Stochastic optimization of thermal EOR

Study of SAGD's steam Injection parameterizations

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ABSTRACT

Due to the high demand of hydrocarbon consumption across industries and for personal use, improving existing hydrocarbon recovery methods (i.e., Enhanced oil recovery techniques (EOR)), have become a hot topic in research and development both within academia and industry. In order to increase the production of heavy and extra heavy oils and bitumen, several tertiary recovery techniques can be performed. Within this framework, steam assisted gravity drainage (SAGD) is considered the reference technique to increase oil production. This method consists of drilling two horizontal wells spaced vertically between each other around 5 to 7 m, where the upper well injects steam with a certain quality, at a given temperature, pressure and enthalpy. With this, a steam chamber will grow first upwards and then horizontally, and the hydrocarbons, due to the decrease of viscosity and because of the gravity, will flow downwards towards the production well. Several parameters regarding fluids and rock reservoir's properties and wells' operating factors can be studied when considering EOR techniques. The main goal of this study is to evaluate three SAGD parameterizations without disregarding the economic viability of the project: steam quality and injection temperature and pressure. To conduct this study, a realistic synthetic bitumen reservoir model, based on real data from Canada's reservoirs (Athabasca fm), was created. Numerical fluid flow simulation was linked with a stochastic adaptive sampling to perform sensitivity analysis in these parameters. Finally, the total amount of produced oil is expected to increase, when compared with the use of primary energy, knowing that for an appealing project in terms of financial viability, the cumulative steam-oil ratio and watercut must be below 4 units and 0.97, respectively.

Keywords: Steam assisted gravity drainage, SAGD, Steam injection parameters, Injection steam quality, Injection steam temperature, Injection steam pressure, Stochastic optimization

1. INTRODUCTION, CONCEPTS DEFINITION & STATE OF ART

SAGD technique was first purposed by Butler et al. (1981) as a way to recover bitumen, and after the first installation happened in 1985, in the Underground Test Facility in Fort Mac Murray in Alberta, Canada, was extended as well to heavy and extra heavy oils. Only in the last past 12 to 15 years is when this type of directional technique has shown good results when talking about unconventional oils (Speight, 2016).

SAGD method consists of drilling two horizontal wells spaced vertically between each other around 5 to 7 m, and with a total length that varies from 500m to 1500m, where the upper well injects steam with a certain quality, at a given enthalpy, temperature and pressure (Banerjee, 2012) (Gates, et al., 2005). With this, a steam chamber will grow first upwards and then horizontally, and the hydrocarbons, due to the decrease of the high viscosity and because of the gravity, will flow down towards the production well.

The total amount of oil that is produced, as well as other fluids, is intrinsically related with the reservoir characteristics and the growth of the steam chamber (Equations 1, 2 and 3). Knowing this, the first variable considered to evaluate its impacts on the efficiency of the SAGD method is the steam quality, which, according to Teixeira et al. (2014), is extremely important, and considering Mollier's Diagram, it cannot be excluded when studying the characteristics of the injected water steam. The other two variables are then selected from a mathematical point of view, once they are needed to expand the steam chamber.

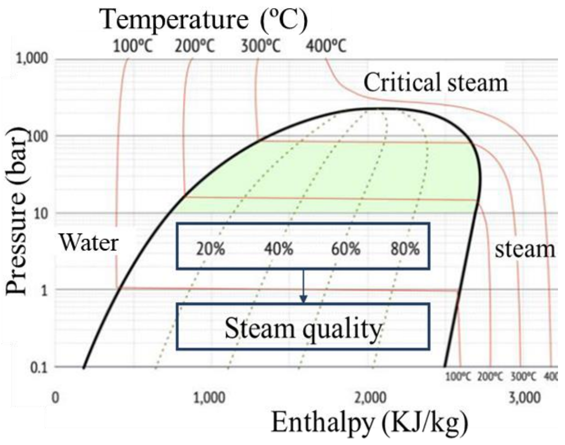

Fig. 1: Mollier diagram for enthalpy, temperature, pressure and steam quality of water steam **(Brown, 2015)**

$$Total\ oil\ production = function\begin{pmatrix} Reservoir\ characteristics \\ \boldsymbol{Chamber's\ growth} \end{pmatrix} \quad \textbf{(1)}$$

$$\boldsymbol{Chamber's\ growth} = function\begin{pmatrix} Conduction\ energy \\ Convection\ energy \end{pmatrix} = function\begin{pmatrix} Reservoir\ characteristics \\ \boldsymbol{Steam\ temperature} \\ \boldsymbol{Chamber's\ velocity} \end{pmatrix} \quad \textbf{(2)}$$

$$\boldsymbol{Chamber's\ velocity} = function\begin{pmatrix} Reservoir\ characteristics \\ \boldsymbol{Steam\ pressure} \end{pmatrix} \quad \textbf{(3)}$$

2. METHODOLOGY WORKFLOW

FIRST STEP (SYNTHETHIC RESERVOIR MODEL)

In order to study the impacts of the characteristics of the injection of a fluid inside of a reservoir when using a SAGD technique, first it is needed to design a synthetic model. To create it, an extended study is performed to understand the unconventional ranges of several properties that can be seen in Fig. 3. Once the study of the petrophysic attributes is complete, the cube of the synthetic reservoir is created in agreement with the following steps:

1. Generation of porosity (ϕ) and permeability(k), for 5 vertical wells;

2. Creation of two cubes: one for porosity, using a direct sequential simulation and one for the permeability by applying a direct sequential co-simulation, having as base information the first property; and verification of the spatial distribution, to know if it is in accordance with the variograms. The correlation coefficient is nearly perfect and the average values at the center of the reservoir (highlighted in orange in Fig. 2), for both properties are between the ranges of 20 to 40 % and 1300 to 2700 mD;

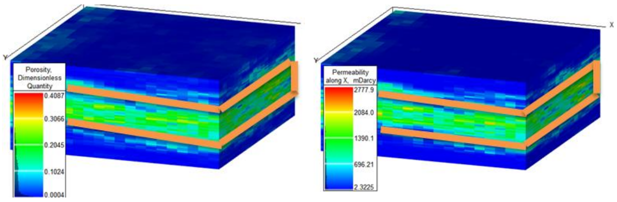

Fig. 2: Cubes of porosity (left) and permeability (right)

3. Definition of remaining reservoir properties, which are detailed in Table 1.

Table 1: Petrophysical reservoir characteristics **(Cusandei, et al., 2014) (Mojarab, et al., 2009) (Suranto, et al., 2014)**

Parameterizations	Data
Reference pressure (bars) (*default*)	1,206
Standard conditions pressure (bars)	1,013
Initial pressure (bars)	33
Rock compressibility (1/bars)	8,26E-5
Initial temperature (°C)	11
Standard conditions temperature (°C)	16
Initial temperature, at the top and bottom of the reservoir (°C)	30
Thermal conductivity $(J/m/dia/°C)$	660
Thermal conductivity, at the top and bottom of the reservoir $(KJ/m/dia/°C)$	660
Volumetric thermal capacity $(KJ/m^3/°K)$	360
Volumetric thermal capacity, at the top and bottom of the reservoir $(KJ/m^3/°C)$	2600

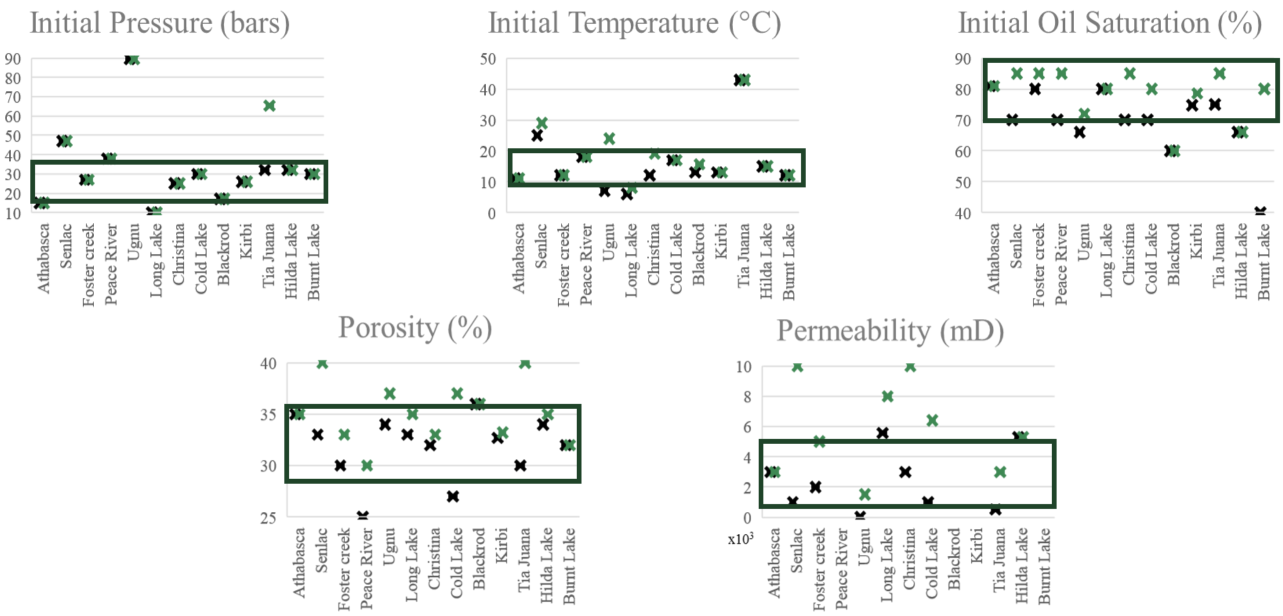

Fig. 3: Ranges of properties for unconventional reservoirs (Baytex Energy Lda. , 2015) (Black Pearl Resources Inc., 2017) (Boyle T. B., et al., 2003) (Bracho, et al., 1991) (Canadian Natural, 2017) (Cenuvus Energy Inc., 2016) (Donnelly, 2000) (Haan, et al., 1969) (Hallam, et al., 1992) (Ito, et al., 2010) (Kamath, et al., 1993) (Keijzer, et al., 1986) (Miller, et al., 2002) (Nexen Energy ULC, 2017) (Osum Production Corp., 2016) (Shell, 2013) (Vásquez, et al., 1999) (Zhao, et al., 2003)

4. Definition of fluid properties – water, oil and gas (Lee, et al., 2017) (Cusandei, et al., 2014) (Mojarab, et al., 2009):

- It is considered a live-oil composed by 80% of pentatetracontane and 20% of methane. The initial saturation is 90% with a thermal conductivity of 11,5 $KJ/m/day/°C$, the viscosity is calculated using the Mehrota & Svrecek's formula (1986) for Athabasca bitumens (Equation 4) and relative permeability curves are used from Bao's (2012) thesis after a LET correlation approximation is performed;

$$ln(ln(\mu)) = 22{,}8515 - 3{,}5784ln(T) \qquad \textbf{(4)}$$

- The water thermal conductivity is 50,11 $KJ/m/day/°C$, with an initial saturation of 10%;

- There is no gas in the beginning of the project. It starts to appear after steam is injected inside of the reservoir, and it's thermal conductivity is 5 $KJ/m/day/°C$.

SECOND STEP (WELLS' OPERATIONAL CHARACTERISTICS)

For the geometry of the injector and producer wells is considered the information of Table 2.

As control parameters, the injector well is assumed to have an injection rate of 36 m^3/day and the producer well, a bottom hole pressure (BHP) of 30 bars. To choose those values, a preliminary study is performed in order to have the highest Net present value (NPV), as well as a cumulative steam oil ratio (CSOR) of 4 units and also a watercut below of 97%.

Table 2: Geometry of SAGD wells

Parameterizations	Data
Diameter of wells (m)	0,25
Effective wells radius (m)	7,0056
Drainage wells radius (m)	0
Injector well depth (m)	529
Vertical space between wells (m)	5
Coordinates of injector well's elbow (m)	(10,4)
Coordinates of producer well's elbow (m)	(10,4)
Horizontal space between wells (m)	0
Length of the wells (m)	48
$(KH)_{effective}$ $(mD \cdot m)$	25000
Roughness (m)	1,0E-3
Flow area, perpendicular to producer well (m^2)	0,055

THIRD STEP (MODEL’S OPTIMIZATION)

This phase consists of defining the objective functions needed, in order to get the optimal values of the tree variables that are being studied, as well as to specify their restriction parameterizations.

To perform this optimization two algorithms from artificial intelligence are used, simultaneously: Particle Swarm Optimization (PSO) and Random Forest (RF).

After a stochastic optimization is performed, to examine if the pair of values (P,SQ) or (T,SQ) are a good selection, a final study is carried, taking into account the watercut, CSOR and finally the NPV.

BASE CASE MODEL

To understand the effect of the SAGD technique it is important to show the results when primary energy is used, without any kind of external stimulation – secondary or tertiary recovery methods.

By using a numerical fluid flow simulation, it is possible to notice the poor results that are achieved, by looking into Fig. 4. The total oil volume produced it ranges only from 0,13 to 0,28%, which corresponds to a negative NPV of 785 and 1300 thousand dollars, respectively, for a producer well control (BHP) of 16 and 30bars.

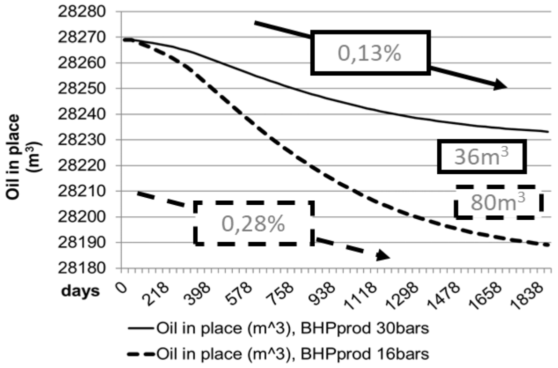

Fig. 4: Oil in place, after 5 years of project

3. RESULTS & DISCUSSION

VARIABLES’ SENSITIVITY ANALYSIS

To comprehend the effect of pressure or temperature and steam quality of the fluid injected on total oil (FOPT) and steam (FSTPT) amount produced, it is essential to perform a stochastic simulation. To do that, first it is explored each one of the variables according to each objective function, separately, and then in parallel. After that, both variables are evaluated, alongside, for a multiobjective function - Fig. 5.

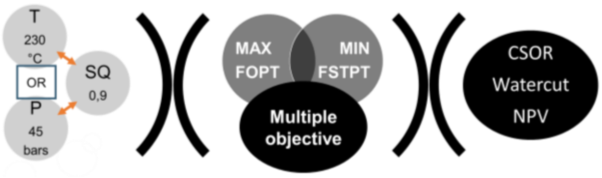

Fig. 5: Workflow of the optimization process

Maximize FOPT

A. One variable (P,SQ=0,9), (T,SQ=0,9) & (P=45,SQ), (T=250,SQ)

By analyzing both Fig. 6 (pressure for a constant SQ of 90%) and Fig. 7 (temperature for a constant SQ of 90%), it is understandable, when looking into Fig. 1, that the 2 images converge to an equivalent pair of values: a pressure of 65bars corresponds to a temperature of around 285ºC. The FOPT function movement grows until those values, and after it starts to decrease, which means that fingering effects can occur, leading to a deficient flow of fluids. When comparing both figures, it can be noticed, as well, that those variables have a week impact on FOPT, once the oscillation is around 162,5m^3, between the maximum and minimum values of total oil production.

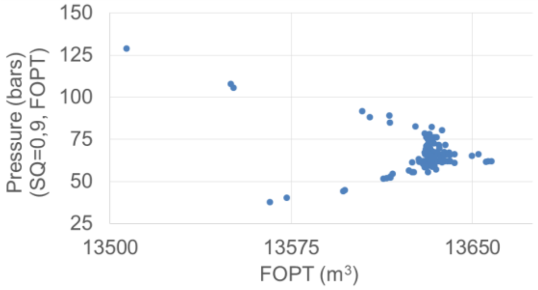

Fig. 6: Pressure effect on FOPT, for a SQ=0,9

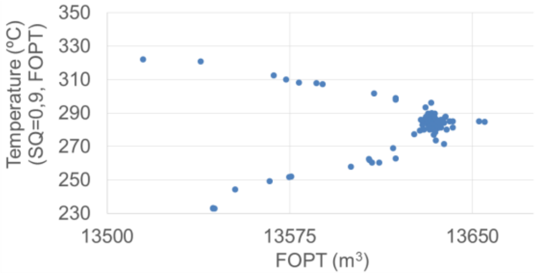

Fig. 7: Temperature effect on FOPT, for a SQ=0,9

By contrast to the last two images, Fig. 8 analyses the repercussion of SQ under a constant pressure (45bars) and the homologous temperature (250ºC). Here it can be observed the high and low results obtained for FOPT, in presence of a good or poor quality of the steam injected, respectively. Once it exists a large range of possible values, depending on the percentage of steam in the gas phase, it can be concluded that this variable has a big influence on FOPT. High percentages means considerable amount of oil volume extracted and, on the other hand, for small qualities the total oil produced is reduced.

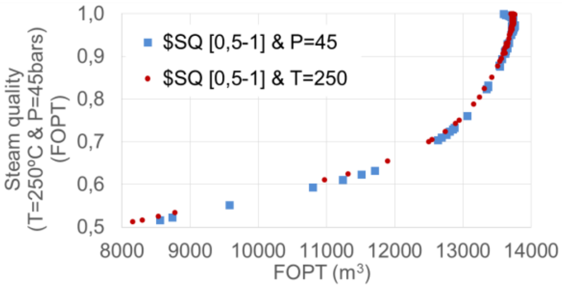

Fig. 8: Steam quality effect on FOPT, for a P=45bars which corresponds to a T=250ºC

B. Two variables: (P,SQ) & (T,SQ)

To conclude the FOPT objective function, the variables are explored in parallel, to perceive if there is a connection between them. Both variables pressure and temperature are correlated, as it was mentioned before: when analyzing Fig. 9 and Fig. 10, once again, the values are at the same level, with a very narrow distance between the average values (orange).

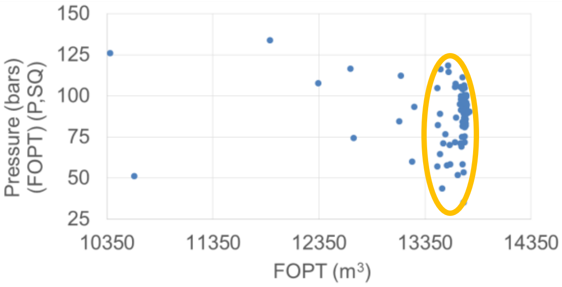

Fig. 9: Pressure effect on FOPT, for a parallel study of (P,SQ)

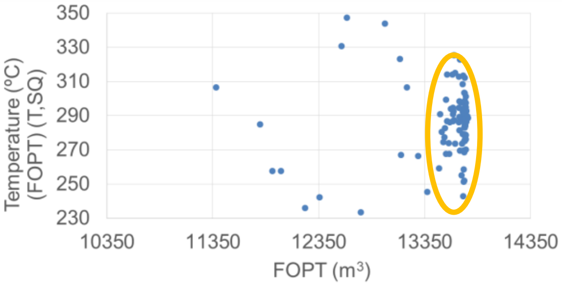

Fig. 10: Temperature effect on FOPT, for a parallel study of (T,SQ)

In terms of the variable steam quality, Fig. 11, the ranges are wide, shifting from around 10500 to 13750m^3, depending on the quality of the steam. As exploring pressure corresponds to temperature, the information of both variables appears overlapped.

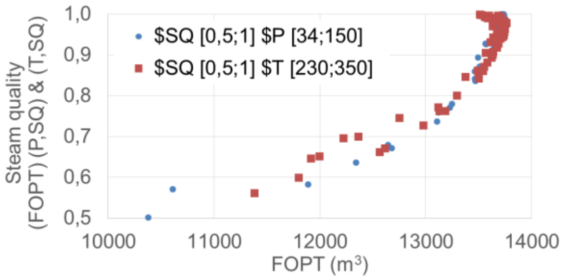

Fig. 11: Steam quality effect on FOPT, for a parallel study of (P,SQ) & (T,SQ)

Minimize FSTPT

A. One variable (P,SQ=0,9), (T,SQ=0,9) & (P=45,SQ), (T=250,SQ)

In terms of conclusions, Fig. 12 and Fig. 13 are similar to Fig. 6 and Fig. 7: FSTPT increases until a pressure of 70bars and to an homologous temperature of 287,5ºC, where, after those it starts to decrease. Both values are in accordance and to that pair of values the maximum value of total steam that is produced is around 13500m^3. Regardless the solutions of pressure and temperature, the volume interval is [10475;13500] m^3. When comparing this domain with the one observed from the Fig. 14, is irrelevant.

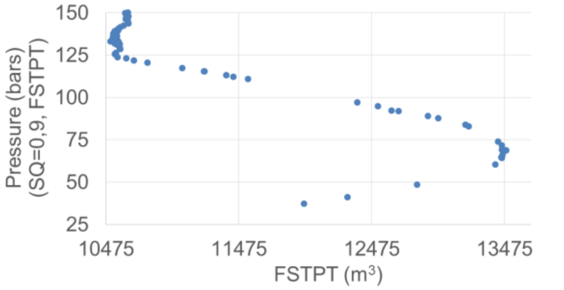

Fig. 12: Pressure effect on FSTPT, for a SQ=0,9

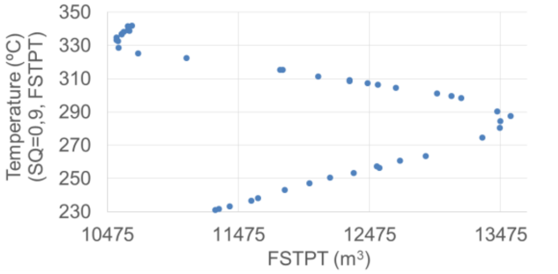

Fig. 13: Temperature effect on FSTPT, for a SQ=0,9

Steam quality, for FOPT, is the most important parameterization, when comparing it with the others variables, as well as for the total amount of volume produced of steam, Fig. 14. There is no difference between choosing either one of the variables, apart from steam quality. The last element is the one is going to dictate the performance of the model.

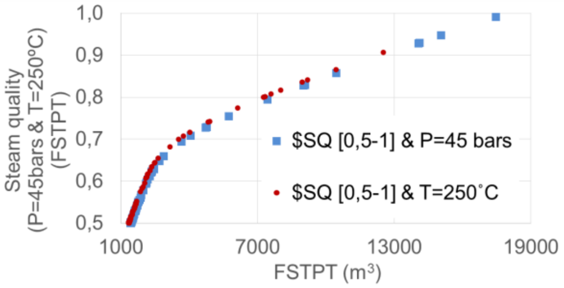

Fig. 14: Steam quality effect on FSTPT, for a P=45bars which corresponds to a T=250ºC

B. Two variables: (P,SQ) & (T,SQ)

FSTPT study continues, but taking into account two variables at the same time, when running the model under the stochastic optimization.

According to Darcy's law, about fluid flow, to have a small amount of drained fluid, the pressure difference between the reservoir and the hole must be low. That is why, in Fig. 15 and Fig. 16, the pressure and temperature, when steam quality is also being verified, both converge to the producer well's bottom hole pressure of 34bars. With such value, the total volume of steam produced is around 1000m^3.

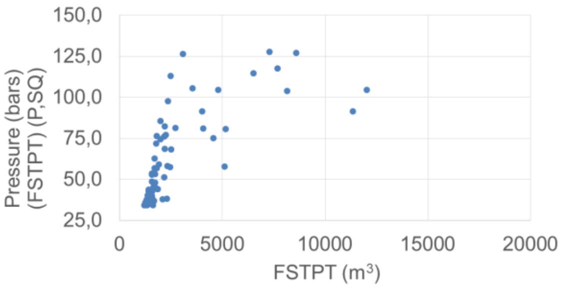

Fig. 15: Pressure effect on FSTPT, for a parallel study of (P,SQ)

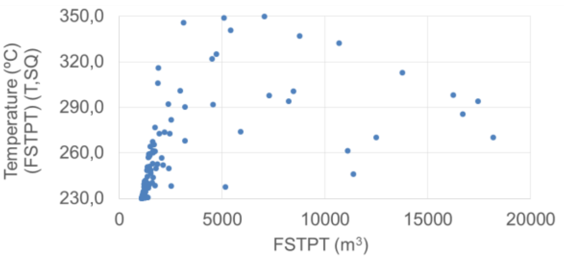

Fig. 16: Temperature effect on FSTPT, for a parallel study of (T,SQ)

Having an inferior quality, related with the injected steam, results in low quantities of vapour. With that, the chamber will grow inadequately, and so the volume of FSTPT is also minimal. FSTPT converges, as well, to around 1000m^3, which is expectable, once the variables are being simulated at once.

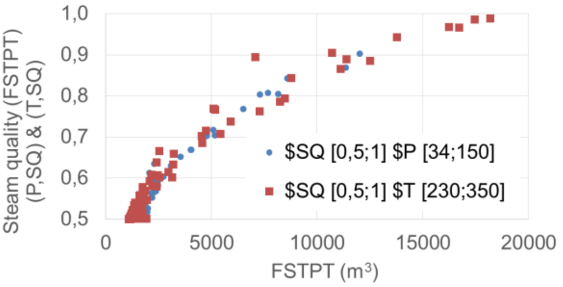

Fig. 17: Steam quality effect on FSTPT, for a parallel study of (P,SQ) & (T,SQ)

Maximize FOPT and minimize FSTPT, simultaneously

To conclude the variables' study on the two objective functions, everything is disturbed, simultaneously. However, as pressure is connected by Fig. 1 with temperature, the examination will proceed just for the pressure: temperature results are homologous to it.

In Fig. 18, comparing the information when is changed the pressure for a certain steam quality of 50% (purple shades), 75% (grey shades) and 90% (green shades), it is understandable that choosing higher qualities leads to higher volumes of FOPT and FSTPT. The offset of values is due to the quality, instead of the pressure variable, so this last element, has almost no representation on the outputs.

On the other hand, in Fig. 19, when looking into the outputs related with the variable steam quality for a constant pressure of 45bars (brown shades) and 150bars (blue shades), it can be analyzed that the pareto function movement is the same for both pressures. This concludes that what is making the ranges of values to vary is the steam quality, once again.

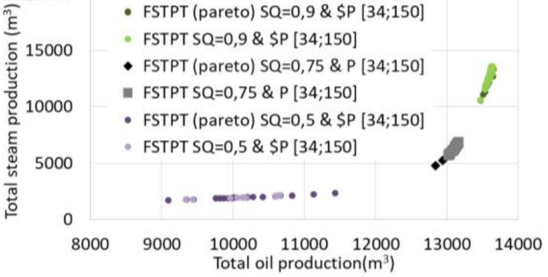

Fig. 18: Pressure effect on FOPT and FSTPT, simultaneously, for a parallel study of (P,SQ)

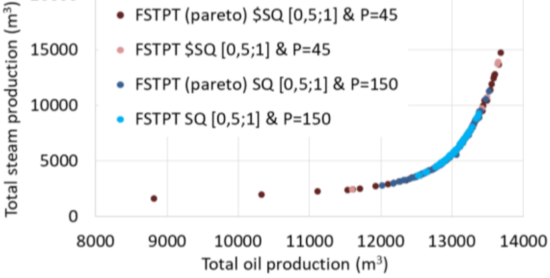

Fig. 19: Effect of SQ, for a parallel study of FOPT and FSTPT functions, for the pair of variables (P,SQ)

In Fig. 20, marked in red, it is represented the values' pair variability, related with pressure and steam quality. This image compiles also the information of the Fig. 18 and Fig. 19, once this way is easier to understand the importance of the 2 variables. Steam quality variable is so relevant that undermines the other 2 (pressure and, by consequence, temperature), once it can be observed there is no translation of the solutions contained in Fig. 18 and Fig. 19. This means, regardless the pressure value (when this fixed parameter is used: brown and blue shades), the effect is the same and, by contrast, depending on steam quality information, the findings are different.

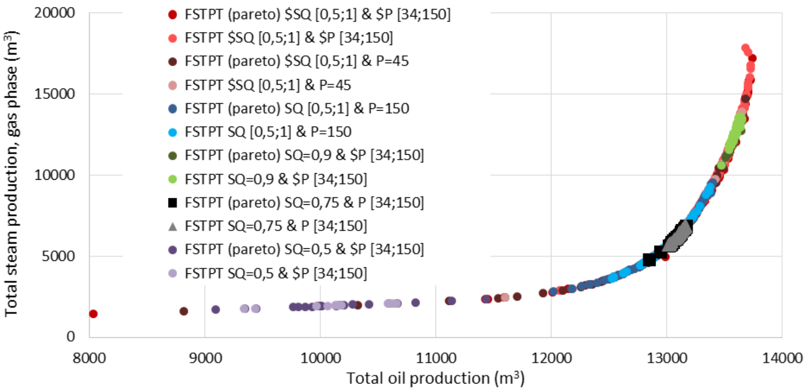

Fig. 20: Effects for a parallel study of FOPT and FSTPT functions, for the variables' pair (P,SQ)

The effect of the steam quality is represented in Fig. 21, where FOPT and FSTPT functions have opposite progress: the first has an exponential growth and the second a logarithmic evolution. This variable, for FOPT when compared with FSTPT, has low repercussions regardless the percentage of gas contained in the steam – for a SQ larger than 60%, the total amount of oil that can be extracted has a narrow variation (from 12000 to around 13750m^3, corresponding to an increase of 14,5%); however, for percentages below that value it can vary widely from 8000 to 12000m^3, which coincides to an improvement of 50%.

In terms of FSTPT, also in Fig. 21, when the steam quality is lower than 65%, the impact is not indicative enough on how the variable makes the function to vary; however, for values of SQ greater than that, until a maximum value of 100%, it is noticeable the impact on the production of steam, once the increase variation is around 414%.

In Fig. 22, where the variable pressure is studied alongside with FOPT and FSTPT objective functions, it can be detected two types of outcomes, whatever the pressure selected: the limited domain extension of FOPT (from around 13000 to 13750m^3) and the wide solutions of FSTPT. For the last function, the set of results can not demonstrates the type of behavior of this variable.

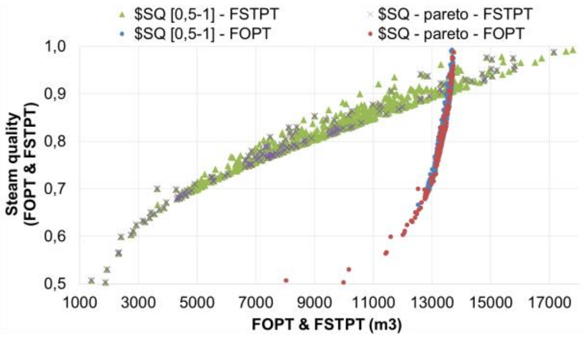

Fig. 21: Steam quality effects for a parallel study of FOPT and FSTPT functions, for the pair of variables (P,SQ)

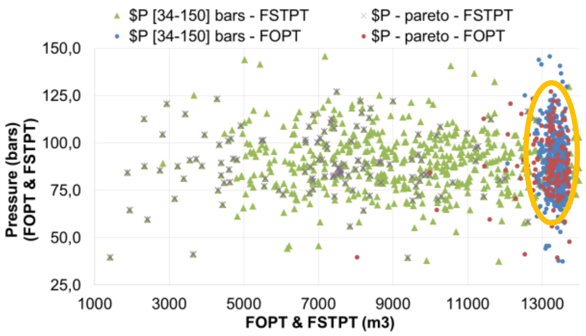

Fig. 22: Pressure effects for a parallel study of FOPT and FSTPT functions, for the pair of variables (P,SQ)

Importance of SQ, P & T

Analyzing both images of Fig. 23, it is easy to understand what has been said previously in this chapter. The graphs show the relevance of each variable on the fluid simulation results: the higher the translation of bars aside from absolute value of 50%, the bigger the impact shown to a certain output.

Pressure and temperature do not produce relevant impacts when compared with steam quality. The results that are more influenced by this last operational factor are:

- Rate and total steam production in gas phase;
- Rate and total oil production and, by consequence, the oil in place;
- Rate and total steam injected in gas phase.

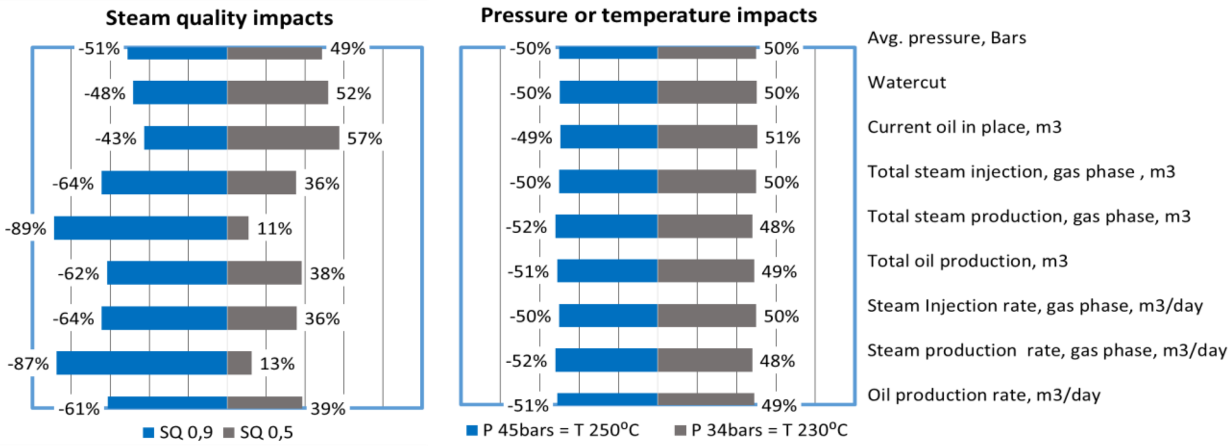

Fig. 23: Relevance of steam quality and pressure or temperature on fluid simulation results

ECONOMIC ANALYSIS

This chapter is useful to choose the pair of values that produces the higher Net Present Value and is divided into 2 phases: the first phase includes a qualitative appreciation of the pressure or temperature, and steam quality variables, in terms of FOPT and FSTPT, when studying each objective function separately; and the second one, by using a multiobjective function (FOPT and FSTPT) will produce a pareto front that will be studied, quantitatively.

Phase one

The pressure chosen (or temperature) needs to ensure that no fingering effects occur in the reservoir; that from an operational point of view, the higher pressure used, the bigger the levels of technology and costs associated and knowing that it is needed a CSOR below 4 units. Taking into account these assumptions, the pair of values can be selected in accordance with that: low pressure, but at a level that still enables the flow movement (Darcy's law), which can be 34 bars, or 230 ºC; and a steam quality of 99%, once it facilitates a higher production of oil, despites a higher steam injection volume. The NPV is around $ 794K.

Phase two

In this phase, only pareto front solutions are considered. Once watercut values are always below 97%, it is only performed a detailed study of CSOR and NPV values, in accordance with Fig. 24 and Fig. 25. The pair of values (P,SQ) that produces the highest NPV solution of around $793K is (85bars;99%).

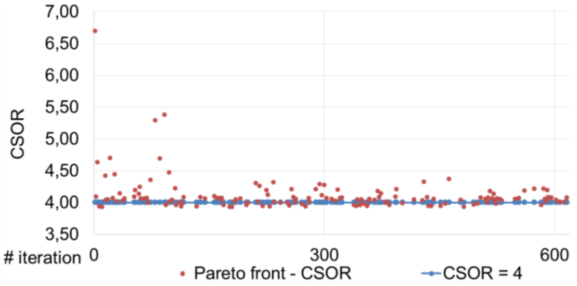

Fig. 24: Pareto front's CSOR from Fig. 20 (marked in red shades)

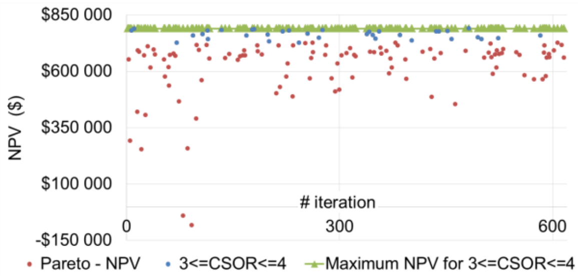

Fig. 25: Pareto front's NPV, from Fig. 20 (marked in red shades)

Pair of values (P,SQ)

When comparing information of phases one and two from Table 3, it can be observed that the discrepancy between the values is minimal, regarding pressure, so this variable is neglectable.

Table 3: Fluid simulator outputs for a study without injection and for phase one and two, which correspond to a pair of variables (P;SQ), respectively of, (34;0,99) and (85;0,99)

Outputs	No injection (BHP prod 30bars)	Phase One	Phase Two
Total oil produced (m^3)	35,83	13730	13742
Total steam injected (m^3)	-	57429	57321
Total steam injected in gas phase (m^3)	-	53978	54003
Total steam produced (m^3)	-	16663	17192
Oil in place (m^3)	28233	14542	14533
Average watercut (%)	-	79,5	79,5
Pressure (bars) (min; avg; max)	(27,3;30,2;33,4)	(30,3; 31,4; 38,2)	(30,3; 31,4; 38,2)
CSOR	-	~4	~4
NPV ($)	-1300×10^3	$\sim 794 \times 10^3$	$\sim 793 \times 10^3$

4. CONCLUSIONS

To know the impact of the pressure, temperature and quality variables of a certain steam on fluid simulator outputs, namely total injected and produced volume of different fluids, is essential to interpret the parameterization of the injection well. This study pretends to show the effect of such variables, so it is enumerated below the important findings:

- Mollier diagram (Fig. 1) is an extremely important graph when a characterization of a certain injected fluid (water) needs to be designed. This plot correlates, in a logarithmic scale, 4 elements (steam quality, pressure, temperature and enthalpy) through the phases of a fluid;

- For a good definition of the steam that is injected, it is only needed 2 parametrizations. The first, which cannot be disregarded, is the steam quality; and the second parameter can be either pressure, temperature or enthalpy;

- The most important variable on the injection system is the steam quality, once all the outputs are intrinsically dependent on the percentages of water on the gas and liquid phases;

- Pressure and temperature are comparable by the Mollier diagram. These two variables have a diminished effect, when compared with steam quality and when considering the steam production/injection rate and its associated volume, as well as oil production rate and its associated volume;

- Pressure and temperature variables are important so oil viscosity can decrease. Without increasing reservoir temperature, it is not possible to drainage viscous fluids such as (extra)heavy oils and bitumens, once the steam chamber does not grow, despite the steam quality is the parameterization that allows the chamber to grow uniformly, rapidly and effectively – necessary condition to allow fluids movement, and therefore the production of distinct nature fluids.

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