced oil recovery (EOR). The efficacy of nanoparticles stems primarily from their ability to affect rock-fluid interactions at the microscale.

Silica nanoparticles (SiO_2)*, have been extensively studied due to their low cost, hydrophilic nature, and surface functionality. Al-Anssari et al. (2016) demonstrated that SiO_2 nanoparticles can significantly alter rock wettability toward more water-wet conditions, leading to increased oil recovery. Similarly, Maghzi et al. (2012) highlighted the role of silica in reducing interfacial tension (IFT) and enhancing displacement efficiency.*

Alumina nanoparticles (Al_2O_3)*, on the other hand, offer high surface area and excellent dispersive capabilities but face challenges in stability under harsh reservoir conditions. Alomair et al. (2014) examined various metal oxide nanoparticles, including alumina, and found they improve displacement mechanisms via plugging pore channels and modifying interfacial properties.*

Hybrid nanofluids*, combining SiO_2 and Al_2O_3, are an emerging concept offering synergistic effects. Although limited studies exist, Jafari et al. (2018) noted that such combinations can benefit from silica's stability and alumina's reactivity, especially when assisted by surfactants like Sodium Dodecyl Sulfate (SDS). Stability remains a critical concern, influenced by temperature, salinity, nanoparticle size, and surface charge.*

Despite encouraging results, challenges persist with long-term dispersion stability and reproducibility under field conditions. This study builds upon existing research by directly exploring temperature's role in hybrid nanofluid stability and performance in micromodel simulations.

Nanoparticle Selection

1.1.1 Nanoparticles*:*

1.1.1.1 *Silica (SiO_2): Hydrophilic nanoparticles, 20–30 nm diameter, with specific surface area of ~220 m^2/g*

1.1.1.2 *Alumina (Al_2O_3): Hydrophilic nanoparticles, ~20 nm diameter, surface area ~138 m^2/g*

1.1.2 *Both nanoparticles obtained from US Research Nanomaterials (Houston, TX) with ≥99% purity.*

1.2 Surfactant

1.2.1 *Sodium Dodecyl Sulfate (SDS) was used to enhance colloidal stability. SDS interacts electrostatically with nanoparticle surfaces, minimizing aggregation and maintaining dispersion.*

1.3 Fluid Formulation

Nanofluids were prepared using the following steps:

1.3.1 *Base fluid:*
Deionized water + NaCl (35,000 ppm) to replicate reservoir salinity

1.3.2 *Nanofluid:*
Nanoparticles were added in varying concentrations (250–1000 ppm)

1.3.3 *SDS:*
SDS added to achieve surfactant concentration of ~288 ppm

1.3.4 *Ultrasonic:*
Ultrasonic mixing (200 W, 1 hour with intervals) to ensure uniform dispersion

*1.4 **Micromodel** Configuration*

A custom-built 2D micromodel was designed using etched glass, representing a carbonate rock matrix. Specifications:

1.4.1 *Porosity:*

The Porosity of the 2D micromodel was ~36.6%.

1.4.2 *Pore Volume:*

The Pore volume of the 2D micromodel was 530 µL.

1.4.3 *Dimensions:*

The dimensions of the 2D micromodel were 10.5 cm × 5.5 cm.

1.4.4 *Design software:*

The design software which the 2D micromodel was designed by it was CorelDRAW.

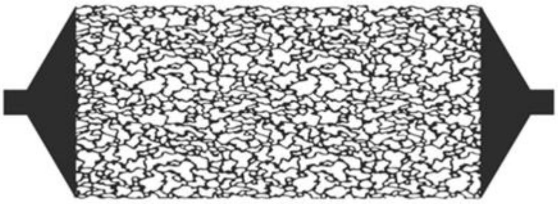

Fig. 1. The schematic of the 2D micromodel

The micromodel was saturated with crude oil (from Gachsaran field, Iran) and aged for 20 days at 100°C to simulate reservoir wettability

*1.5 **Stability** Assessment:*

Stability tests were performed at temperatures 25°C, 47.5°C, and 70°C. Each sample was monitored visually daily for sedimentation. Stability was recorded as the number of days the suspension remained homogenous.

1.6 Interfacial Tension Measurement (IFT):

IFT was measured using a pendant-drop method via Apex DSA analyzer. Tests were conducted at the same three temperatures and repeated three times for accuracy.

1.7 Injection Procedure:

Nanofluid flooding tests were conducted using a syringe pump at a constant rate. Each test involved injecting 4 pore volumes of nanofluid into the saturated micromodel.

Digital imaging and ImageJ analysis were used to calculate oil recovery percentages.

2. Results and Discussion

2.1 Nanofluid Stability under Temperature Variation

Visual inspection of nanofluid samples showed a direct correlation between increased temperature and improved stability. The hybrid silica-alumina fluids-maintained dispersion longer at elevated temperatures. Specifically:

2.1.1 At 25°C: average stability ranged between 2 to 8 days depending on concentration.

2.1.2 At 45°C: stability extended to 5–10 days.

2.1.3 At 70°C: several formulations remained stable up to 11 days, showing minimal** sedimentation**.

The improved stability at higher temperatures is attributed to enhanced Brownian motion, reduced viscosity, and better surfactant activation. Alumina nanoparticles were more prone to aggregation than silica, but in the presence of SDS, their dispersion was significantly improved.

2.2 Effect on Interfacial Tension (IFT)

Measurements using pendant-drop methods revealed that temperature inversely affected IFT. As temperature increased, IFT decreased, improving displacement potential.

Table 1. Temperature effect on the IFT

Temperature (°C)	SiO_2 (ppm)	Al_2O_3 (ppm)	IFT (mN/m)
25	1000	250	2.21
47.5	1000	250	1.93
70	1000	250	1.71

Lower IFT values support enhanced capillary displacement of oil in porous media.

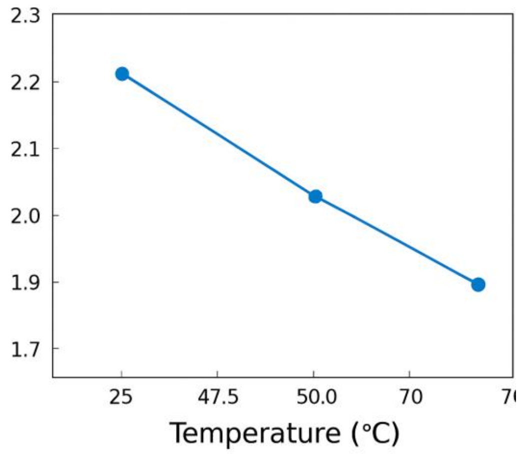

Fig. 2. Interfacial tension (IFT) values measured at 25°C, 47.5°C, and 70°C for hybrid nanofluids containing silica and alumina nanoparticles.

2.3 Oil Recovery Performance

Oil recovery from micromodel injections was calculated using ImageJ by measuring the change in oil-saturated area before and after nanofluid injection. Each test injected 4 pore volumes (PV) at constant flow rate. Recovery performance increased with temperature and decreased IFT.

Table 2. Results of the stability and oil recovery

Sample	Temp(°C)	SiO_2 (ppm)	Al_2O_3 (ppm)	Stability (days)	Recovery (%)
A	25	1000	250	8	44.52
B	47.5	1000	625	5	49.62
C	70	250	1000	2	61.32
D	70	1000	1000	6	68.86

The highest recovery was observed in sample D with equal concentrations of silica and alumina at 70°C, confirming the hypothesis that hybrid nanofluids, when stabilized, outperform single-particle formulations.

2.4 Observations from Micromodel Displacement

Digital imaging revealed distinct flow patterns:

2.4.1 At lower temperatures, nanofluids migrated along edges, showing limited central displacement.

2.4.2 At elevated temperatures, the flow path became more uniform, indicating improved sweep efficiency

2.5 Statistical Analysis (ANOVA)

2.5.1 ANOVA Results and Statistical

An Analysis of Variance (ANOVA) was conducted to assess the statistical significance and adequacy of the developed two-factor interaction (2FI) model for the response variable stability. The results demonstrated that the model was highly significant, with a model F-value of 17.19 and a p-value of < 0.0001, indicating that the probability of such a result occurring due to noise is only 0.02%.

2.5.1.1 Significant Factors

Among the studied factors, A (Al_2O_3 concentration), B (SiO_2 concentration), C (Temperature), and the interaction term AB ($Al_2O_3 \times SiO_2$) exhibited statistically significant effects on stability ($p < 0.05$). These terms contributed significantly to the response variation, as evidenced by their respective F-values:

A (Al_2O_3): $F = 70.09$, $p < 0.0001$

B (SiO_2): $F = 11.21$, $p = 0.0085$

C (Temperature): $F = 9.08$, $p = 0.0146$

AB ($Al_2O_3 \times SiO_2$): $F = 11.36$, $p = 0.0083$

In contrast, interaction terms AC (Al_2O_3 × Temperature) and BC (SiO_2 × Temperature) were found to be statistically insignificant ($p > 0.05$), suggesting negligible interaction effects between those variables.

2.5.1.2 Model Adequacy

The Lack of Fit test was found to be non-significant ($p = 1.0000$), indicating that the model adequately fits the experimental data. Furthermore, the model demonstrated a high coefficient of determination ($R^2 = 0.9197$), indicating that approximately 92% of the variability in the response was explained by the model.

Additional fit statistics included:

2.5.1.2.1 Adjusted $R^2 = 0.8662$, confirming the reliability of the model after accounting for the number of predictors.

2.5.1.2.2 Predicted $R^2 = 0.6901$, indicating reasonable predictive capability and within acceptable agreement (< 0.2 difference) with Adjusted R^2.

2.5.1.2.3 Adequate Precision = 14.89, which is well above the desirable threshold of 4, suggesting a strong signal-to-noise ratio.

2.5.1.3 Regression Equation (in Coded Factors)

The regression model for predicting stability in terms of coded factors is given as:

$$Stability = 4.50 - 2.50A + 1.00B + 0.90C - 1.13AB - 0.38AC + 0.13BC$$

Where:

I. *A = Al_2O_3 concentration*

II. *B = SiO_2 concentration*

III. *C = Temperature*

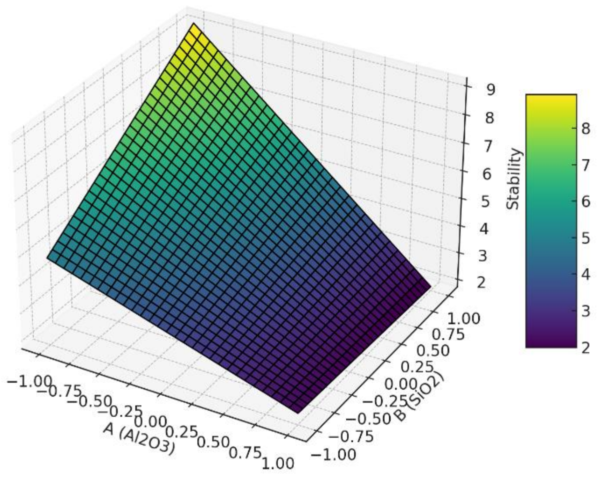

Fig 3. 3D Surface Plot: Interaction between Al_2O_3 and SiO_2 at C=0

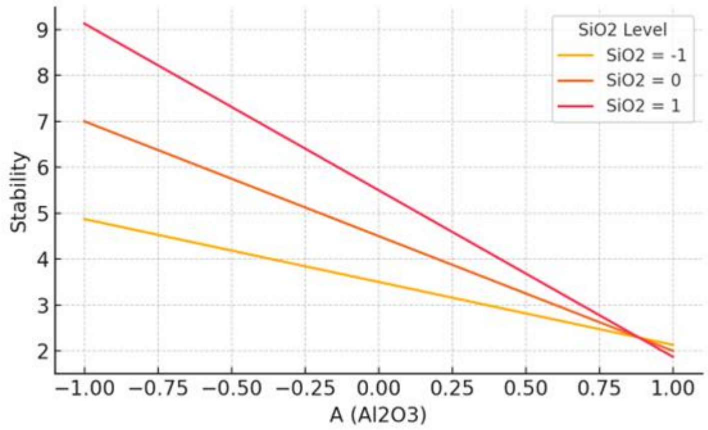

Fig 4. Interaction Plot: $Al_2O_3 \times SiO_2$ at C=0

The statistical analysis confirms that the developed 2FI model is robust and statistically significant. The model captures the essential behavior of the system with high accuracy and can be reliably used for further prediction and optimization of nanofluid stability under varying experimental conditions

3. Conclusion

This study has demonstrated that hybrid nanofluids composed of silica and alumina nanoparticles can significantly improve oil recovery performance under elevated temperature conditions. The findings show that:

I. *Stability of nanofluids increases with temperature, reaching up to 11 days at 70°C.*

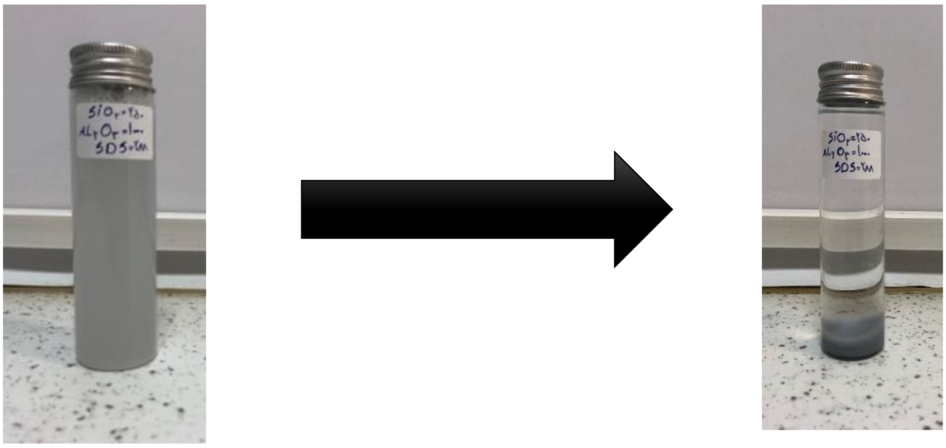

Fig 4. *Stability of the nanofluid with 250 ppm SiO_2 and 1000 ppm Al_2O_3 in 70°C*

II. *Interfacial tension decreases as temperature rises, leading to more efficient oil displacement.*

III. *Micromodel flooding at 70°C achieved a maximum oil recovery of 68.86%, surpassing recovery observed in lower-temperature trials.*

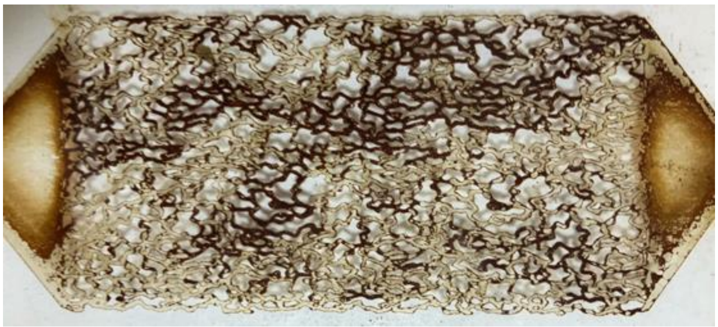

Fig 5. oil displacement of the nanofluid with 250 ppm SiO_2 and 1000 ppm Al_2O_3 in 70°C.

IV. *The combination of SiO_2 and Al_2O_3 provides a synergistic effect when stabilized using surfactants like SDS.*

This study systematically investigated the impact of temperature on the stability and performance of hybrid nanofluids—comprising silica (SiO_2) and alumina (Al_2O_3) nanoparticles—for enhanced oil recovery (EOR) applications. The results clearly demonstrate that temperature plays a crucial role in improving both nanofluid stability and oil displacement efficiency. Visual sedimentation tests confirmed that increasing temperature prolongs the dispersion stability of hybrid nanofluids, with some formulations remaining homogenous for up to 11 days at 70°C. Interfacial tension (IFT) measurements showed a consistent decrease with rising temperature, which enhanced capillary-driven displacement and overall sweep efficiency in micromodel experiments. The highest oil recovery of 68.86% was achieved at 70°C using a balanced hybrid formulation (1000 ppm SiO_2 and 1000 ppm Al_2O_3), validating the synergistic effect of combining both nanoparticles under thermally favorable conditions. Statistical analysis using ANOVA confirmed the *significance of Al_2O_3 concentration, SiO_2 concentration, temperature, and the $Al_2O_3 \times SiO_2$ interaction on nanofluid stability, with a robust model fit ($R^2 = 0.9197$). The predictive strength of the model (Predicted $R^2 = 0.6901$) was within acceptable limits, and the non-significant Lack of Fit further supports the model's reliability. Overall, hybrid nanofluids stabilized with surfactants like SDS offer a promising EOR strategy, especially for high-temperature reservoirs where traditional chemical methods may be less effective. These results encourage further pilot-scale studies and field trials to optimize hybrid formulations for practical deployment.*

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