

Comparative Simulation Study of Water flooding and CO₂ Injection in Sandstone Reservoirs: Asphaltene Stability Considerations

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Abstract: This comparative simulation study investigates the impact of asphaltene stability on oil recovery in sandstone reservoirs using waterflooding and CO₂ injection. Asphaltene precipitation poses significant risks to reservoir performance, particularly in high-risk scenarios. The simulation study utilized a range of reservoir properties, including permeability, porosity, viscosity, temperature, pressure, and salinity. The asphaltene stability index was varied from 0.4 (high precipitation risk) to 0.6 (moderate precipitation risk) and 0.8 (low precipitation risk). Waterflooding and CO₂ injection methods were simulated, and oil recovery rates were evaluated. The study evaluates the effects of varying asphaltene stability indices (0.4, 0.6, and 0.8) on oil recovery using both waterflooding and CO₂ injection methods. The results indicate that waterflooding consistently outperforms CO₂ injection across all asphaltene stability indices, with recovery rates ranging from 20-22% at high precipitation risk (0.4) to 25-28% at low precipitation risk (0.8). In contrast, CO₂ injection yields lower recovery rates, ranging from 15-18% at high precipitation risk to 22-28% at low precipitation risk. The findings suggest that waterflooding is a more effective method for oil recovery in sandstone reservoirs with high asphaltene content, while CO₂ injection may be more suitable for reservoirs with lower asphaltene precipitation risks.

Keywords: Asphaltene Stability, Oil Recovery, Waterflooding, CO₂ Injection, Sandstone Reservoirs, Enhanced Oil Recovery (EOR)

1. INTRODUCTION

Waterflooding and CO₂ injection are two common enhanced oil recovery (EOR) techniques used to extract oil from sandstone reservoirs. The effectiveness of these methods depends on various factors, including asphaltene stability and reservoir properties. Asphaltene precipitation is a significant concern in oil production, particularly in sandstone reservoirs. The stability of asphaltenes in crude oil can significantly impact oil recovery efficiency. This study aims to compare the effectiveness of waterflooding and CO₂ injection in sandstone reservoirs with varying asphaltene stability indices Bagheri, Kharrat, & Ghotby, (2011)

Waterflooding is a widely used enhanced oil recovery (EOR) method that involves injecting water into the reservoir to displace oil and increase production. This withdrawal technique can be effective in sandstone reservoirs, but its effectiveness can be impacted by factors such as reservoir heterogeneity, rock properties, and fluid properties (Ndem 2025).

Studies have shown that waterflooding can lead to asphaltene precipitation in some reservoirs, particularly those with high concentrations of asphaltenes and low concentrations of resins and aromatics. (Chapman & Hirasaki, 2008). The study of asphaltene stability in crude oil systems has gained significant attention in recent years due to its potential impact on oil recovery and production (Buckley, 1999; Wiehe & Kennedy, 2000).

CO₂ injection is another EOR method that involves injecting CO₂ into the reservoir to displace oil and increase production (Holm & Josendal, 1982). CO₂ injection has been shown to be effective in sandstone reservoirs, particularly in reservoirs with light oil. However, CO₂ injection can also lead to asphaltene precipitation, particularly in reservoirs with high concentrations of asphaltenes and low concentrations of resins and aromatics (Chapman, & Hirasaki 2008)

Wang, Zhang, and Liao (2020) underlined asphaltene precipitation during flue injection in sandstone reservoir. It mentioned CO₂ injection as a common gas injection technique, but the primary focus is on flue gas rather than a direct comparison between waterflooding and CO₂ injection. The study evaluates the impact of asphaltene precipitation on sandstones and conglomerate reservoirs

Asphaltenes are a complex mixture of heavy, polar molecules that can precipitate out of solution under certain conditions, leading to formation damage and reduced oil production. Asphaltene stability is influenced by a range of factors, including the composition of the crude oil, the pressure and temperature of the system, and the presence of other components such as resins and aromatics (Buckley, 1999).

Studies have shown that asphaltenes are unstable in certain crude oil systems, particularly those with high concentrations of saturates and low concentrations of resins and aromatics (Wiehe & Kennedy, 2000).

Akbarzadeh et al. (2007) found that the stability of asphaltenes in crude oil systems is influenced by the ratio of resins to asphaltenes.

Wang, Li, Gao, Zhao, & Li (2017) focused on asphaltene precipitation during CO₂ flooding in tight sandstone core samples using NMR to analyze pore scale formation

Several models have been developed to predict asphaltene precipitation in crude oil systems, including the colloidal model, the solubility model, and the equation of state (EOS) model (Pedersen & Christensen, 2007).

Bui, D et al (2025) A study compared water flooding and CO₂ injection methods for oil recovery in a heterogeneous reservoir. Continuous CO₂ injection outperformed water flooding, with water-alternating-gas (WAG) injection being most effective after water flooding. The optimal strategy was 15 years of water flooding followed by 15 years of CO₂ injection.

Wang, C., Cui, M., Wang, K., Wei, Y., Wang, K., & Gao, H. (2023) examined the impact of CO₂-crude oil -rock interactions on asphaltene deposition and reservoir performance

Ahmadi, Aghajanzadeh, Asadian and Kord (2022) used molecular dynamic simulator to study the effects of seawater ions on asphaltene adsorption on carbonate and sandstone surfaces. The work investigated smart water flooding as an enhanced oil recovery technique and its impact on oil recovery

Cruz, Bastos, Santana, Pereira, Costa, Vieira de Melo (2023). Researchers studied CO₂-water alternating injection (WAG) and its impact on oil recovery and asphaltene precipitation. The result showed that higher WAG ratios reduced asphaltene precipitation but led to earlier water breakthrough and decreased oil production efficiency and intermediate WAG ratios often achieved the highest oil recovery

Zhou et al (2024) worked on asphaltene precipitation during CO₂ flooding in tight sandstone reservoirs by analyzing the impact of micro-heterogeneous wettability on this process.

Qian, Yang, Dou, Pang & Huang (2019) focused on asphaltene precipitation during CO₂ injection flooding in tight sandstone reservoirs by applying core flood tests and NMR in evaluating pore scale formation damage the study highlighted higher injection pressure as a factor that leads to more asphaltene precipitation, affecting medium and large pores significantly

Hu, Li, Liu, Chu, Park, Mansoori, & Guo (2004) evaluated asphaltene precipitation in oil samples from the Jinlin oil field under pressure depletion and CO₂ injection conditions. No precipitation occurred without CO₂ injection, but significant precipitation was observed when operating pressure approached or exceeded the minimum miscibility pressure (MMP) with CO₂ injection. A generalized corresponding state principle (CSP) theory was developed to predict asphaltene precipitation behavior in high-pressure CO₂-injected crude oil systems.

Behbahani, Ghotbi, Taghikhani, & Shahrabadi, (2012). studied the impact of asphaltene deposition on oil recovery and permeability in tight sandstone cores during miscible CO₂ flooding. Experiments showed that increasing CO₂ flow rate led to significant pressure drops, indicating asphaltene deposition and permeability reduction. Results indicated that 20-40% of permeability reduction was due to adsorption, while 60-80% was caused by mechanical plugging. A modified model based on multilayer

adsorption theory accurately predicted asphaltene adsorption and permeability reduction, showing better agreement with experimental data than existing models.

Bagheri, Kharrat, & Ghotby,(2011) evaluated asphaltene precipitation and deposition under reservoir conditions for lean gas injection, CO₂ injection, and natural depletion. Lean gas injection caused more severe asphaltene deposition than CO₂ injection and natural depletion. Increasing flow rate and gas concentration exacerbated asphaltene deposition, leading to significant permeability reduction in the core matrix.

Takahashi et al (2003) studied asphaltene precipitation during CO₂ injection in Middle East crude oil using sandstone and carbonate cores. They found that asphaltene content decreased in produced oil after CO₂ breakthrough, indicating precipitation within the core. More asphaltene accumulated in carbonate cores than sandstone cores. Simulations showed that rock heterogeneities increased asphaltene accumulation, affecting oil recovery.

The objective of this research is to highlight

2. MATERIALS

Commercial simulator Eclipse

3. METHODOLOGY

A 3D sandstone reservoir model was created using a commercial simulator Eclipse. Reservoir properties such as permeability, porosity, thickness and initial conditions were defined, the crude oil properties such as composition, viscosity, and asphaltene content were characterized, then, an equation of state model for CO₂ – crude oil interaction was developed.

PC-SAFT was employed to implement an asphaltene precipitation model to simulate asphaltene instability furthermore, the model was calibrated. Finally, waterflooding and CO₂ injection scenarios were designed, asphaltene stability index and other reservoir properties (permeability, porosity, viscosity, temperature, pressure and salinity) were varied. Simulations for each scenario were carried out with proper monitoring of oil recovery and asphaltene precipitation and deposition. The simulation results were analyzed, and comparison of waterflooding and CO₂ injection performances under varying asphaltene stability conditions

The crude oil properties were characterized in terms of its various components, The viscosity of the crude oil was measured and used in the simulation model. The asphaltene content of the crude oil was determined and used to simulate asphaltene precipitation and deposition.

An equation of state (EOS) model was developed to describe the phase behavior of the CO₂-crude oil system. The EOS model was used to predict the interactions between CO₂ and crude oil, including the miscibility and phase behavior. The Peng-Robinson EOS was employed in this study.

The Perturbed-Chain Statistical Associating Fluid Theory (PC-SAFT) equation of state was employed to model asphaltene precipitation. The model was calibrated to ensure accurate predictions of asphaltene instability.

Two scenarios were designed to investigate the impact of asphaltene stability on oil recovery. Water was injected into the reservoir to displace oil and improve recovery. CO₂ was injected into the reservoir to displace oil and improve recovery. The asphaltene stability index and other reservoir properties, including permeability, porosity, viscosity, temperature, pressure, and salinity, were varied to investigate their impact on oil recovery and asphaltene precipitation.

Simulations were carried out for each scenario, and oil recovery and asphaltene precipitation and deposition were monitored. The simulation results were analyzed to compare the performance of waterflooding and CO₂ injection under varying asphaltene stability conditions. The results were used to identify the most effective recovery method and to optimize the injection strategy.

4. OBJECTIVE OF STUDY

The objective of this work is to investigate the impact of asphaltene stability on oil recovery in sandstone reservoirs using waterflooding and CO₂ injection methods. This study contributes to the understanding

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of optimal oil recovery methods in reservoirs with asphaltene stability issues, which can inform decision-making in the oil industry.

5. CONTRIBUTION TO KNOWLEDGE

The contribution to knowledge is that this study provides insights into the effectiveness of waterflooding and CO₂ injection methods in oil recovery under varying asphaltene stability conditions, specifically:

- Waterflooding outperforms CO₂ injection in sandstone reservoirs with high asphaltene content.
- CO₂ injection may be more suitable for reservoirs with lower asphaltene precipitation risks.

6. RESULTS

Analysis of simulation results to understand the impact of influencing factors on asphaltene stability during waterflooding and CO₂ injection scenarios in sandstone reservoirs was carry out and the graphs were used to represent the data and identify trends and patterns.

Table1. Crude Oil Sample

Asphaltene Content (wt %)	Resin Content wt %	API Gravity
3	15	32.1

Table2. Recovery with Waterflooding and CO₂ Injection at Asphaltene Stability Index: 0.4 (high Precipitation Risk)

Reservoir Property	Permeability		Porosity		Viscosity		Temperature		Pressure		Salinity	
	100	500	10	20	5	10	150	180	2000	2500	5000	10000
Water flooding	20	22	18	22	22	20	20	22	20	22	22	20
CO₂ Injection	15	18	12	18	18	15	15	20	15	20	18	15

Table3. Recovery with Waterflooding and CO₂ Injection at Asphaltene Stability Index: 0.6 (Moderate Precipitation Risk)

Reservoir Property	Permeability		Porosity		Viscosity		Temperature		Pressure		Salinity	
	100	500	10	20	5	10	150	180	2000	2500	5000	10000
Water flooding	22	25	20	25	25	22	22	25	22	25	25	22
CO₂ Injection	18	12	15	20	22	18	18	25	18	25	22	18

Table4. Recovery with Waterflooding and CO₂ Injection at Asphaltene Stability Index: 0.8 (Low Precipitation Risk)

Reservoir Property	Permeability		Porosity		Viscosity		Temperature		Pressure		Salinity	
	100	500	10	20	5	10	150	180	2000	2500	5000	10000
Water flooding	25	28	22	28	28	25	25	28	25	28	28	25
CO₂ Injection	22	28	18	28	28	22	22	30	22	30	25	22

Table5. Recovery (max) with Waterflooding and CO₂ Injection at varying Asphaltene Stability Index

Asphaltene Stability Index	Water flooding	CO ₂ injection
0.4	20-22	15-18
0.6	22-25	18-22
0.8	25-28	22-28

7. DISCUSSIONS

Across all asphaltene stability indices (0.4, 0.6, and 0.8), waterflooding consistently yields higher oil recovery rates than CO₂ injection (Table 5).

As the asphaltene stability index increases (i.e., lower precipitation risk), oil recovery rates improve for both waterflooding and CO₂ injection (Table 5).

Permeability, porosity, viscosity, temperature, pressure, and salinity affect oil recovery rates (Tables 2-4).

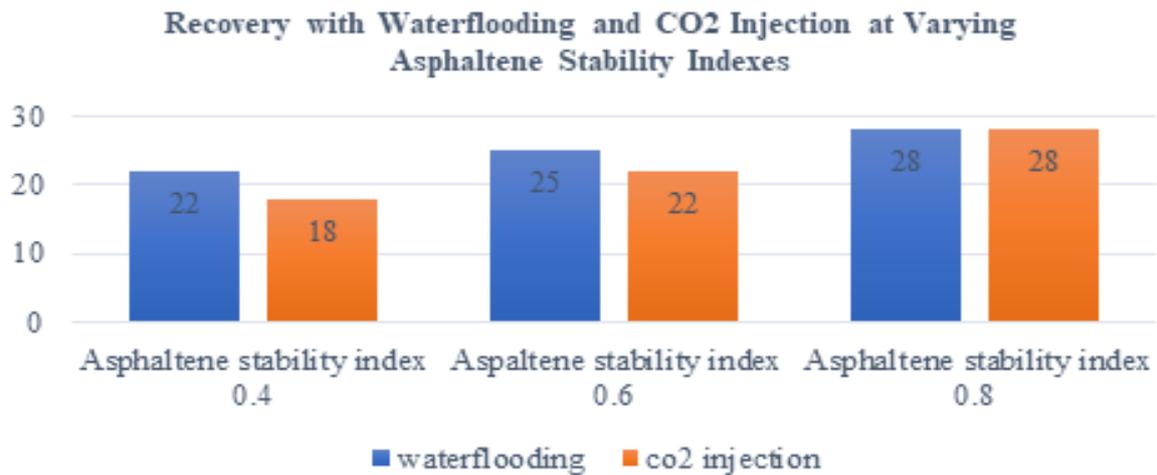


Figure1. Recovery with waterflooding and CO₂ Injection at different Asphaltene Indexes

The range of oil recovery rates for CO₂ injection increases more significantly with asphaltene stability index (15-18% at 0.4 to 22-28% at 0.8) compared to waterflooding (20-22% at 0.4 to 25-28% at 0.8) (Table 5).

The results suggest that waterflooding is a more effective method for oil recovery in sandstone reservoirs with high asphaltene content, particularly in scenarios with high precipitation risk (low asphaltene stability index). CO₂ injection, however, may be more suitable for reservoirs with lower asphaltene precipitation risks.

The impact of reservoir properties on oil recovery rates highlights the importance of considering these factors when designing and optimizing oil recovery strategies.

factors when designing and optimizing oil recovery strategies. The variability in oil recovery rates across different reservoir properties also underscores the need for site-specific evaluations. Overall, the research provides valuable insights into the effects of asphaltene stability and reservoir properties on oil recovery using waterflooding and CO₂ injection. The findings can inform the development of more effective oil recovery strategies for asphaltene-rich sandstone reservoirs.

8. CONCLUSION

- Waterflooding outperforms CO₂ injection in oil recovery for sandstone reservoirs with asphaltene content
- Oil recovery rates for waterflooding range from 20-22% at high asphaltene precipitation risk to 25-28% at low precipitation risk.
- CO₂ injection yields lower oil recovery rates, ranging from 15-18% at high asphaltene precipitation risk to 22-28% at low precipitation risk.
- Asphaltene stability significantly impacts oil recovery, with higher stability (lower precipitation risk) resulting in higher recovery rates.
- Waterflooding is a more effective method for oil recovery in sandstone reservoirs with high asphaltene content.
- CO₂ injection may be more suitable for reservoirs with lower asphaltene precipitation risks, where it can achieve comparable recovery rates to waterflooding
- The results of this study demonstrate the significance of asphaltene stability in determining oil recovery efficiency in sandstone reservoirs. Waterflooding appears to be a more effective method for oil recovery in reservoirs with high asphaltene content, while CO₂ injection may be more suitable for reservoirs with lower asphaltene precipitation risks. The findings of this study can inform the design and optimization of oil recovery strategies in asphaltene-rich sandstone reservoirs

9. COMPETING INTEREST

No funding was received for conducting this study

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