Transference of Reservoir Uncertainty in Multi SAGD Well Pairs

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Extensive computational time is required to predict SAGD production performance by thermal reservoir simulation. The common practice is to evaluate the performance of a single well pair and combine the results to pads and projects. Production forecasts for multiple SAGD well pairs simultaneously are computational expensive. At the same time, there is a need to make reservoir management decision in presence of reservoir uncertainty. Accounting for joint uncertainty across the reservoir requires simultaneous management of multiple realizations. Thermal simulators cannot be applied to the transference of such uncertainty to SAGD performance of many well pairs. A proxy model based on the Butler's SAGD theory has been developed to overcome this challenge. The proxy is able to account for reservoir heterogeneity. Modifying factors are included to fit the proxy results to simulation outcomes. The methodology for the transference of the reservoir uncertainty includes: generation of the reservoir uncertainty model using geostatistical tools; ranking the geologic realizations using the Cumulative Steam Oil Ratio (CSOR) calculated by the unfitted proxy. The ranking process is done in a reservoir volume representative of a single well pair: reservoir simulation for the P10 to P90 realizations, fitting the proxy model to simulation results, and assessment of the uncertainty of the SAGD performance by Monte Carlo Simulation (MCS). This methodology was applied to a synthetic example of a pad of eight SAGD well pairs, using 3D geometry and based on hard data from an Athabasca bitumen deposit. The results show the uncertainty in the dynamic performance of SAGD production variables for the entire pad. The results permit decision making under the uncertainty. It is shown that approximate models accounting for uncertainty are better than precise models that cannot be used in stochastic calculations.

Introduction

After the success of the AOSTRA's Underground Test Facility (UTF) project [1-3], the Steam Assisted Gravity Drainage (SAGD) has become the standard recovery technology of oil sands industry to exploit the vast in-situ bitumen resources in Canada. Numerous commercial applications and pilot projects have been implemented since the UTF. As March 2008, eighteen commercial applications are being operated or approved by ERCB in Alberta [4].

There is a significant amount of technical work focused on the best strategy to successfully implement the SAGD process. Lab experiments, numerical simulation and field data analyses have been used to identify the key components that affect SAGD performance. There is a general agreement that the success of the SAGD operation relies on the adequate conformance of the steam chamber along the well pair. Oil rates and final recoveries depend heavily on the extension of the steam chamber [5]. In turn, the extension and conformance of the steam chamber are closely related to the geological parameters of the oil deposit. Thus, the key factor for a successful application of SAGD is the reservoir geology. High pay zones; high vertical and horizontal permeability; good vertical continuity; high oil saturations; and the presence of no top/bottom gas/water caps, i.e. thief zones, are the primary controllers for the SAGD process [6].

A good operational strategy is also required for the success of a SAGD project in a reservoir with the proper reservoir geology. Vertical and horizontal spacing, steam injection pressure, subcooling, steam quality at the sand face, start-up procedure, well length and number of well pairs per pad are among the most important operational factors that affect the SAGD process.

A pad is a group of well pairs that normally share the same surface facilities. In subsurface, they define a common portion of the reservoir volume to be drained. The definition of those volumes of reservoir, within the entire oil deposit, is a challenge. The use of reservoir simulation in this stage is limited if not impossible due to the extensive computational time that would require the SAGD modeling of large areas. The decision of the developable drainage volumes is then based on static reservoir parameters that measure the reservoir quality [7]. Areas that meet certain minimum cutoffs of vertical and horizontal permeability, porosity, oil saturation, net continuous bitumen and presence of thief zones would be the natural choice. Once the drainage volumes are selected, the SAGD production potential is analyzed in each of them. Again, the computational cost of using reservoir simulation at this scale is huge. The approach of the operators is to study the SAGD performance usually on a well pair basis and combine the results for the entire drainage volume and projects.

Besides the restriction of using simulation over multi SAGD well pair areas, there is a need to incorporate the uncertainty of reservoir/fluid properties as well as the uncertainty of operating strategy into the making decision process of SAGD projects. The conventional simulation workflow cannot be applied to account for the joint uncertainty across the reservoir in SAGD projects. Not modeling adequately the uncertainties during a SAGD development project increases the chance of making biased decisions and underestimate the risk. Therefore, alternative solutions should be developed to expand the spectrum of reservoir engineering studies on the transference the reservoir uncertainty to the production performance of SAGD process.

The use of proxies or simplified models has been identified as a reliable methodology to substitute the conventional simulation workflow in reservoir studies that require extensive simulation work; such is the case of optimization studies, sensitivity analyses and particularly, uncertainty assessments of SAGD performance.

Three different strategies of proxy-models generation for SAGD projects have been identified in the literature: 1) static measures of the goodness of reservoir fitted to a reservoir simulation response, see for example [8]; 2) use of Design of Experiments (DOE) and Response Surface Methodology (RSM) to generate polynomials fitted to reservoir simulator responses, see for example [9, 10]; and 3) physical-based proxies which are also adjusted to SAGD simulation responses, [11].

This paper is an extension of the work presented in [11]. In that work, a physical based proxy-model based on the Butler's SAGD theory described in [12, 13] was developed. The proxy allows the prediction of oil flow rate, cumulative oil production and cumulative steam injection time-profiles for a confined SAGD well pair. A complete MCS simulation scheme was implemented to incorporate efficiently the uncertainty in reservoir, fluid and operating parameters into the SAGD performance forecasting. The resulting tool was named as: Forecasting Analytical SAGD model for Transference of Reservoir Uncertainty (FastRun).

In this work, FastRun was used to assess the uncertainty on the dynamic performance of cumulative oil production and cumulative steam injection of a SAGD pad comprised by eight well pairs using a 3D geometry, where the conventional reservoir flow simulation work flow has no applicability.

Methodology

SAGD modeling has evolved from the original analytical solution proposed by Butler in 1981 to the use of very detailed thermal reservoir simulators. At the time that SAGD theory emerged, reservoir simulation was very limited by the computer capabilities and considerable effort was put to refine analytical solutions. Much work on developing the basis of the SAGD theory was based on lab scale experimental studies. The physical lab models have helped to increase the understanding of the SAGD process and to test the accuracy of the mathematical solutions. In the early 1990's when the UTF started, the first field scale simulation models were done to predict the SAGD performance at the tested well pairs and to design UTF's production/injection capabilities. Initially, 2D models were common since the limited computer resources impeded to run more complex 3-D geometries. Nowadays, with the rapid evolution of computer systems and the improvement of the numerical solutions, flow simulation has become the industry standard to predict SAGD performance and support development decisions. Although the high performance of current computer technology, the complexity of this recovery process still restricts the application of simulation to single well pair scenarios and mostly to deterministic predictions.

Each modeling approach, analytical solutions or numeric simulation models, has its specific application. The first has been used as mechanistic model of easy application, essentially to capture the main parameters affecting the recovery process and screen among possible prospects. The second is used to refined studies at field scale and to support investment decisions based on more rigorous predictions.

Despite of their simplicity, since they are based on ideal conditions, analytical models of oil recovery processes as SAGD are able to include the main mechanisms that drive the production process. The physical foundation of those simple models generates mathematical relationships that correctly describe the physical phenomena. This is an ideal feature for a proxy model that seeks efficiency with a considerable degree of precision. This special characteristic makes SAGD analytical solutions excellent candidates to build efficient and very reliable proxies for the assessment of uncertainty of SAGD performance.

The basis of the physical based proxy-model used in this work is explained with details in [11] and the workflow for the application of this methodology as stochastic prediction tool is shown is Figure 1.

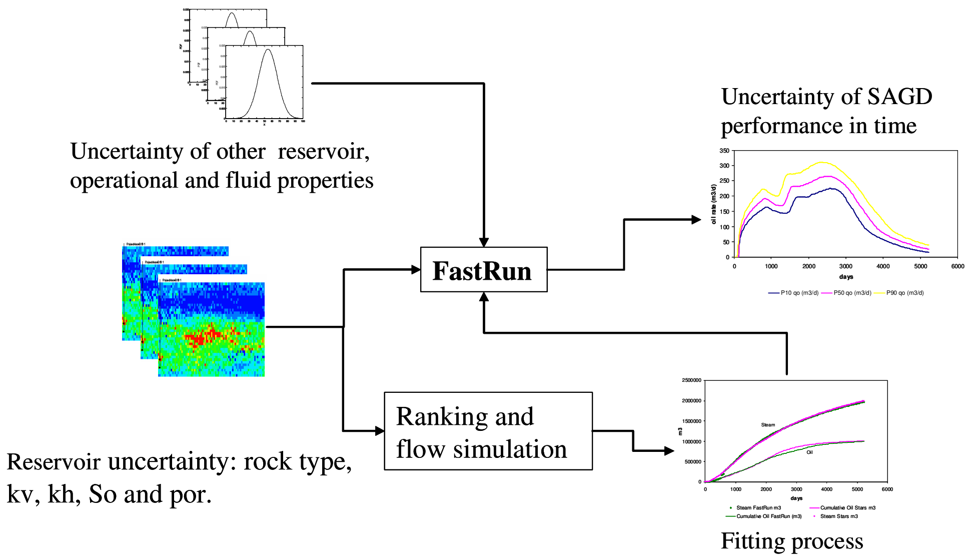

Figure 1. Workflow for the uncertainty assessment of SAGD performance using a physic based proxy model, from [14]

The first step in the application of this methodology is the generation of the reservoir uncertainty model. This model should parameterize the uncertainties that affect the SAGD performance, including the spatial distribution of the geologic variables as well as the different reservoir/fluid and operating factors. Geostatistics tools are used to provide multiple equi-probable realizations of geological variables honoring all available data. The proper modeling of the geologic uncertainty is crucial to adequately capture the SAGD performance uncertainty, since geology is the main driver in the SAGD process. On other hand, the uncertainties of the other operational and fluid variables are given as proper probability distribution functions.

Since the proxy uses an analytical model as forecasting tool there is a recognized deficiency in its power of prediction. To complement this deficiency the proxy needs to be fitted to more truthful production information, which in this case is the output of a reservoir simulation model. Adjusting factors were included in the analytical model to accomplish this task. In order to obtain a solution of wider applicability, the fitting process has to be done over a set of different and probable production possibilities including a range of equally probable reservoir realizations.

A ranking parameter allows the selection of the set of geological realizations to perform the simulation work, whose results are required during the fitting process. The prediction of the unfitted proxy was the option used as ranking parameter during this work. Ten realizations, P10 to maximum value, covering a wide range of possible SAGD performance, are selected to perform the fitting process.

The fitted proxy is then used as engine during the stochastic calculation of the SAGD production variables, including cumulative oil production, cumulative steam injection and oil flow rate time-profiles. Besides the transference of the uncertainty in the spatial distribution of geological variables as rock type (reservoir and no reservoir facies), vertical and horizontal permeability, oil saturation and porosity, the proxy allows the transference of uncertainties in the reservoir/fluid thermal properties, residual oil saturation, steam injection pressure, steam quality, oil API and start-up time defined from specific probability distribution functions, through the SAGD production variables.

The output of the probabilistic forecasting tool includes the uncertainty at any time during the expected production time of a SAGD project. This information, incorporated into the production management, would help to make sounder and better decisions during the development of a SAGD production project.

Application to SAGD multi-well pair areas

A synthetic 3D geomodel, comprised of 100 realizations of facies (reservoir, non-reservoir), horizontal permeability, vertical permeability, porosity and oil saturation, was generated to represent the geologic uncertainty. A random sampling of 0.07% of values from a porosity data set of a typical Athabasca oil sand was used as conditioned data during the modeling exercise. The geological grid is given by 1120x8x40 blocks with dimensions of 1x100x1 m. Eight SAGD well pairs drain this volume with regular spacing of 140 m and well length of 800 m.

Figure 2 shows the reservoir uncertainty as histograms of the geological variables. The reservoir volume used in this application is a clean sand with porosity and oil saturation being roughly homogeneous and having almost all reservoir heterogeneity represented by the heterogeneity in the directional permeabilities. The shales represent just an average of 2% of the reservoir volume. The mean, maximum and minimum values of the variables along with their quartiles are shown in Table 1.

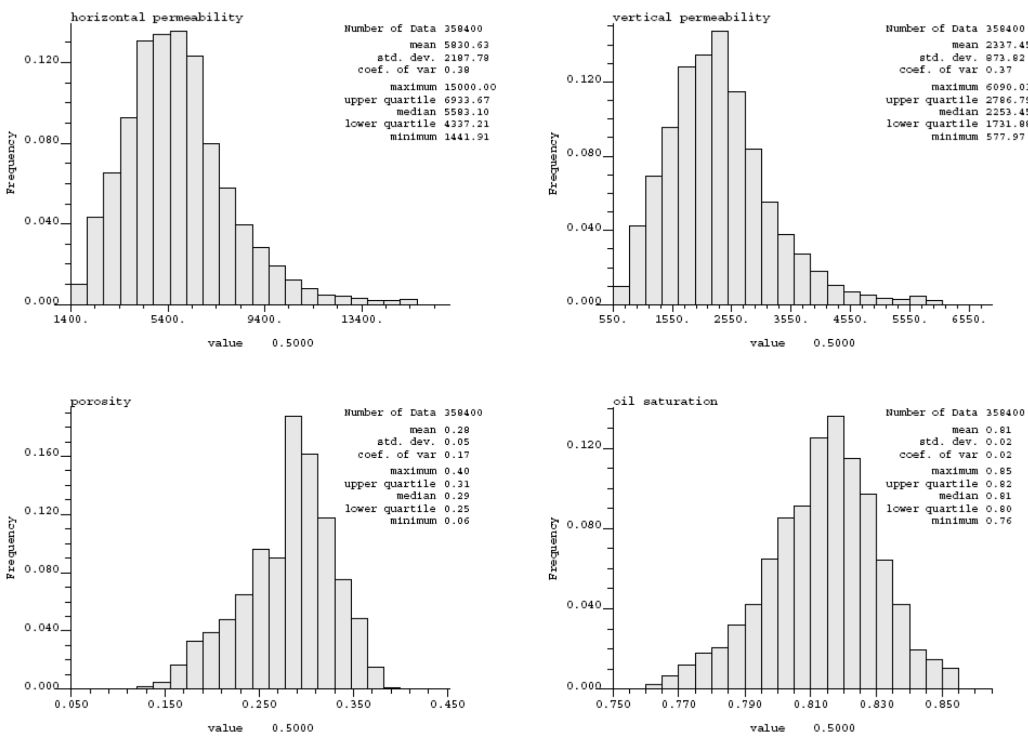

Figure 2. Histogram of geologic variables

Table 1. Geologic uncertainty of the reservoir drainage volume

Input Variable	Mean	Minimum	Maximum	Lower quartile	Median	Upper quartile
Horizontal perm. (md)	5831	1442	15000	4337	5583	6934
Vertical perm. (md)	2337	578	6090	1732	2253	2787
Porosity	0.28	0.06	0.4	0.25	0.29	0.31
Oil saturation	0.81	0.76	0.85	0.8	0.81	0.82

The Cumulative Steam Oil Ratio (CSOR) calculated at the end of the well pair life (usually 10 years) with the unfitted proxy was used to rank individual SAGD well pairs volumes across the 100 realizations of the drainage volume. Figure 3 shows the Cumulative Distribution Function (CDF) of the single SAGD well pair CSOR for 10 years of production. The individual SAGD well pairs geology realizations corresponding to P10 to maximum value of CSOR were selected to perform simulation.

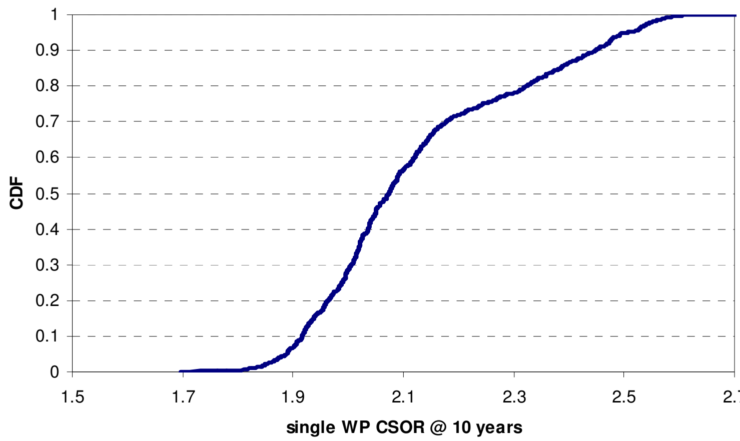

Figure 3. CDF of single well pair CSOR obtained from unfitted proxy to perform fitting process

The simulation work was performed using the geological realizations corresponding to the 10 deciles from the ranking procedure. The remaining input parameters of the simulation file represented the most likely values of the range of uncertainty considered during the uncertainty analysis (Table 2).

3D simulations models considered two parallel and horizontal wells of 800 m length oriented in *j* direction, within a reservoir with top at 200 m depth. Initial reservoir pressure was 1500 kPa and no flow boundary but heat loss is assumed at the overburden. No thief zones were considered in the simulations and a black oil fluid system was assumed. The operating strategy was oriented to maximize production with no production liquid or steam rate limitations. A steam trap control, allowing a maximum steam rate of 0.5 m^3/d, was used to ensure that all latent heat remains in the reservoir. Constant steam injection of 1500 kPa at 0.95% quality along with a bottom hole production pressure of 1510 kPa were used.

Simulations were performed using the compositional and thermal reservoir simulator STARS®. All simulation cases were run over a period of 10 years and each simulation case lasted in average 12 hours using a 2.33 GHz, 2.00 GB of RAM, Centrino® Duo PC.

tting process was performed with the results of the ten 3D reservoir simulations. The fitting process uses a simulated annealing type of optimization algorithm for the minimization of the mean square error of the cumulative oil production and cumulative steam injection. After 384 iterations comparing the proxy solution and the simulation results for all ten 3D single SAGD well pairs cases, the algorithm did not find a better answer than the plain unfitted proxy solution.

The next step is the calculation of the uncertainty over each well pair and the whole pad. The probabilistic forecasting tool is run over the pad using the 100 geologic realizations and 30 data sets sampled from the triangular distribution functions shown in Table 2.

Table 2. Parameters of the triangular distribution functions for some input reservoir/fluid properties and operational variables used in the proxy-model.

Input Variable	Minimum	Likeliest	Maximum
Sand thermal conductivity, J/m.d-C	93,100	133,000	173,000
Shale thermal conductivity, J/m.d.C	93,100	133,000	173,000
Water thermal conductivity, J/m.d-C	273,000	390,000	507,000
Oil thermal conductivity, J/m.d-C	93,100	133,000	173,000
Overburden thermal conductivity, J/m.d-C	102,800	146,900	191,000
Sand heat capacity, volumetric, J/m3-C	1,670,000	2,390,000	3,110,000
Shale heat capacity, volumetric, J/m3-C	1,670,000	2,390,000	3,110,000
Oil fluid heat capacity, J/Kg-C	1,466	2,094	2,722
Heat capacity of overburden, volumetric, J/m3-C	1,640,000	2,350,000	3,060,000
Oil API density, deg	7.91	11.30	14.70
Residual oil saturation, fraction	0.20	0.22	0.24
WOR/SOR for calculation fractional flow of water, fraction	0.95	1.00	1.05
Steam chamber pressure, kPa	1,057	1,510	1,963
Injeciton Steam quality, fraction	0.82	0.90	0.98
Temperature of production fluids, C	130	150	170
Initial reservoir temperature, C	10	18	26
Start up time, days	100	120	140

In total, 3,000 different cases were run to assess the uncertainty of the cumulative oil production and the cumulative steam injection during 10 years of operation of a SAGD pad comprised by 8 well pairs. The computational time to perform this task was around 18 days, which is a considerable period of time, however it is worthy compared to impossibility of using reservoir simulation.

Figure 4 shows the output of the probabilistic forecasting tool as the uncertainty in the dynamic response of oil rate, oil production, steam injection and CSOR of the whole pad. Table 3 also shows a summary of the uncertainty for each well and for the whole pad.

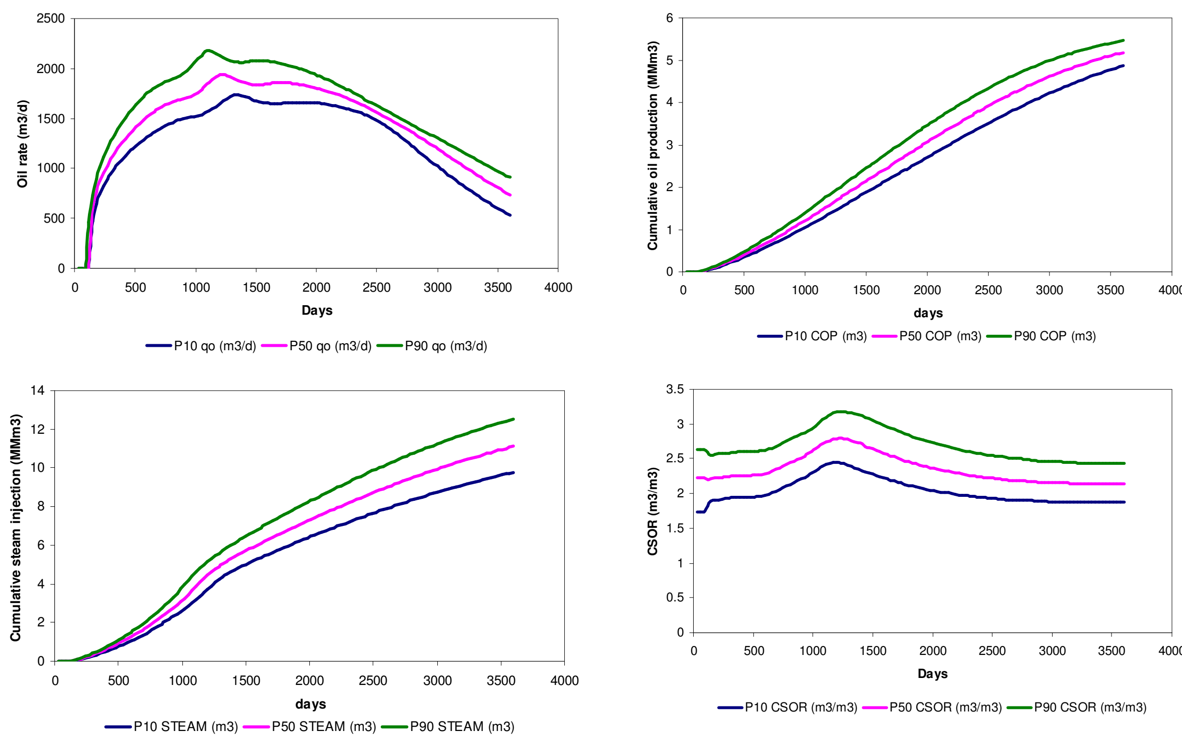

Figure 4. Uncertainty of dynamic response of SAGD performance in a pad with 8 well pairs

Table 3. Summary results of the uncertainty of a SAGD pad performance

	Well: Well_1				Well: Well_2				Well: Well_3			
	mean	P10	P50	P90	mean	P10	P50	P90	mean	P10	P50	P90
Reserves (MM m3/d)	0.677	0.63	0.679	0.719	0.732	0.689	0.734	0.774	0.724	0.682	0.728	0.766
CSOR over well life	2.069	1.79	2.059	2.353	1.942	1.691	1.932	2.209	1.988	1.734	1.979	2.254
Cum.Steam over well life (MM m3/d)	1.4	1.225	1.398	1.578	1.421	1.242	1.419	1.602	1.439	1.254	1.44	1.629
SAGD OOIP (MM m3/d)	1.008	0.972	1.008	1.039	1.073	1.044	1.074	1.104	1.077	1.047	1.079	1.103
Recov. Factor	0.672	0.627	0.675	0.712	0.682	0.647	0.684	0.714	0.672	0.637	0.676	0.705

	Well: Well_4				Well: Well_5				Well: Well_6			
	mean	P10	P50	P90	mean	P10	P50	P90	mean	P10	P50	P90
Reserves (MM m3/d)	0.687	0.647	0.688	0.724	0.662	0.622	0.664	0.702	0.629	0.581	0.631	0.675
CSOR over well life	2.106	1.84	2.099	2.382	2.134	1.862	2.126	2.422	2.214	1.928	2.205	2.517
Cum.Steam over well life (MM m3/d)	1.446	1.27	1.444	1.628	1.414	1.241	1.41	1.593	1.393	1.223	1.391	1.57
SAGD OOIP (MM m3/d)	1.048	1.021	1.051	1.073	1.02	0.995	1.02	1.046	0.956	0.925	0.956	0.986
Recov. Factor	0.655	0.621	0.657	0.687	0.649	0.611	0.651	0.685	0.658	0.609	0.661	0.703

	Well: Well_7				Well: Well_8				PAD			
	mean	P10	P50	P90	mean	P10	P50	P90	mean	P10	P50	P90
Reserves (MM m3/d)	0.557	0.51	0.56	0.606	0.503	0.454	0.506	0.549	5.171	4.868	5.185	5.462
CSOR over well life	2.413	2.093	2.403	2.745	2.541	2.205	2.53	2.895	2.154	1.88	2.143	2.436
Cum.Steam over well life (MM m3/d)	1.344	1.175	1.345	1.522	1.278	1.112	1.272	1.453	11.136	9.78	11.11	12.516
SAGD OOIP (MM m3/d)	0.878	0.852	0.875	0.905	0.846	0.817	0.845	0.876	7.906	7.781	7.913	8.018
Recov. Factor	0.635	0.58	0.638	0.686	0.595	0.54	0.597	0.645	0.654	0.616	0.656	0.69

The previous results are essential to assess the economic risk of developing a SAGD project and would help to make sounder and better decisions.

Limitations of the methodology

The results of applying the proxy methodology for SAGD projects are encouraging, although some drawbacks have been identified, including:

- The proxy calculates the SAGD performance in 3D geometries assuming independent production behavior of each vertical section of the 3D model along the SAGD well pair. No pressure gradients between adjacent vertical sections are considered. Although, in real situations, pressure gradients might be developed in the reservoir along the well pair due to temperature gradients within the steam chamber and to reservoir heterogeneity, this assumption is not completely incorrect. Gravity being the main production mechanism of the SAGD process makes that the bulk of the flow occurs across the vertical 2D section perpendicular to the well pair.
- The proxy prediction in multiple well pair areas is based on the strong assumption that each well pair will drain a given volume specified by its geometry parameters: thickness, well pair spacing and well pair length. No interaction between contiguous steam chambers is considered, which implies that there is symmetry in the distribution of the reservoir properties of each half reservoir volume between two adjacent well pairs. In actual SAGD applications coalescence of contiguous steam chambers are not expected to follow a symmetric pattern.
- The Cartesian grid system considered in the proxy (a simple cube) makes difficult the application of reservoir models constructed with a different grid system as it is the case of z-corner.
- No modeling the thief zones. The averaging procedure along the steam chamber-reservoir interface implemented in the proxy over estimate the degradation effects of thief zones on the SAGD performance.
- A constant pressure along the well pair life considered in the proxy does not allow modeling a lower pressure period and neither the final blow down.
- The proxy considers the production from a single layer (fixed *i* or *j*,*k* block) along the well pair. This lack of flexibility in the well production placement makes difficult the proxy application to real SAGD well pairs.

The proxy modeling methodology presented here makes possible the integration of the joint reservoir uncertainty, therefore is oriented to screening prospects and decision making at higher level. The objective is not to replace the simulation work. Reservoir simulation will be needed always to make rigorous predictions and make decisions on a single well pair basis.

Conclusions

Proxy modeling offers an efficient a reliable methodology to integrate the joint reservoir uncertainty into the SAGD performance in multi-well pair areas; task that would be impossible to accomplish using conventional simulation as a transfer function of uncertainty.

The physical based proxy allows the correct balance of precision and efficiency, making it ideal to use it as surrogate of complex reservoir simulator during reservoir engineering studies demanding extensive computational work, includingoptimization studies and uncertainty assessments.

Future work will be focusing to overcome the proxy limitiations to adapt the probabilistic forecasting tool to more realistic field application.

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