Optimization of the Operating Strategy for the ES-SAGD Process in different Oil sands Reservoir Quality

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Summary

This study investigates the optimization of oil sands production in the McMurray formation through the application of steam-assisted gravity drainage (SAGD), expanded solvent SAGD (ES-SAGD), and a combined SAGD–ES-SAGD processes. Three simulation models representing low-, medium-, and high-quality reservoirs were utilized to assess the performance of these processes. The objective function considers the project's net present value (NPV), incorporating capital expenses, operating expenses, and carbon tax for CO2 emissions. The results indicate that ES-SAGD demonstrates superior performance, yielding the highest NPV. Furthermore, pentane emerges as the optimal solvent for both ES-SAGD and SAGD–ES-SAGD processes. Additionally, initiating ES-SAGD at the earliest stage possible within the SAGD–ES-SAGD process maximizes performance. Notably, ES-SAGD and SAGD–ES-SAGD processes exhibit greater enhancements for low-quality reservoir models compared to the SAGD reference process, with diminishing improvements observed for high-quality models. This research provides valuable insights for the strategic development of oil sands resources in the McMurray Formation, offering a comprehensive framework for the selection and implementation of enhanced oil recovery techniques.

Methodology

The main target of this study is to propose an optimal operating strategy for oil sands production in the McMurray formation utilizing SAGD, ES-SAGD, and SAGD–ES-SAGD processes.
Three simulation models representing low-, medium-, and high-quality reservoirs were employed to evaluate the performance of these processes. These models, denoted as Model-A, Model-B, and Model-C, differ in pore volumes, average porosities, average oil saturations, and Original Bitumen in Place (OBIP) values (Table 1).

Table 1. Summary of reservoir simulation models.

Model	Pore volume, m3	Average porosity	Average oil saturation	OBIP, m3
Model-A	8.57E+05	0.302	0.76	6.53E+05
Model-B	9.26E+05	0.305	0.90	8.32E+05
Model-C	1.10E+06	0.315	0.81	8.95E+05

The operating conditions of each recovery process are summarized in Table 2, including injection pressures, solvent types, and concentrations. Butane, pentane, and hexane have been selected as solvents for ES-SAGD operation. Butane has been found to be the most commonly used solvent, as it has a lower boiling point and requires less energy for vaporization (Irani et al., 2021; Mohan et al., 2022; Orr, 2009). Pentane has also been found to be effective in reducing the viscosity of heavy oil and bitumen and improving oil recovery rates (Liu et al., 2021; Orr, 2009). Hexane has been used as a solvent in some studies and has shown promising results in improving oil recovery rates (Orr, 2009; Venkatramani and Okuno, 2018; Wu et al., 2020). The solvent concentration plays a critical role in the ES-SAGD process, which is used to extract heavy oil and bitumen from oil sands. The solvent concentration refers to the concentration of solvent in the injection fluid, and it affects the efficiency of oil recovery, process stability, and economic feasibility. The solvent is responsible for reducing the viscosity of the heavy oil and bitumen, and the solvent concentration is an essential factor that determines the degree of viscosity reduction. A higher solvent concentration typically results in a greater reduction in viscosity and improved oil recovery rates. Bryan Orr (2009) suggested an ideal solvent concentration of four to eight percent. In this study, a solvent concentration of 4-12 volume percent was used for ES-SAGD simulation.

Table 2. Summary of operating conditions of the recovery processes.

Process	Parameter	Lower value	Average value	Upper value
SAGD	Injection pressure, kPa	2,800	3,600	4,500
ES-SAGD	Injection pressure, kPa	2,800	3,600	4,500
	Solvent type	Butane	Pentane	Hexane
	Solvent concentration, %	4	8	12
SAGD – ES-SAGD	ES-SAGD starting time, year	1	3	5
	Injection pressure, kPa	2,800	3,600	4,500
	Solvent type	Butane	Pentane	Hexane
	Solvent concentration, %	4	8	12

Net Present Value (NPV) is used to evaluate the economic viability of a project. The NPV is calculated using equation (1), which incorporates project revenue, operating expenses, carbon dioxide tax, and capital expenses.

$$NPV = \sum_{j=1}^{n} \frac{Revenue_j}{(1+i)^j} - \sum_{j=1}^{n} \frac{OPEX_j}{(1+i)^j} - \sum_{j=1}^{n} \frac{CO2\_Tax_j}{(1+i)^j} - \text{CAPEX} \quad (1)$$

where *i* is the interest rate; the *Revenue* consists of revenue from bitumen production and recovered solvent; *OPEX* is the operating expenses including costs for steam and solvent injection; *CO2_Tax* is the tax applied to CO2 emission during the process. The CO2 emissions were estimated at an average rate of about 200 kg CO2 per m3 of water used for the processes (Gates and Larter, 2014). Carbon tax of 80 Canadian dollar per ton of CO2 emission (Government of Canada, 2023) was included in the NPV calculation. In addition, *CAPEX* is the capital expense. The CAPEX refers to the total drilling and completion costs for all the wells under investigation. The drilling and completion cost for each well is approximately 3 million USD (Kim and Shin, 2020). For instance, the CAPEX for a SAGD well pair would be 6 million USD, representing the combined cost of the two wells. The price of bitumen, steam, and solvent used for NPV analysis is presented in Table 3. In addition, an interest rate of 10% is used in all the analyses.

Table 3. Solvent cost data for economic analysis (Jaimes et al., 2020; Sidahmed et al., 2019).

Product	Price	
	USD/bbl	USD/m3
Bitumen	48.0	301.9
Steam	12.0	75.5
Butane	52.0	327.1
Pentane	77.2	485.6
Hexane	120.0	754.8

In the following sections, each of the SAGD, ES-SAGD, and SAGD–ES-SAGD processes was individually optimized by varying parameters such as injection pressures, solvent types, solvent concentrations, and ES-SAGD starting times to maximize NPV. Results from the individual optimizations were compared to identify the most effective operating strategy for each reservoir model. Subsequently, a comprehensive framework for selecting and implementing enhanced oil recovery techniques was proposed based on the optimization results and economic analysis.

SAGD Optimization

Injection pressure was varied to optimize the SAGD process. The optimal injection pressures for operating SAGD in Model-A, Model-B, and Model-C are 3,600, 4,500, and 3,600 kPa, respectively. The performance of the optimal SAGD process for each model is summarized in Table 4. The results show that Model-C yields the highest NPV compared to the other models. Although Model-A produced more bitumen, more steam injection was required, making it less economically feasible compared to the other models. On the other hand, NPV was calculated using two approaches: one excluding and the other including carbon tax. Incorporating carbon tax slightly reduces the NPV of the project. However, it is noteworthy that the economic feasibility of the project remains unaffected.

Table 4. Optimal SAGD performance.

Model	iSOR	Time to iSOR, year	cSOR	CDOR, m3/d	Cum. production, m3	RF, %	NPV, $MMUSD	NPV (CO2 tax), $MMUSD
Model-A	4.00	8.83	3.17	93.76	302,391	46.31	6.80	6.56
	5.00	9.92	3.27	89.93	325,731	49.88	21.67	21.41
	5.11	10.00	3.28	89.59	327,273	50.12	6.38	6.13
	9.80	15.00	3.66	71.70	392,864	60.16	4.05	3.76
Model-B	4.00	6.17	2.71	127.71	287,730	35.27	15.86	15.64
	5.00	7.33	2.83	115.72	310,027	37.70	32.48	32.24
	7.65	10.00	3.13	93.16	340,297	41.24	13.44	13.16
	7.23	15.00	3.59	68.88	377,372	45.51	10.24	9.93
Model-C	4.00	7.50	2.46	95.19	260,625	29.11	17.55	17.37
	5.00	8.58	2.57	88.18	276,360	30.86	32.10	31.91

	5.92	10.00	2.73	79.97	292,125	32.62	16.58	16.38
	10.12	15.00	3.25	59.61	326,590	36.47	13.78	13.55

ES-SAGD Optimization

The ES-SAGD process was optimized by varying injection pressures (BHP), solvent types, and solvent concentrations. The optimal operating conditions for ES-SAGD are summarized in Table 5. Across all models, Pentane emerged as the optimal solvent type, with a consistent solvent concentration of 12%. Notably, the ES-SAGD process demonstrates a notable reduction in the steam-oil ratio (cSOR) and a substantial improvement in the bitumen production rate (CDOR), consequently enhancing the recovery factor and net present value (NPV) compared to the conventional SAGD process (Table 6). Furthermore, the high rate of solvent recovery contributes to cost savings in solvent injection.

Moreover, the ES-SAGD process exhibits the most significant improvement for Model-A compared to the other models. This enhancement emphasizes the efficacy of ES-SAGD, particularly in scenarios with challenging reservoir characteristics. The optimization results highlight the potential of ES-SAGD as a viable and economically attractive enhanced oil recovery technique, offering promising prospects for the optimization of oil sands production in the McMurray Formation.

Table 5. Optimal ES-SAGD operating parameters.

Model	BHP, kPa	Solvent type	Solvent concentration, %
Model-A	4,500	Pentane	12
Model-B	3,600	Pentane	12
Model-C	3,600	Pentane	12

Table 6. Optimal ES-SAGD performance.

Model	iSOR	Time to iSOR, year	cSOR	CDOR, m3/d	Cum. production, m3	Solvent recovered, %	RF, %	NPV, $MMUSD	NPV (CO2 tax), $MMUSD
Model-A	4.00	8.42	1.90	181.12	556,958	87.04	81.58	37.53	37.15
	5.00	11.66	2.08	137.20	584,466	88.66	85.64	65.10	64.68
	4.20	10.00	1.99	156.74	572,584	87.69	83.83	35.25	34.85
	5.37	15.00	2.25	109.27	598,708	89.93	87.75	29.42	28.98
Model-B	4.00	9.75	1.75	136.75	486,955	86.51	54.71	36.74	36.46
	5.00	-	-	-	-	-	-	-	-
	2.91	10.00	1.76	134.38	490,897	86.90	55.21	36.69	36.40
	4.00	15.00	1.97	102.23	560,142	90.84	64.13	35.05	34.72
Model-C	4.00	-	-	-	-	-	-	-	-
	5.00	-	-	-	-	-	-	-	-
	3.18	10.00	1.97	132.07	482,465	90.03	51.96	28.40	28.06
	2.12	15.00	2.04	111.21	609,330	90.34	65.59	29.56	29.17

SAGD – ES-SAGD Optimization

The optimization of the SAGD–ES-SAGD hybrid process involved adjusting parameters such as the ES-SAGD starting time, injection pressure, solvent type, and solvent concentration. Table 7 presents the optimal operating parameters determined for each model, highlighting the ES-SAGD starting time, BHP, solvent type, and solvent concentration.

Across all models, pentane was identified as the optimal solvent type for the SAGD–ES-SAGD process, with varying solvent concentrations. Furthermore, the results suggested initiating the ES-SAGD process as early as possible to maximize the NPV.

Table 8 illustrates the performance of the SAGD–ES-SAGD process under these optimized conditions. The optimization results demonstrate the effectiveness of the SAGD–ES-SAGD hybrid process in enhancing bitumen recovery and economic viability across different reservoir models. Notably, the SAGD–ES-SAGD process exhibits varying degrees of improvement in NPV compared to standalone SAGD or ES-SAGD processes, with Model-B showcasing substantial enhancements in particular configurations. These findings underscore the potential of the SAGD–ES-SAGD hybrid approach as a strategic tool for optimizing oil sands production in the McMurray Formation.

Table 7. Optimal SAGD – ES-SAGD operating parameters.

Model	ES-SAGD starting time, year	BHP, kPa	Solvent type	Solvent concentration, %
Model-A	3	4,500	Pentane	8
Model-B	1	3,600	Pentane	12
Model-C	1	3,600	Pentane	8

Table 8. Optimal SAGD – ES-SAGD performance.

Model	iSOR	Time to iSOR, year	cSOR	CDOR, m3/d	Cum. production, m3	Solvent recovered, %	RF, %	NPV, $MMUSD	NPV (CO2 tax), $MMUSD
Model-A	4.00	8.17	2.44	153.17	456,898	81.72	67.68	24.08	23.76
	5.00	8.83	2.51	145.44	469,035	82.99	69.50	46.63	46.29
	6.98	10.00	2.65	131.36	479,847	85.37	71.22	20.07	19.71
	10.07	15.00	3.17	90.48	495,735	88.89	73.49	10.72	10.31
Model-B	4.00	11.66	1.98	127.58	543,481	90.29	61.81	32.22	31.88
	5.00	-	-	-	-	-	-	-	-
	3.01	10.00	1.88	142.54	520,701	88.07	58.81	33.86	33.54
	3.08	15.00	2.10	106.63	584,216	91.62	66.95	30.63	30.27
Model-C	4.00	6.50	1.97	124.81	296,184	82.45	32.05	21.48	21.29
	5.00	9.58	2.23	93.33	326,665	82.89	35.16	36.59	36.37
	4.92	10.00	2.27	90.23	329,617	82.84	35.45	18.31	18.08
	3.83	15.00	2.56	67.83	371,621	82.82	39.68	15.32	15.06

Conclusions

This study investigated the optimization of oil sands production in the McMurray Formation through the application of SAGD, ES-SAGD, and a combined SAGD–ES-SAGD processes. The following conclusions were drawn:

(1) ES-SAGD and SAGD–ES-SAGD processes offer significant enhancements in terms of bitumen production rates, recovery factors, solvent recovery rates, and net present value compared to conventional SAGD operations. The integration of solvents in these processes plays an important role in reducing steam-oil ratio, improving recovery efficiency, and mitigating operational costs through solvent recycling.

(2) ES-SAGD yields the best performance among the processes. Therefore, it is suggested to produce oil sands production in McMurray formation using ES-SAGD. For existing SAGD wells, it is suggested to initiate the ES-SAGD process as early as possible to maximize the NPV.

(3) This study highlights the importance of considering environmental factors, such as carbon tax, in NPV calculations. While the inclusion of carbon tax may slightly impact the economic feasibility of projects, ES-SAGD and SAGD–ES-SAGD processes demonstrate resilience and potentially lower environmental footprints compared to traditional SAGD operations.

Nomenclature

SAGD	Steam assisted gravity drainage
ES-SAGD	Expanded solvent SAGD
OBIP	Original bitumen in place
NPV	Net present value
OPEX	Operating expenses
CAPEX	Capital expenses
CO2_Tax	Carbon tax
iSOR	Instantaneous steam-oil ratio
cSOR	Cumulative steam-oil ratio
CDOR	Calendar day oil rate
RF	Recovery factor
BHP	Bottomhole pressure

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References

Gates, I.D., Larter, S.R., 2014. Energy efficiency and emissions intensity of SAGD. Fuel 115, 706–713. https://doi.org/10.1016/j.fuel.2013.07.073

Government of Canada, 2023. Update to the Pan-Canadian Approach to Carbon Pollution Pricing 2023-2030 [WWW Document]. URL https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information/federal-benchmark-2023-2030.html%0A

Irani, M., Sabet, N., Bashtani, F., 2021. Horizontal producers deliverability in SAGD and solvent aided-SAGD processes: Pure and partial solvent injection. Fuel 294, 120363. https://doi.org/10.1016/j.fuel.2021.120363

Jaimes, D.M., Clarke, M., Manfre Jaimes, D., Clarke, M., 2020. Analytical Modeling of the Cyclic ES-SAGD Process. Energies 13, 4243. https://doi.org/10.3390/en13164243

Kim, M., Shin, H., 2020. Machine learning-based prediction of the shale barrier size and spatial location using key features of SAGD production curves. J. Pet. Sci. Eng. 191, 107205. https://doi.org/10.1016/j.petrol.2020.107205
Liu, H., Xiong, H., Rao, X., Huang, D., 2021. Rising-phase performance evaluation of Expanding-Solvent SAGD: Considering the horizontal-wellbore effect. J. Pet. Sci. Eng. 202, 107865. https://doi.org/10.1016/j.petrol.2020.107865
Mohan, V., Su, Y., Wang, J., Gates, I.D., 2022. Rich solvent - Steam assisted gravity drainage (RS-SAGD): An option for clean oil sands recovery processes. Clean. Eng. Technol. 8, 100463. https://doi.org/10.1016/j.clet.2022.100463
Orr, B., 2009. ES-SAGD; Past, Present and Future, in: All Days. SPE, New Orleans, Louisiana. https://doi.org/10.2118/129518-STU
Sidahmed, A., Nejadi, S., Nouri, A., 2019. A Workflow for Optimization of Flow Control Devices in SAGD. Energies 12, 3237. https://doi.org/10.3390/en12173237
Venkatramani, A.V., Okuno, R., 2018. Mechanistic simulation study of expanding-solvent steam-assisted gravity drainage under reservoir heterogeneity. J. Pet. Sci. Eng. 169, 146–156. https://doi.org/10.1016/j.petrol.2018.04.074
Wu, Y., Liu, X., Du, X., Zhou, X., Wang, L., Li, J., Li, Yanhong, Li, X., Li, Yang, 2020. Scaled physical experiments on drainage mechanisms of solvent-expanded SAGD in super-heavy oil reservoirs. Pet. Explor. Dev. 47, 820–826. https://doi.org/10.1016/S1876-3804(20)60097-0