Enhancing SAGD Efficiency: A Study on Steam Quality and Injection Rate Optimization

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Abstract

The production of heavy oil presents a significant challenge due to its high viscosity, which limits natural flow. This study aims to assess the effectiveness of Steam Assisted Gravity Drainage (SAGD) in enhancing heavy oil recovery by employing a comprehensive numerical simulation model. A commercial compositional simulator was utilized to evaluate the impact of steam quality and injection rate on recovery efficiency, using reservoir properties from Oilfield Alpha. The results demonstrate that optimizing steam quality is critical, with an increase from 0.6 to 0.8 leading to an improvement in recovery from 43.58% to 46.16%. Additionally, higher injection rates were shown to substantially boost oil production, with simulations at 700 bbl/day achieving a final recovery factor of 52.691%. These findings highlight the importance of optimizing both steam quality and injection rates to maximize SAGD performance, providing valuable insights for future field applications and the refinement of heavy oil production strategies.

Introduction

Global energy demands are increasing rapidly, while conventional resources are depleting. Consequently, there is a growing need to tap into unconventional energy resources, which include tight gas/oil, gas/oil shale, coalbed methane, gas hydrates, and heavy oil. Extracting hydrocarbons from these subsurface sources requires advanced technological solutions. Within the oil sector, a distinction is made between conventional (light) oils and unconventional oils, which include heavy oil, extra-heavy oil, and bitumen. Differentiating between these requires laboratory analysis of fluid samples. Heavy oils are characterized by higher levels of oxygen, nitrogen, sulfur, and heavier oil fractions compared to light oils (Santos et al. 2014).

Heavy crude oil is a type of reservoir oil with greater viscosity and density than light oil, making it more difficult to flow through reservoirs. It has a higher molecular weight and complex composition. Heavy crude oil is defined as any petroleum liquid with a gravity of less than 20°API and a reservoir viscosity ranging from 50 to 5,000 centipoises. Although there is some variation in classification, crude oils with viscosities exceeding 10 cp and up to 10,000 cp are also considered heavy. According to the World Energy Council (2007), heavy oil is defined as having a gravity below 22.3°API or a density above 0.920, while oils with an API gravity of less than 10° are classified as extra-heavy. Heavy oils are further characterized by high viscosity, specific gravity, asphaltene content, carbon residues, low hydrogen-to-carbon ratios, and elevated levels of sulfur, nitrogen, heavy metals, and acid numbers. These characteristics are typically the result of microbial degradation of conventional light crude oil reservoirs over geological time (Wei 2016; Çağdaş 2007; Luo 2012).

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In the oil and gas industry, bitumen from oil sands is occasionally classified as extra-heavy crude oil, even if its API gravity is below 10 ° . However, some experts distinguish bitumen from extra-heavy oil due to differences in the degree of microbial degradation and erosion over extended geological periods.

Overall, producing heavy oil is generally less challenging than extracting bitumen, primarily due to differences in viscosity. In **Figure 1**, the global distribution of heavy oil reserves and the corresponding production technologies are depicted. Canada, the United States, Venezuela, and several other nations are among the largest holders of heavy oil reserves worldwide. Among the various extraction methods, steam-assisted gravity drainage (SAGD) stands out as the most commonly employed. This preference is due to its ability to achieve the highest recovery factors, making it the favored method for enhancing oil production from challenging reservoirs.

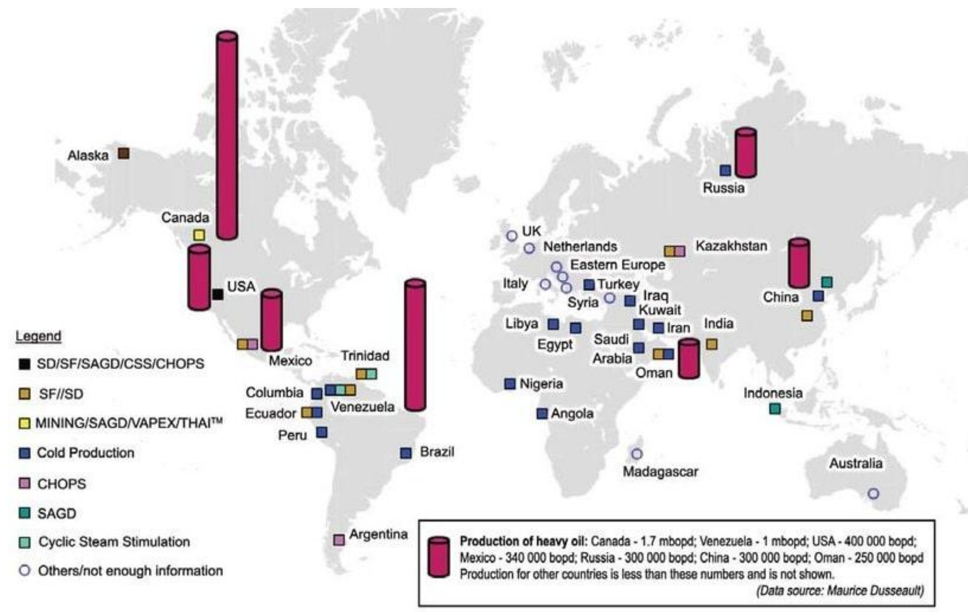

Figure 1—Distribution of heavy oil around the world (Chopra and Lines 2008).

As the demand for energy continues to rise, heavy oil extraction is becoming an increasingly attractive option. However, heavy oils pose significant challenges due to their higher viscosity compared to light oils, necessitating the use of thermal technologies for efficient reservoir exploitation. Thermal methods, which include hot water injection, steam injection or steam drive, steam-assisted gravity drainage (SAGD), cyclic steam stimulation, and in-situ combustion, are essential for reducing the viscosity of heavy oils, as viscosity decreases with increasing temperature.

Steam-Assisted Gravity Drainage (SAGD) is a widely used thermal recovery method for extracting bitumen and super-heavy oil. Despite its effectiveness, SAGD is associated with high costs and significant carbon intensity due to the extensive use of steam. According to Nduagu et al. (2017), SAGD reservoirs rank among the most expensive to produce worldwide, making the optimization of steam utilization a critical factor for operators.

SAGD operates by first injecting high-quality steam into the reservoir to mobilize the viscous crude oil between injection and production wells (**Figure 2**). The process involves the formation of a steam chamber as steam is injected from an upper horizontal well, heating the oil, which then drains by gravity into a lower horizontal well along with the steam condensate (Singfield 2016; Li et al. 2020).

Common well configurations for SAGD include dual-horizontal and vertical-horizontal well patterns. The dual-horizontal well setup typically involves two parallel horizontal wells spaced 4-6 meters apart, with the lower well dedicated to oil production and the upper well used for steam injection (Tian and Sun 2013; Li et al.

2017). In the vertical-horizontal configuration, steam is injected through vertical wells while oil is produced from a lower horizontal well. This setup is advantageous for reservoirs with thick layers of super-heavy oil but is less effective for thin-layer reservoirs due to the limited rise of the steam chamber and constrained gravity drainage.

To improve the economic viability of exploiting thin-layer super-heavy oil reservoirs, one strategy involves reducing the vertical distance between the injection and production wells in the dual-horizontal well SAGD configuration. Li (2014) conducted research on applying SAGD in narrow super-heavy oil reservoirs, focusing on increasing the horizontal distance between wells to expand the steam chamber and enhance recovery.

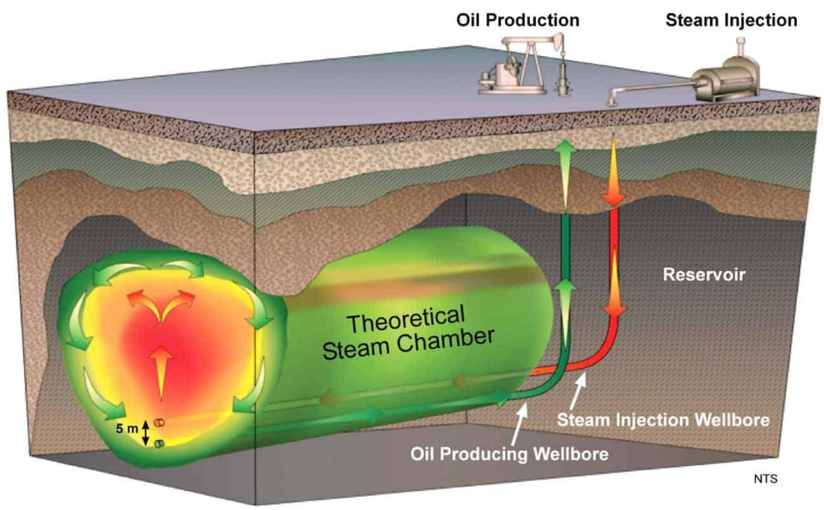

Figure 2—Schematic representation of SAGD process (Singfield 2016).

Steam quality, defined as the proportion of steam vapor in a steam-water mixture, plays a critical role in heat transfer and enhancing oil mobility during Steam-Assisted Gravity Drainage (SAGD) operations. The injection rate, representing the volume of steam injected per unit time, directly influences oil production and the development of the steam chamber. The Cumulative Steam-Oil Ratio (CSOR), which is the total volume of steam injected divided by the total volume of oil produced, serves as a key metric for evaluating the efficiency of steam usage in oil recovery. Economically viable CSOR values typically range from 2 to 10 bbl/bbl (Gates and Chakrabarty 2006).

Recent studies have focused on optimizing SAGD through various parameters. For instance, Swadesi et al. (2020) explored the impact of steam quality and injection rate on Cyclic Steam Stimulation (CSS) using the CMG STARS simulator, highlighting the importance of optimizing these factors to improve steam injection efficiency. However, despite advancements in SAGD technology, most research has primarily concentrated on well spacing and its influence on SAGD efficiency, leaving a significant gap in understanding how steam quality and injection rate specifically affect SAGD performance.

Addressing these parameters is critical as they are more easily adjusted compared to well patterns, which require extensive geological data. With the development of tools like CMG STARS, it is now possible to analyze and optimize SAGD processes by varying steam quality and injection rates. This research aims to bridge the existing gap by investigating how modifications in these two factors can enhance the effectiveness and cost-efficiency of heavy oil recovery methods.

Methodology

In this study, the SAGD process was applied to a heavy oil reservoir, utilizing a dual-horizontal well configuration. The upper horizontal well was employed for steam injection, while the lower horizontal well facilitated the production of oil and condensed steam. The study focused on varying key parameters, including well spacing, steam quality, and injection rate. To analyze these variables, the CMG STARS reservoir simulator was employed to create and assess a model, providing critical insights into the process. Key technical metrics such as the oil recovery factor (RF), the cumulative steam-oil-ratio (CSOR), and cumulative oil production were used to evaluate the system's performance.

The methodology was developed with reference to the CMG STARS Manual (2021), which guided the simulation process. Input parameters relevant to common heavy oils, including rock and fluid properties, were determined. **Table 1** presents these parameters and values for Oilfield Alpha.

Table 1—Input parameters and their values for the reservoir simulation model.

Input parameter	Value
Grid type	Cartesian
Number of Grid Blocks	25 × 15× 10
Grid Block Dimensions	1000 ft × 300 ft × 90 ft
Grid top	1300 ft
Reference depth	1300 ft
OWC depth	1380 ft
Initial pressure	650 psi
Reservoir temperature	110 F
Porosity	0.308 or 30,8 %
Horizontal permeability	1700 mD
Vertical permeability	1400 mD
Initial oil saturation	0.8 or 80 %
Oil Gravity	9.8 API
Oil Viscosity	15780 cp

In this model, the absence of a gas phase results in certain parameters exhibiting a linear relationship with pressure. **Figures 3** and **5** demonstrate this by showing how the formation volume factor of oil (B_o), oil density, and oil viscosity vary with changes in pressure.

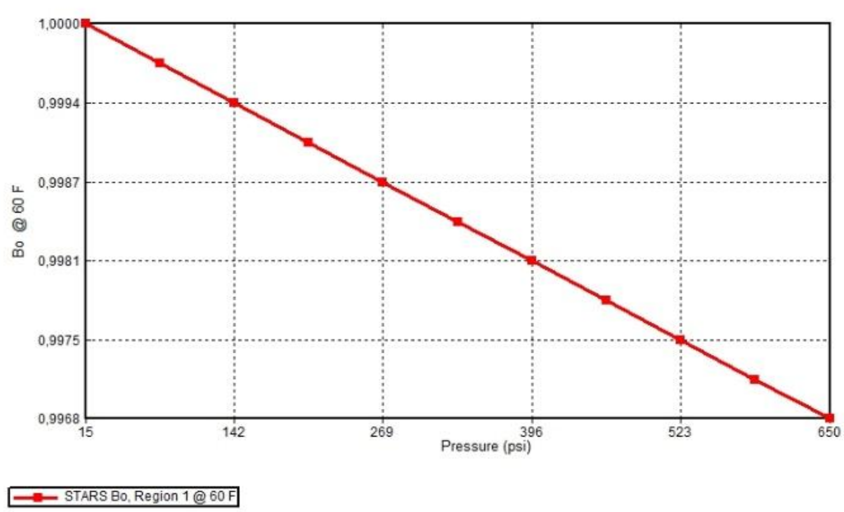

Figure 3—Variation of oil formation volume factor (Bo) with pressure.

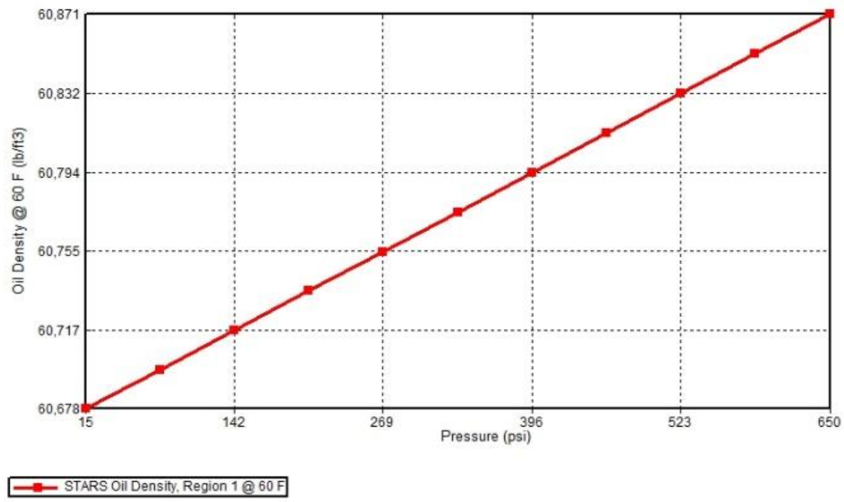

Figure 4—Variation of oil density with pressure.

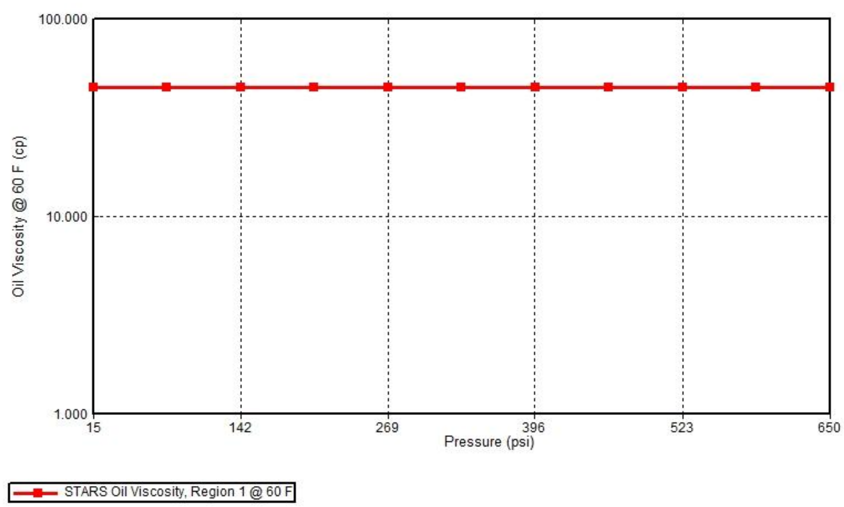

Figure 5—Variation of oil viscosity with pressure.

The primary challenge in heavy oil production is the high viscosity of the oil. Thermal methods are employed to reduce viscosity by raising the temperature. Since each heavy oil type possesses unique properties, the viscosity-temperature relationship can differ across fields. This variation is depicted in **Figure 6** for the current model.

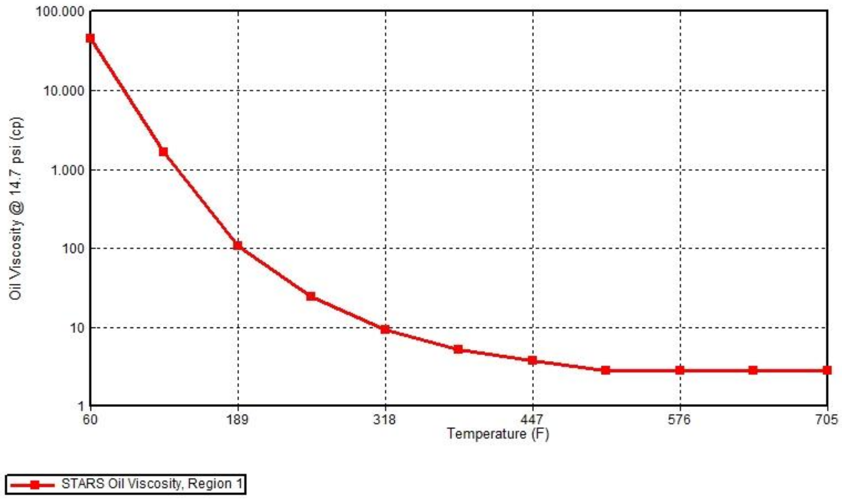

Figure 6—Relationship between oil viscosity and temperature.

As previously noted, the absence of a gas phase in this context is significant. **Figure 7** presents the water-oil relative permeability curves, providing further insight into the fluid flow characteristics and aiding in the refinement of the reservoir model.

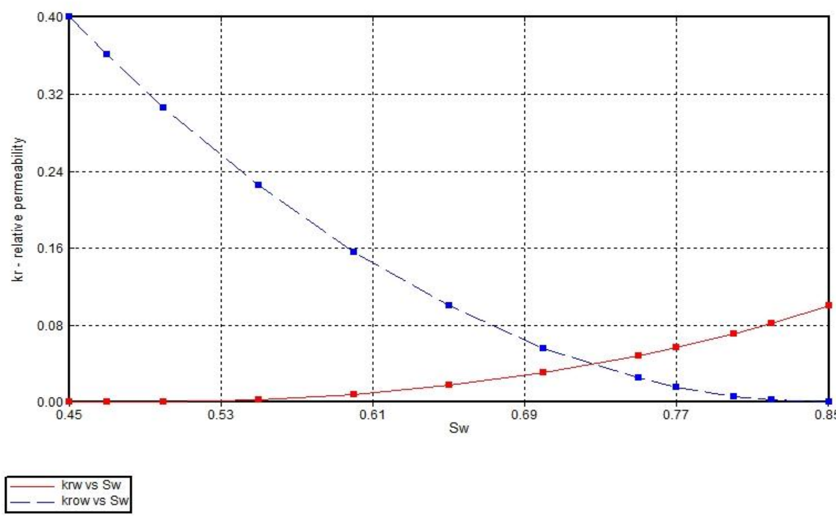

Figure 7—Relative permeability curves for water and oil.

After defining all input parameters, the CMG STARS simulator was employed to create a 3D representation of the conceptual model, as shown in **Figure 8**. This figure illustrates the grid layout and the depth of each layer.

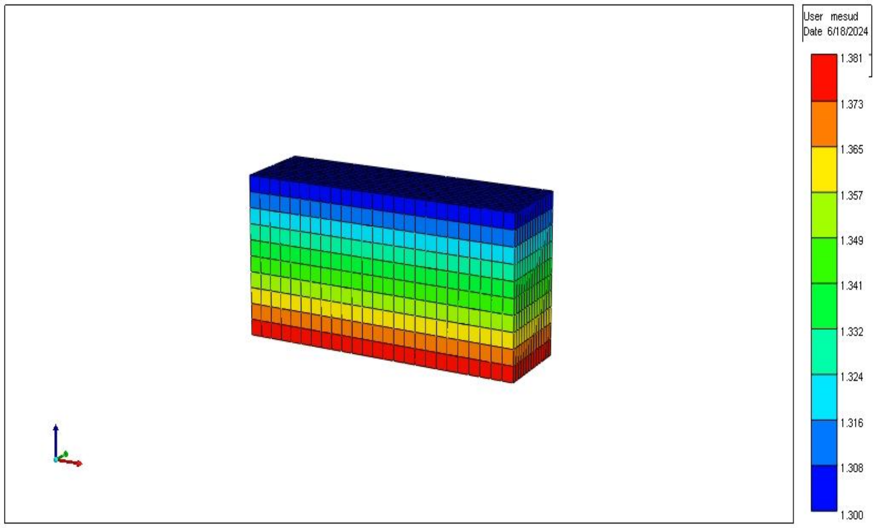

Figure 8—3D view of the conceptual reservoir model.

For the SAGD process, two horizontal wells were drilled with an 18-foot (5.4864 m) spacing, selected as the optimal distance for production. This spacing falls within the commonly cited range of 4-6 meters in the literature. A smaller spacing could result in early water breakthrough due to high vertical permeability. **Figure 9** provides a cross-sectional view of the setup. **Table 2** lists the operational parameters required to initiate the simulation.

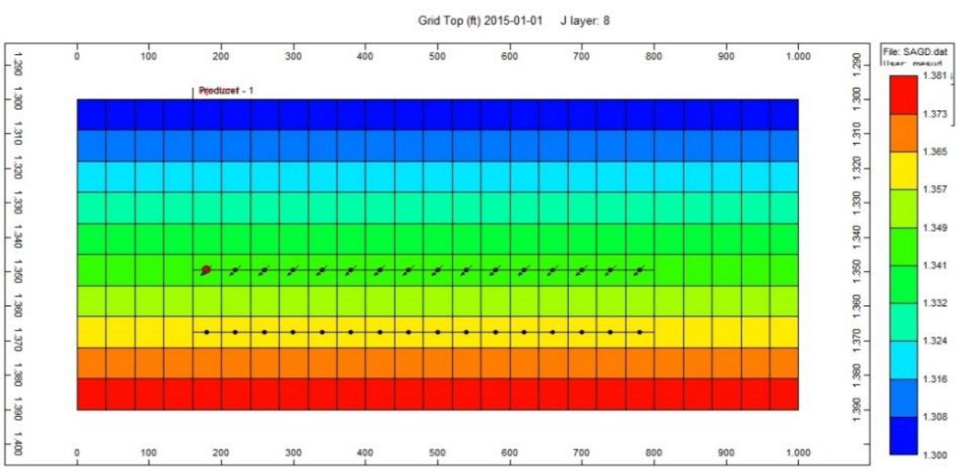

Figure 9—Cross-sectional view of SAGD process.

Table 2—Operational constraints and parameters for wells.

Recovery Method	Injector Constraint	Producer Constraint
SAGD	max BHP-950 psi max STF - 400 bbl/day	min BHP-500 psi max STW - 500 bbl/day

Results And Discussions

After the initial simulation run, the calculated reserves are summarized in **Table 3**. This table reflects only the oil and water phases, as there is no gas phase present.

Table 3—Results of reserves calculation from reservoir simulation.

Volume	Unit	Value
Gross formation	ft^3	2.70×10^7
Formation pore	ft^3	8.316×10^6
Aqueous phase	ft^3	1.6632×10^6
Oil phase	ft^3	6.6528×10^6
Gaseous phase	ft^3	0

The analysis evaluates the effectiveness of SAGD operations using two horizontal wells, emphasizing the role of steam quality in optimizing performance. The sensitivity analysis investigates the impact of steam quality at ratios of 0.6, 0.7, and 0.8 on SAGD efficiency. **Figure 10**, derived from CMG STARS data, compares steam characteristics with the recovery factor (RF). The key parameters assessed include the Steam-Oil Ratio (SOR) and the recovery factor.

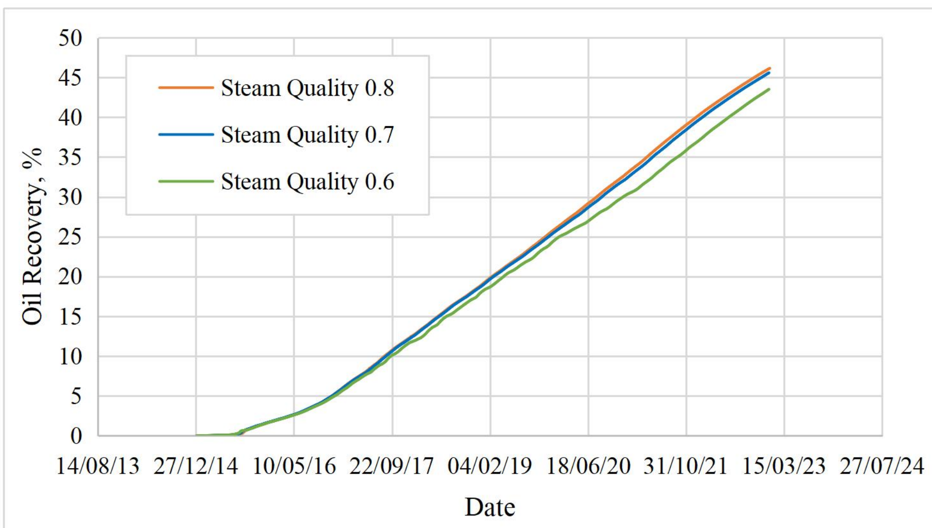

Figure 10—Effect of steam quality on oil recovery factor

As depicted in **Figure 10**, the orange line associated with a steam quality of 0.8 indicates a superior recovery factor, suggesting that higher steam quality corresponds to increased recovery efficiency. Conversely, the green line demonstrates the lowest recovery factor. Until 2017, both lines exhibit similar trends; however, they diverge thereafter, with the orange line achieving its peak performance. This trend contrasts with the steam-oil ratio, where higher steam quality results in a lower ratio. This behavior is attributed to the enhanced oil production potential at higher steam quality, as illustrated in **Figure 11**.

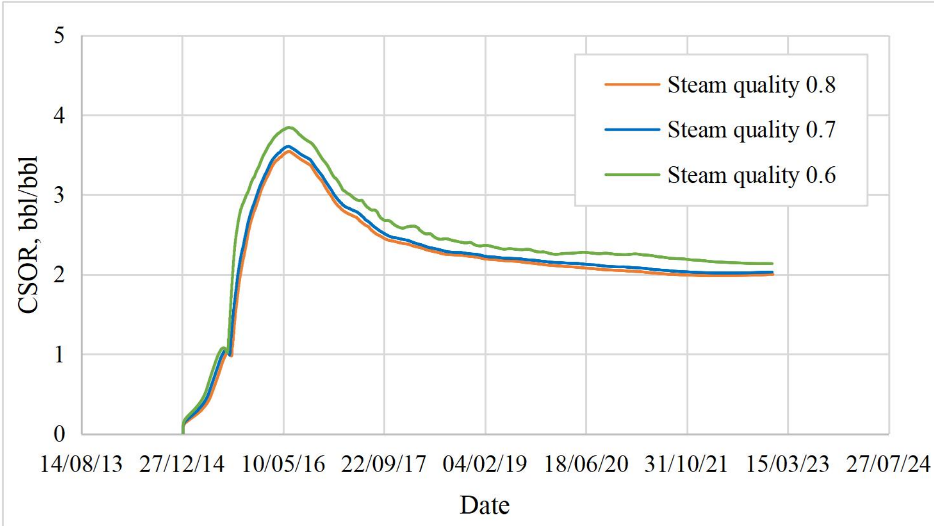

Figure 11—CSOR for different steam qualities.

The final simulation results are summarized in **Table 4**, offering a detailed comparison of the outcomes. After identifying the optimal steam quality of 0.8, the next step is to determine the maximum injection rate. While higher injection rates theoretically enhance production, it is crucial to account for the associated steam consumption. The evaluation includes injecting water at rates of 400, 500, 600, and 700 barrels per day (bbl/day), with steam generation adjusted according to the specified steam quality. Figures 12 and 13 compare the versatility of different injection rates, revealing that increased injection generally leads to improved optimization. Figure 11 illustrates the Recovery Factor (RF), showing that the results for 700 bbl/day and 600 bbl/day are quite similar, with only minor differences. This similarity underscores the importance of considering economic factors in the decision-making process.

Table 4—RF, CSOR, and Cumulative oil production for various steam qualities.

Steam Quality	Recovery Factor, %	Cum. Steam-Oil Ratio, bbl/bbl	Cum. Oil Production, bbl
0.8	46.16	2.003	538457.12
0.7	45.65	2.032	532477.12
0.6	43.58	2.137	508422.03

After identifying the optimal steam quality of 0.8, the next step is to determine the maximum injection rate. While higher injection rates theoretically enhance production, it is crucial to account for the associated steam consumption. The evaluation includes injecting water at rates of 400, 500, 600, and 700 barrels per day (bbl/day), with steam generation adjusted according to the specified steam quality. **Figures 12** and **13** compare the versatility of different injection rates, revealing that increased injection generally leads to improved optimization. Figure 12 illustrates the recovery factor (RF), showing that the results for 700 bbl/day and 600 bbl/day are quite similar, with only minor differences. This similarity underscores the importance of considering economic factors in the decision-making process.

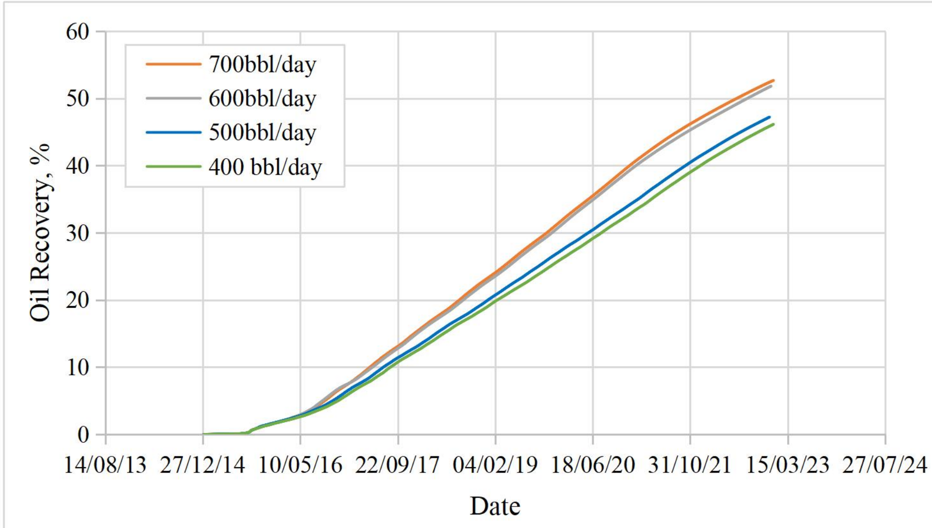

Figure 12—Impact of injection rates on recovery factor.

Recovery Factor (RF) alone is not a sufficient metric for evaluating economic viability. Specifically, the Cumulative Steam-Oil Ratio (CSOR) at an injection rate of 400 bbl/day is not the most economical option. According to Gates and Chakrabarty (2006), an economically acceptable CSOR falls within the range of 2 to 10 bbl/bbl. During the 2015-2017 period, higher CSOR values were observed due to the initial kick-off phase; however, all rates eventually decreased below this threshold. The 700 bbl/day injection rate maintains a stable CSOR similar to that of the 600 bbl/day rate but achieves a lower ratio compared to the latter. Thus, in terms of balancing economic viability and recovery efficiency, the 700 bbl/day rate is preferable over the 600 bbl/day rate. For a detailed comparison of CSOR at different injection rates, refer to Figure 13.

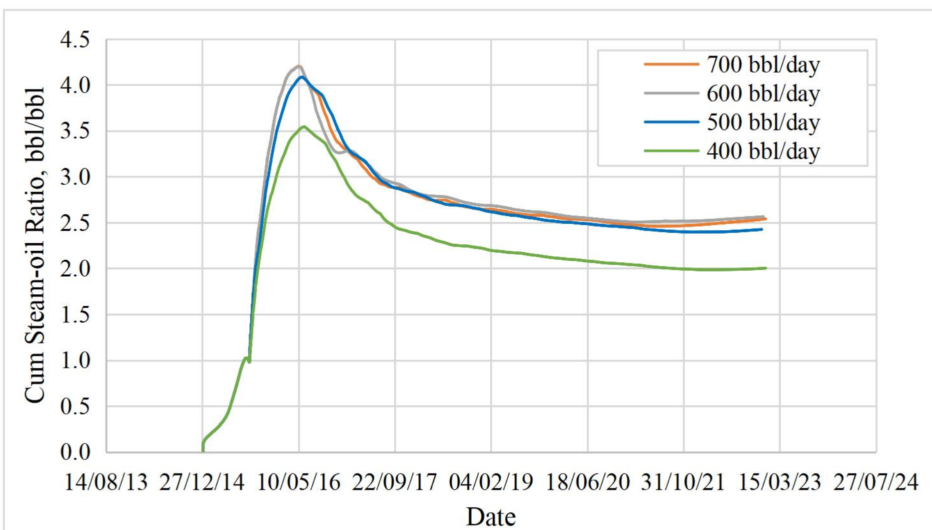

Figure 13—CSOR for various injection rates.

Table 5 outlines the sensitivity of SAGD operations to variations in both steam quality and injection rate. In the initial scenario, with a steam quality of 0.6 and an injection rate of 400 bbl/day, the recovery factor (RF) was 46.159%. However, as both steam quality and injection rate were increased, the recovery improved significantly, with the RF rising to 52.691% in the subsequent scenario. While further increases in the injection rate could potentially enhance recovery, it is important to note that under an injection pressure of 950 psi, the maximum injection rate achieved was 700 bbl/day. The 950 psi injection pressure is a critical parameter included in the operational considerations for this analysis.

Table 5—RF and CSOR for varying injection rates.

Steam Quality	Injection rate (bbl/day)	Oil Recovery Factor (%)	Cum. Steam-Oil Ratio (bbl/bbl)	Cum. Oil Production (bbl)
0.8	400	46.159	2.002	538457.12
	500	47.514	2.428	554441.62
	600	52.015	2.566	606867.43
	700	52.691	2.541	614627.5

Conclusions

This study utilized the CMG STARS simulator to assess the impact of steam quality and injection rate on the effectiveness of steam-assisted gravity drainage (SAGD) techniques. The methodology involved conducting multiple simulation scenarios with varying steam qualities and injection rates to analyze their influence on recovery factors and steam-oil ratios. The results clearly indicate that these parameters play a crucial role in determining the efficiency and success of SAGD operations.

1. Steam Quality: The analysis revealed that higher steam quality leads to improved oil recovery while reducing the steam-oil ratio. The sensitivity analysis focused on steam qualities of 0.6, 0.7, and 0.8, with the highest recovery factor observed at a steam quality of 0.8. Therefore, optimizing steam quality is essential for achieving better energy efficiency in SAGD operations.
2. Injection Rate:The injection rate was identified as another critical factor in enhancing SAGD process efficiency. Higher injection rates result in improved recovery factors by expanding the steam coverage area. For instance, at an injection rate of 700 bbl/day under 950 psi-the maximum rate achieved-a significant increase in oil production was observed. Optimizing the injection rate is, therefore, a key requirement for maximizing oil recovery in SAGD processes.

In conclusion, by strategically improving steam quality and injection rates, SAGD operations in heavy oil fields can achieve optimal performance levels. This research underscores the importance of adjusting these parameters to enhance recovery factors and boost oil production.

Nomenclature

BHP	=	Bottom hole pressure, psi;
CSOR	=	Cumulative steam-oil ratio, bbl/bbl;
EOR	=	Enhanced oil recovery, %;
Injection Rate	=	Volume of fluid injected into a well per day, bbl/day;
OWC	=	Oil-water contact;
RF	=	Recovery factor, %;
SAGD	=	Steam-assisted gravity drainage;
SOR	=	Steam-oil ratio, bbl/bbl;
Steam Quality	=	Percentage of steam in a steam-water mixture, %;
STF	=	Surface fluid rate, stb/day;
STW	=	Surface water rate, stb/day;
B_o	=	Formation volume factor;
g	=	Gravity, API;
k_{row}	=	Relative permeability to oil;

k_{rw} = Relative permeability to water;
P = Pressure, psi;
S_w = Water saturation, %;
T = Temperature, °F;
μ = Viscosity, cP;
ρ = Density, lb/ft³.

Conflicting Interests

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

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