Gas Cap Size in Thin Oil Rims: Effect on Oil Recovery Efficiency

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Abstract

Oil recovery efficiency from thin oil rims is generally low due to various contributing factors. The influence of gas cap size on oil recovery is particularly critical, as the gas cap drive mechanism can become predominant, significantly impacting the oil recovery factor, especially in the presence of a large gas cap. While a water drive mechanism is typically considered optimal for oil displacement in petroleum reservoirs, its effectiveness in thin oil rims is contingent on not displacing oil into the gas zone. This simulation study investigates the impact of gas cap size on oil recovery efficiency under the influence of both strong and weak aquifers, utilizing data from a thin oil rim in the Niger Delta. The study simulates four scenarios: a strong aquifer with a large gas cap, a weak aquifer with a large gas cap, a strong aquifer with a small gas cap, and a weak aquifer with a small gas cap. The results indicate that oil recovery efficiency ranges from 29% to 31% in scenarios with large gas caps, whereas scenarios with small gas caps achieve recovery efficiencies between 49% and 62%. These findings suggest that large gas caps in thin oil rims constrain oil recovery, regardless of aquifer strength. Consequently, the study supports a field development strategy that prioritizes the extraction of gas from large gas caps in thin oil rims prior to oil production.

Introduction

There is typically only one opportunity to optimize the development of a real-life petroleum reservoir. When errors occur during the development phase, often due to an incomplete understanding of the reservoir system, they are not only costly to rectify but also challenging to reverse. However, reservoir simulation allows for the creation and examination of multiple scenarios, highlighting the importance of conducting comprehensive simulation studies, particularly when dealing with complex situations such as production from thin oil rims. These studies are crucial for determining the most effective exploitation techniques for each specific scenario, thereby preventing resource wastage during development and maximizing oil recovery efficiency. Additionally, simulation provides a deeper understanding of the unique characteristics of each reservoir, which in turn leads to more informed production strategies.

Oil production from thin oil rims with large gas caps and strong aquifers presents significant challenges to the petroleum industry, primarily due to low oil recovery efficiencies and other associated issues. The difficulties posed by large gas caps in thin oil rims have been extensively discussed in the literature (Olabode et al. 2023; Peter 2019). Water is an effective agent for oil displacement in petroleum reservoirs; however, in thin oil rims under strong water drive conditions, early water breakthrough often occurs, leading to substantial volumes of produced water. This can shift portions of the oil zone into the gas cap, further reducing the volume of recoverable oil. Therefore, it is imperative to investigate the influence of a large gas cap on oil recovery efficiency in the context of both strong and weak aquifers within thin oil rims. Understanding these mechanisms is crucial for devising a strategic production technique that maximizes oil recovery efficiency.

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Under the gas cap drive mechanism, one of the primary assumptions is minimal or negligible water production (Ahmed 2006). However, this assumption does not hold for thin oil rims with strong underlying aquifers. In such scenarios, water coning occurs early in the reservoir's life due to the thinness of the pay zone, making well placement a critical issue. This has led to recommendations such as the use of horizontal wells for oil recovery from thin oil rim reservoirs (Akpabio et al. 2013; Aladeitan et al. 2016; Yang et al. 2013). Research indicates that in thin oil rims with large gas caps, oil recovery increases with horizontal permeability and decreases with higher oil production rates and longer horizontal wells (Agi et al. 2017). Another study on thin oil rims with large gas caps concluded that it is preferable to place horizontal wells below the oil-water contact, whereas for reservoirs with small gas caps and strong aquifers, horizontal wells should be placed above the gas-oil contact (Iyare et al. 2012). Various methods for effectively exploiting thin oil rims have been proposed (Uwaga and Lawal 2006; Billiter et al. 1998; Billiter et al. 1999; Chan et al. 2011; Wojtanowicz 2006; Razak et al. 2011; Olabode 2020). This study aims to evaluate the effect of gas cap size on oil recovery efficiency in the presence and absence of a strong water drive, using vertical wells in thin oil rims.

Statement of Theory and Definitions

Reservoir performance, particularly in terms of oil recovery, is largely determined by the dominant drive mechanism operating within the reservoir. These drive mechanisms include water drive, gravity drainage, rock and liquid expansion, depletion (solution gas) drive, gas cap drive, and combination drive mechanisms. This study investigates the impact of gas cap size on oil recovery efficiency, with the expectation that the gas cap drive mechanism will dominate in reservoirs with large gas caps, significantly influencing oil recovery. In reservoirs with strong aquifers, the water drive mechanism also plays a critical role, with oil recovery efficiencies ranging from 35% to 75% (Ahmed 2006). Given that some thin oil rims with gas caps are underlain by aquifers, it is essential to conduct simulation studies to assess how gas cap size affects oil recovery efficiency in the presence of both strong and weak underlying aquifers.

Oil recovery efficiency is a critical parameter that determines the economic viability of an oil reservoir and justifies the investments made in production. Therefore, it is imperative to investigate any factors influencing this parameter during production to facilitate the implementation of an effective reservoir management strategy. The reservoir drive mechanism is a key factor in this regard, and this paper focuses on the gas cap drive in the context of water drive within thin oil rims. Under the gas cap drive mechanism, the energy available for oil production is primarily derived from the expansion of the gas cap and the solution gas, resulting in oil recovery efficiencies ranging from 20% to 40% (Ahmed 2006). This study specifically examines oil recovery efficiency in thin oil rims with varying gas cap sizes, considering both strong and weak aquifer strengths.

Description and Application of Equipment and Processes

The primary objective of this study is to examine the variation in oil recovery in a thin oil rim under different gas cap sizes—specifically, large and small gas caps—while considering the influence of both strong and weak aquifer strengths. The investigation was conducted through numerical simulation using the ECLIPSE. The reservoir model, constructed using data from a thin oil rim in the Niger Delta, is depicted in **Figure 1**. The fundamental rock and fluid properties, prior to any necessary modifications, are detailed in **Table 1**.

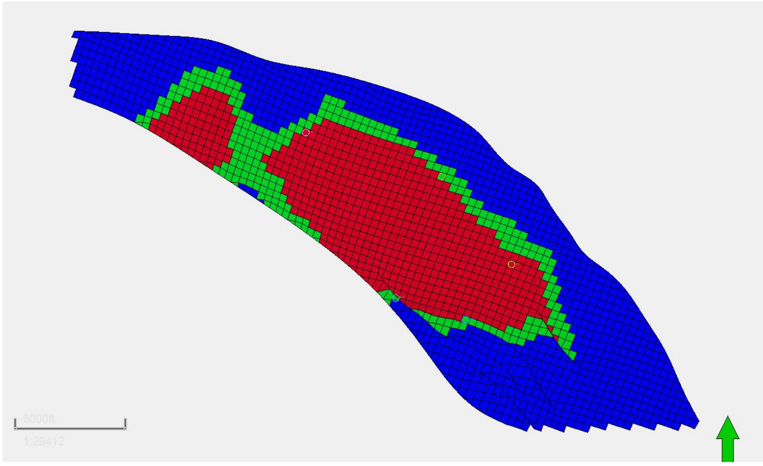

Figure 1—A View of the thin oil rim model.

Table 1—Reservoir rock and fluid properties.

Rock and fluid property	Property	Value
Average reservoir properties	Depth, ft	10421
	Porosity (ϕ)	0.23
	Permeability (k), mD	1292
	Reservoir thickness, ft	45
	Net to gross	0.81
	Initial reservoir pressure (p_i), psia	4540
	Initial water saturation (S_{wi})	0.15
	Formation water compressibility (c_w), psi^{-1}	2.986×10^{-6}
	Rock compressibility (c_f), psi^{-1}	1.1767×10^{-6}
Initial fluid properties	Viscosity (μ_{oi}), cp	0.42110
	Formation volume factor (B_{oi}), rb/stb	1.512
	Saturation pressure (p_b), psia	4540
	Instantaneous GOR, scf/STB	963.5
Average aquifer properties	Porosity (ϕ_a)	0.24
	Permeability (k_a), mD	1292
	Thickness, ft	70
	Inner radius (r_e), ft	5604

In this study, four scenarios were simulated at six different oil production flow rates over a 40-year period, spanning from 1968 to 2008. The production flow rates applied were 2,000, 4,000, 6,000, 8,000, 10,000, and 12,000 stb/day. However, oil recovery comparisons were primarily focused on the flow rates of 2,000 and

12,000 stb/day across the four scenarios under consideration. The analysis of results concentrated on the cumulative volume of recovered oil and the oil recovery efficiency achieved in the four simulated cases.

The four scenarios considered in this study include: (1) a strong aquifer with a large gas cap (SA&LGC); 2) a weak aquifer with a large gas cap (WA&LGC); 3) a strong aquifer with a small gas cap (SA&SGC); and (4) a weak aquifer with a small gas cap (WA&SGC). These scenarios represent various reservoir drive mechanisms, including those dominated by water drive and gas cap drive, exclusively gas cap drive, exclusively water drive, and a case where neither drive mechanism is predominant.

For all wells and cases, a minimum bottom-hole pressure constraint of 1,000 psia was maintained. The aquifer strength was varied by adjusting the permeability, with a factor of 0.01 applied for a weak aquifer and a tenfold increase from the base permeability value for a strong aquifer. The gas cap size was modified using pore volume multipliers for grid block cells around the initial gas-oil contact. For large gas caps, the pore volumes of cells 50 feet above the initial gas-oil contact were multiplied by a factor of 100, whereas for small gas caps, this factor was set at 0.01.

Presentation of Data and Results

The detailed results of the simulation study for the four cases under consideration are presented and analyzed. **Figures 2** and **3** depict the oil production rate profiles for scenarios initiated at 2,000 and 12,000 stb/day, respectively. The results indicate that scenarios with small gas caps sustained slightly higher production rates over time compared to those with large gas caps. Additionally, it was observed that the production rate declined more rapidly at the higher rate of 12,000 stb/day than at 2,000 stb/day.

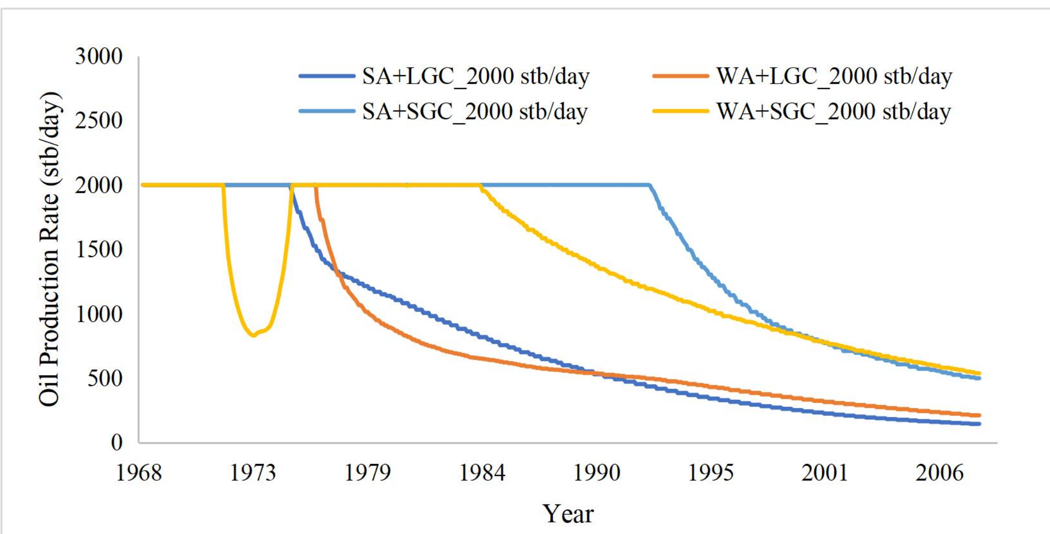

Figure 2—Oil production of the four scenarios at 2,000 stb/d.

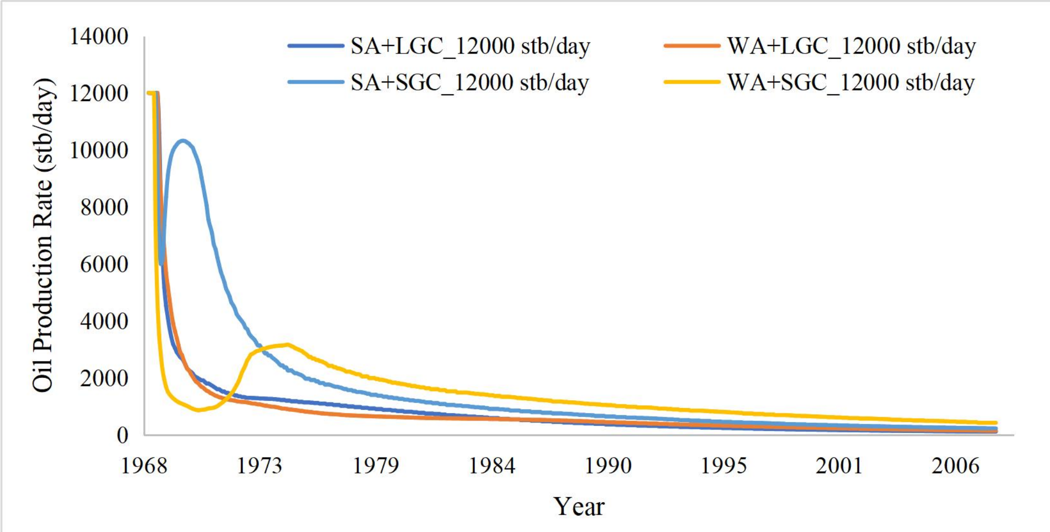

Figure 3—Oil production of the four scenarios at 12,000 stb/d.

Figures 4 and **5** illustrate the cumulative oil production over time for scenarios with production rates of 2,000 and 12,000 stb/day, respectively. The results indicate that scenarios with small gas caps achieve higher cumulative oil recovery volumes compared to those with large gas caps. Notably, the outcomes for the two scenarios with large gas caps are similar, despite one having a stronger aquifer strength than the other. This suggests that, in this study, the impact of a large gas cap on oil recovery is more significant than the influence of a strong water drive in thin oil rims. Furthermore, it is observed that the differences in oil recovery between the four scenarios are more pronounced at the higher production rate of 12,000 stb/day (Figure 5) compared to 2,000 stb/day (Figure 4).

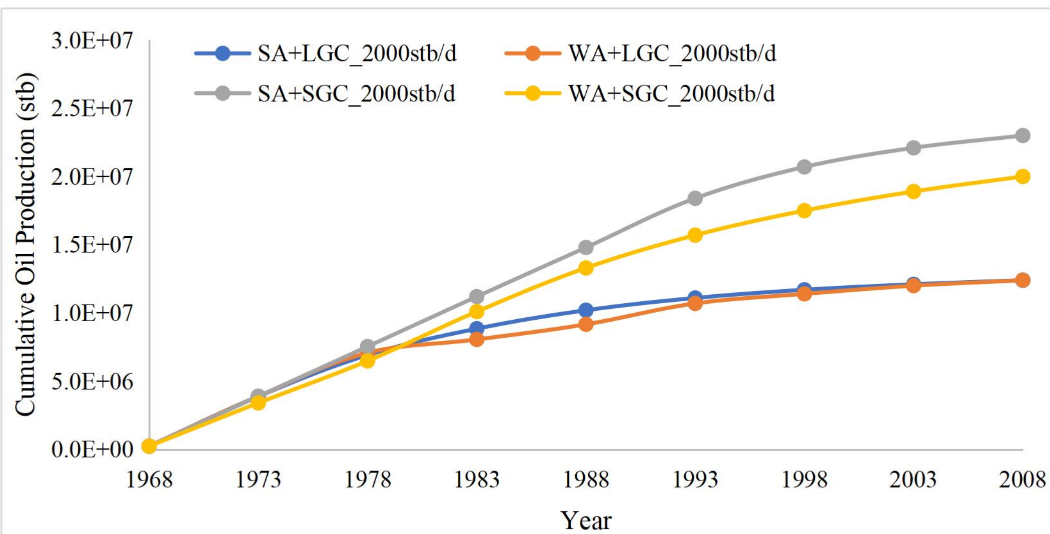

Figure 4—Cumulative oil production of the four scenarios at 2,000 stb/d.

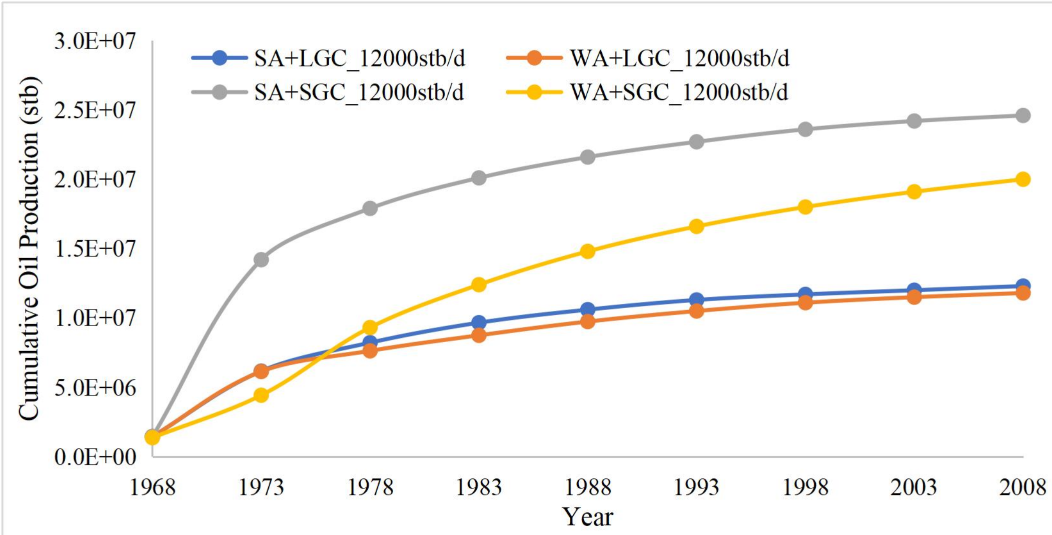

Figure 5— Cumulative oil production of the four scenarios at 12,000 stb/d.

Figure 6 presents the oil recovery efficiencies for the four scenarios at production rates of 2,000 and 12,000 stb/day. The data clearly indicate that oil recovery efficiencies are higher in scenarios with small gas caps. Specifically, at production rates of 12,000 and 2,000 stb/day, the recovery efficiencies for strong aquifers with small gas caps are 61.5% and 57.6%, respectively. For weak aquifers with small gas caps, the recovery efficiencies are 49.9% and 49.8%, respectively. The presence of a strong aquifer appears to significantly contribute to the higher oil recovery factor, as the small gas cap has a minimal impact on oil recovery.

In contrast, for scenarios involving large gas caps, the oil recovery efficiencies at 12,000 and 2,000 stb/day for strong aquifers are 30.6% and 30.9%, respectively, while for weak aquifers, the efficiencies are 29.5% and 30.9%, respectively. Notably, higher oil recovery efficiencies are observed at 12,000 stb/day for scenarios with small gas caps, whereas higher efficiencies for large gas caps are observed at 2,000 stb/day. This suggests that the effect of production rate on oil recovery efficiency varies with the size of the gas cap. Therefore, further research is necessary to explore the impact of production rate on oil recovery efficiency in these scenarios.

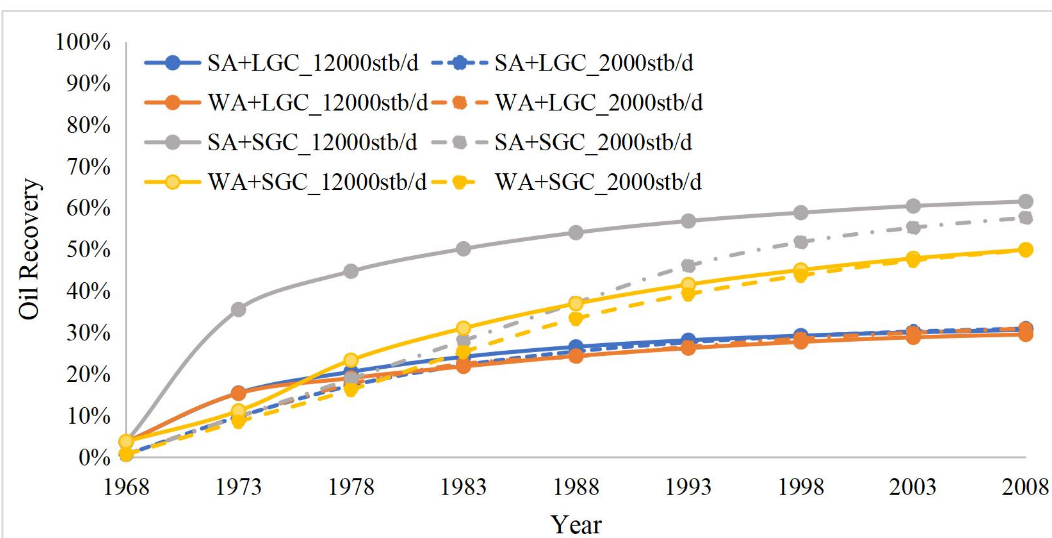

Figure 6—Oil recovery of the four scenarios at 2000stb/d and 12000stb/d.

The oil recovery efficiencies for production rates of 4,000, 6,000, 8,000, and 10,000 stb/day were also derived from the simulation study, with a more comprehensive result presented in **Figure 7**. For scenarios involving large gas caps, the presence of a strong aquifer consistently resulted in slightly higher oil recovery efficiencies across all flow rates compared to scenarios with weak aquifers. In contrast, for scenarios with small gas caps, the oil recovery efficiencies were significantly higher in the presence of strong aquifers compared to weak aquifers. This trend aligns with expectations, as water drive is effective in displacing oil from petroleum reservoirs, with strong water drives providing better sweep efficiency.

Specifically, the cases with a strong aquifer and small gas cap (SA&SGC) exemplify the water drive mechanism in operation, with minimal influence from the gas cap drive. These scenarios yielded oil recovery factors ranging from 57% to 62%, which is consistent with the expected recovery efficiencies of 35% to 75% for water drive reservoirs (Ahmed 2006).

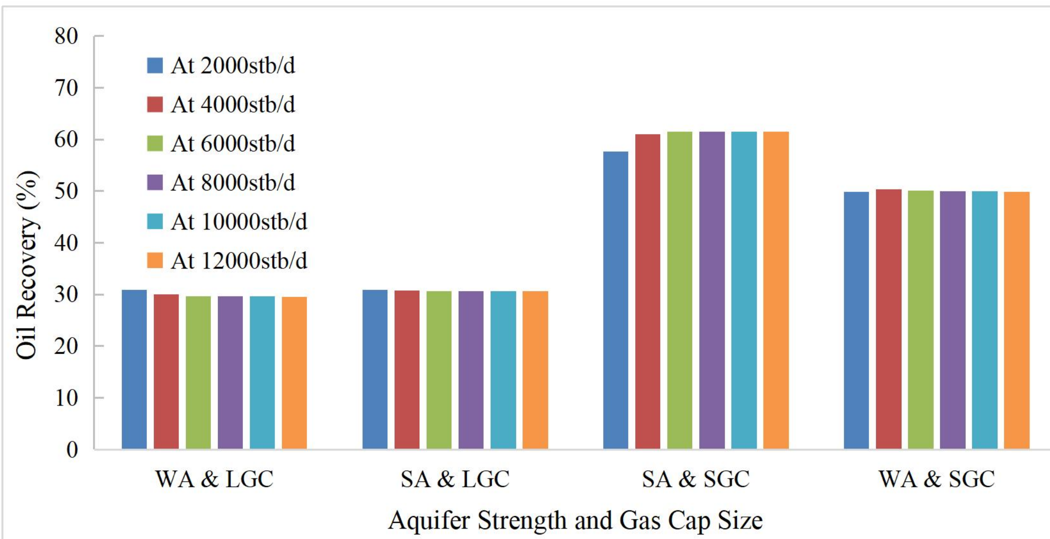

Figure 7—Results of oil recovery efficiency for the four scenarios at different production rates.

In scenarios involving weak aquifers with small gas caps, neither the water drive nor the gas cap drive mechanism is dominant, resulting in an oil recovery efficiency of approximately 49%. This situation allows other drive mechanisms, such as gravity drainage, solution gas drive, and combination drive, to influence the oil recovery efficiency. However, for this study, it is important to note that in both scenarios with a strong aquifer and small gas cap (SA&SGC) and a weak aquifer with a small gas cap (WA&SGC), the influence of a large gas cap and its associated drive mechanism were absent, leading to higher oil recovery efficiencies. This indicates that the presence of large gas caps in thin oil rims restricts oil recovery efficiency, which is highly undesirable.

The oil recovery efficiencies for scenarios with large gas caps ranged from 29% to 31%, which aligns with the expected range of 20% to 40% for gas cap drive mechanisms (Ahmed 2006). Improving oil recovery efficiency is a primary objective in the petroleum industry, necessitating the adoption of optimal production strategies to achieve this goal.

Overall, the results demonstrate that the presence of a large gas cap in thin oil rims significantly reduces oil recovery efficiency, regardless of production rate and aquifer strength. Oil recovery efficiencies are notably higher in thin oil rims with small gas caps compared to those with large gas caps. One possible explanation for the reduced efficiency in thin oil rims with a large gas cap and a strong aquifer is oil smearing, where the gas-oil contact shifts upward into the gas zone, potentially pushing part of the oil zone into the gas zone and thereby trapping and losing recoverable oil.

The scenario with a weak aquifer and a large gas cap (WA&LGC) represents a typical gas cap drive mechanism, with an expected oil recovery efficiency of 20% to 40% (Ahmed 2006). Therefore, a recommended strategy for oil production from thin oil rims with large gas caps is to first produce the gas to reduce the gas cap size and minimize its impact on oil recovery efficiency before subsequently producing the oil. This production approach, supported by various studies, is validated by the results of this simulation study but is applicable specifically to cases with large gas caps and not to those with small gas caps.

Conclusions

The conclusions derived from this study are as follows:

1. The presence of a strong water drive in thin oil rims with large gas caps does not necessarily enhance oil recovery efficiency. This is due to the risk of oil smearing, which can lead to a substantial loss of recoverable oil.
2. Large gas caps in thin oil rims significantly limit oil recovery efficiency. To mitigate the impact of the gas cap drive mechanism on oil recovery, it is recommended to first produce the gas before extracting the oil.
3. Thin oil rims with small gas caps yield better oil recovery efficiencies compared to those with large gas caps. Additionally, a strong water drive in thin oil rims with small gas caps markedly improves oil recovery efficiency.

Recommendation

For thin oil rims with large gas caps, producing the gas first before producing the oil is recommended in order to improve oil recovery efficiency.

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Conflicting Interests

The author(s) declare that they have no conflicting interests.

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