Production optimization for a conceptual model through combined use of polymer flooding and intelligent well technology under uncertainties

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Abstract

To mitigate high reservoir heterogeneities and fluids mobility differences, oil industry has developed methodologies and technologies like recovery methods at reservoir level, and intelligent completion system at well level. Polymer flooding is a method used to enhance the sweep efficiency in order to lead as much oil as possible to the producer wells, meanwhile the intelligent well technology allows to manage the flow of fluids into the wellbore, thus reducing water production and its costs involved. This work aims to study the behavior change of production due to the implementation in parallel of polymer flooding and intelligent well technology through conceptual reservoir simulations, risk management and geological and economic uncertainty analysis. Furthermore, it was stablished the resulting profit as main comparison criterion, under a simplified Brazilian fiscal regime. It was verified the largest project profit increase due to the combined use of both technologies.

Keywords: Intelligent Wells, Polymer Flooding, Oil and Gas Production, Reservoir Simulation, Uncertainties, Economic Analysis, Brazil.

Optimización de la producción para un campo conceptual a través del uso combinado de inyección de polímero y tecnología de pozo inteligente

Resumen

Con el fin de mitigar las altas heterogeneidades presentes en los yacimientos y la diferencia de movilidad de los fluidos, la industria petrolera ha desarrollado metodologías y tecnologías a nivel de yacimiento conocidas como métodos de recobro, y a nivel de pozo como el sistema de completamiento inteligente. La inyección de polímero es un método que mejora la eficiencia de barrido con el fin de contactar la mayor cantidad posible de hidrocarburos a los pozos productores, mientras que la tecnología de pozo inteligente permite administrar el flujo de fluidos en el pozo y de esta manera, reducir la producción de agua y los costos que implica. Este trabajo tiene como objetivo estudiar el cambio en el comportamiento de la producción debido a la implementación en paralelo de la inyección de polímero y la tecnología de pozo inteligente por medio de simulaciones de un yacimiento conceptual, gestión de riesgo y análisis de incertidumbre económica y geológica. Así mismo, se estableció la rentabilidad generada como principal criterio de comparación, bajo un régimen fiscal brasilero simplificado. Se verificó el mayor incremento en la rentabilidad del proyecto a causa del uso combinado de ambas tecnologías.

Palabras clave: Pozos Inteligentes, Inyección de Polímero, Producción de Petróleo y Gas, Simulación de Yacimientos, Incertidumbre, Análisis Económico, Brasil.

Introduction

Oilfields development has been presenting different issues challenging even the modern engineering. High water production rates are usually involved due to high mobility ratio and reservoir heterogeneity, creating a negative impact on the field development (Velandia, 2013). A lot of options have been employed to mitigate it, for example, EOR methods help to attain a better displacement efficiency, just like a polymeric solution

injection improving the conventional water flooding and achieving a more homogenous displacement (Galvis, Suárez & Navarro, 2013).

Polymer flooding consists on applying a polymeric material to the injection water, which can strongly improve the sweep efficiencies (Molano, Navarro & Díaz, 2014). Although a reduction in the average molecular weight could take place due to mechanical, thermal, chemical, or biological degradation of polymer, this is a good method to optimize a waterflooding process, because the polymer let it possible to reduce the mobility ratio, increasing oil recovery and reducing water cut (Yuming et al. , 2013). However, it is one of the different methods which could be applied to a reservoir level, and general landscape offers a lot of more points to keep working.

The wells performance is another parameter which has been analyzed its feasibility to be modified with novel engineering systems, to attain a better production behavior. Intelligent well technology (IWT) is a relatively new method, which uses a set of devices to make it possible to get flexible control from surface over production fluids flow, through each pay zone of the well individually. The system is based in swelling elastomer packers to isolate each zone, wireline from surface to bottom hole for data management, sensors to capture information and inflow control valves (ICVs) to choking flow pursuant of be required (Ordoñez, Velez & Florez, 2015).

The production performance thus can be enhanced from ways which involve a process through the reservoir, and others with just a completion modification (Páez, González & Duarte, 2016). Both mentioned technologies have a great potential and could result interesting to implement them simultaneously. In this sense, the focus for this study is to combine a polymer injection process with IWT to the producer wells, the feasibility to apply them was studied using reservoir simulation, together and individually for an offshore conceptual field. Also, this work involves a risk and uncertainty analysis of polymer flooding with IWT, acting together.

Statement of theory

Polymer flooding

It is a chemical enhanced oil recovery (CEOR) method, in which a large macromolecule is used to increase the displacing fluid viscosity and lead to better vertical and areal sweep efficiencies (Terry, 2001). Polymer flooding (PF) is designed to improve sweep efficiency by reducing

the mobility ratio. Polymers are large-molecular-weight molecules added to an injected water to increase its viscosity, improving the effectiveness of a conventional waterflooding (Alvarado & Manrique, 2010). However, it is important to consider the main issues involved for this method, like polymer degradation and its adsorption at reservoir.

Intelligent wells

They are wells with an intelligent completion system which is capable of monitoring production and reservoir data, and controlling downhole production (and injection) processes without any well interventions to help maximize the asset value (Ajayi & Konopczynski, 2003). The monitoring systems count with permanent downhole pressure and temperature sensors supplying reservoir information to a surface data gathering system. The controlling capability is accomplished by using a hydraulic, electric, or electrohydraulic control valves (ICVs). Each ICV can either be a binary on/off system or have variable chocking system (García & Saldanha, 2016).

The application of intelligent well technology (IWT) provides a capability to remotely control, monitor and manage multiple zones in each well. It has provided significant value, through its ability to manage multiple zones independently, reduce total number of wells, reduce number of expensive well interventions, and accelerate the production of zones to maintain a plateau for extended period of time (Ajayi & Konopczynski, 2003). Initially used in subsea wells, where intervention is very expensive and present high-risk, intelligent completions have proven their value in managing production from multilateral wells, horizontal wells with multiple zones, wells in heterogeneous and mature reservoirs. Figure 1 shows an example of the intelligent completion system applied to a producer well. It is worth mentioning that IWT can be applied to producer and injector wells, it allows to individualize the flows for each zone. Nevertheless, this study contemplates only the implementation in the producer well of the conceptual field, reason the study did not consider mechanical degradation of the polymer by the flow through ICVs.

Risk management

Volatility and risk are latent factors which nowadays affect different industries, and the Oil & Gas is not exempt. A lot of uncertainties could be involved around an oilfield project, usually are geological by low reservoir data, economic by country or company

policies and oil price, and technical by equipment failures (Quinteiro, 2008). Risk management is necessary due to the high degree of uncertainty that can be managed in oil & gas projects (Pari, Kabir, Motahhari & Behrouz, 2009). There are typically used three methods to analyze the project risk involved: decision trees, Monte Carlo simulation and real options theory; the first one was implemented for this study (Díaz et al. ,2012).

The comparison between all cases was based about the net present value (NPV) obtained from the economic analysis due to production fluids, following a simplified Brazilian fiscal regime. Also, there was evaluated the expected monetary value (EMV) of each strategy for further analysis, risk management and to generate representative conclusions about implementation of both technologies. Equation 1 shows how it was calculated the EVM values using two probability levels involved in this study, due to geological and economic uncertainties.
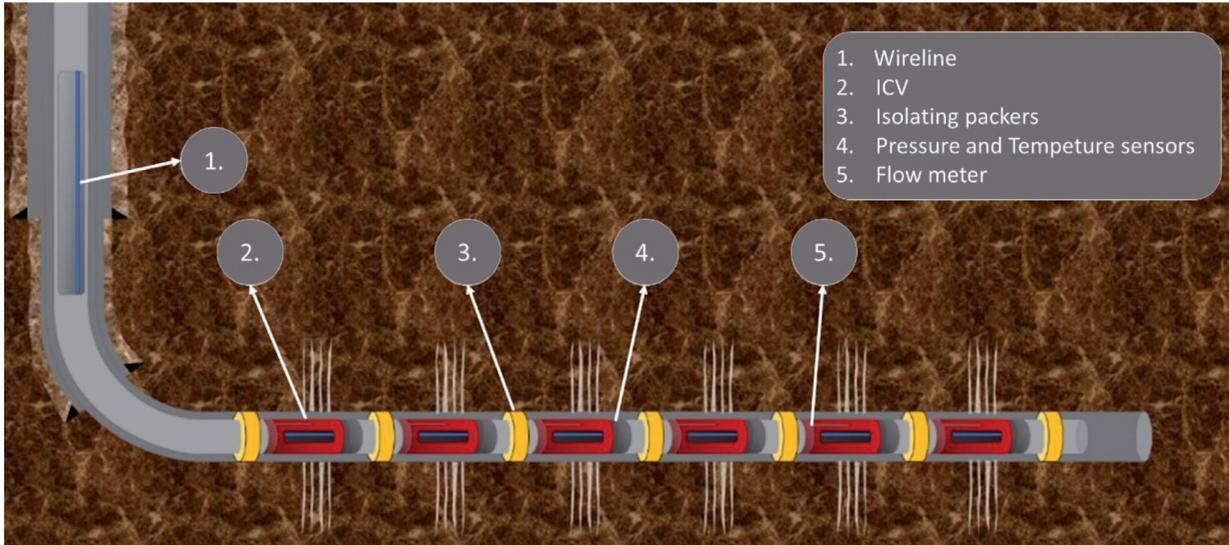

Figure 1. Intelligent completion system.

$$EMV = \Sigma_{i=1}^{n} \Sigma_{j=1}^{m} p_{i,j} * NPV_{i,j} \qquad (1)$$

Where: $p_{i,j}$ is the case probability, $NPV_{i,j}$ is the case NPV, n is the number of geological models and m the number of economic scenarios.

Methodology

Stage 1. conventional water management

At first, a water injection process was simulated, and the wells constraints were optimized using the CMG DECE method in the CMOST module (CMG) with the NPV as objective function, to achieve the highest performance for the base case.

Stage 2. intelligent well implementation

At this stage, each simulation file was modified to generate new files with a representation of intelligent completion for the producer well. There was implemented one ICV for each layer, modifying the code to use the water cut as a control variable, to close

the flow at the pay zone when it achieves a limit value. Also, were optimized the water cut limit value and the number of valves for each case using the NPV and EMV's values as objective functions. Figure 2 shows the code that represents the ICVs effect.

```
Grid block logging   *LAYERRLUMP 'rlump7'
for ICV              'WellName' 18 27 1 1

Control log          *LAYERCLUMP 'Control_rlump_7'
                     'WellName' 18 27 1

Control setting      *CLUMPSETTING
                     'Control_rlump_7' 1

Conditional event    *TRIGGER 'trigger7'
                     ON_CTRLLUMP 'Control_rlump_7' WCUT > 82
                     APPLY_TIMES 1

Closing action       *CLUMPSETTING
                     'Control_rlump_7' 0
                     END_TRIGGER
```

Figure 2. Code lines to represent ICVs effect.

Stage 3. polymer flooding establishment

It was added a soluble polymeric material on the waterflooding model to simulate and evaluate the polymer injection process. The concentration of

polymer and the injected pore volumes were optimized using the CMG DECE method in the CMOST module (CMG) with the NPV as objective function, to achieve the highest performance for the polymer flooding case.

Stage 4. both integrated technologies

It was used the same method at stage 2 to implement the IWT with polymer flooding for this case. Furthermore, the water cut limit value and the number of valves were optimized for each case, using the NPV and EMV as objective functions.

Stage 5. risk and production strategies analysis

Finally, all results data was used to develop a detailed analysis about risk management and production behavior, pursuant of each applied strategy. Risk curve was plotted, and the simulations results were studied to asset the feasibility for implementing the both technologies (PF and IWT), together and individually.

Case studies

This work was developed from implementation of the STARS simulator to represent the reservoir and his behavior under adopted conditions, and the CMOST module to optimize different parameters along the study. At first, was built a cubic reservoir model (Figure 3) of 10 layers with 16,810 grid blocks, each one with measures of 65.62 ft x 65.62 ft x 29.5 ft; and the presented properties in the Table 1.

Table 1. Model properties.

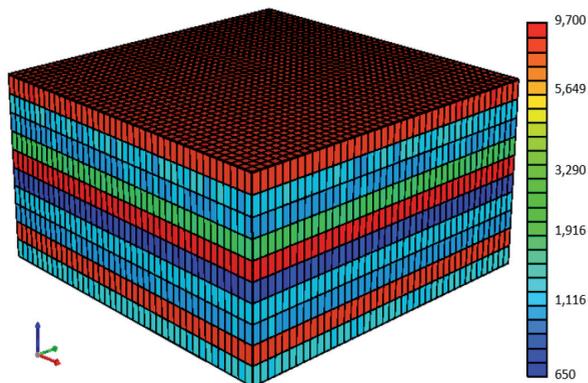| Pb (psi)	Pi (psi)	Tres (°F)	API (°)	Depth (ft)
1,600	3,500	172.4	14.7	9,834 – 10,138

Figure 3. Reservoir model permeability.

Likewise, it was used the PVT data of a field in the Campos Basin. Figure 4 shows the oil formation volume factor (Bo) and the viscosity vs pressure. On the other hand, Figure 5 shows the relative permeability.
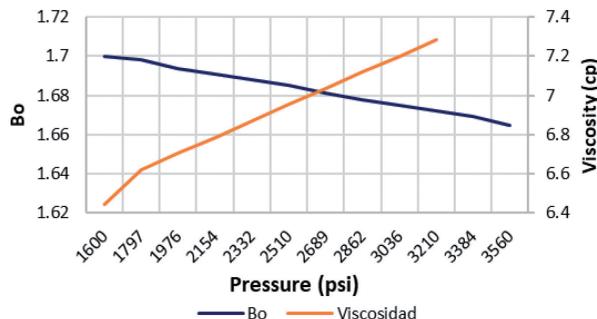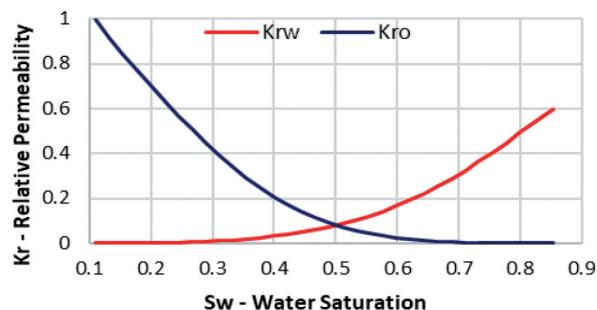
Figure 4. Bo and Viscosity vs Pressure.

Figure 5. Relative Permeability.

Also, this study involved an uncertainty analysis, thus were created nine possibilities using three geological models (Table 2) under three economic scenarios (Table 3), and it was stablished a probability of occurrence for each one (Table 4) as follows.

Table 2. Geological models and their Dykstra-Parsons coefficients.

Geological Model	Dykstra-Parsons coefficient
Heterogeneous 1 (H1)	0.4721
Heterogeneous 2 (H2)	0.554
Heterogeneous 3 (H3)	0.6309

Table 3. Economic scenarios data.

Economic Scenario	Barrel Price (USD/bl)	Oil Prod. Cost (USD/bl)	Water Prod. Cost (USD/bl)	Water Injection Cost (USD/bl)	Polymer Cost (USD/Kg)
ES1	30	15	1.5	1	6
ES2	45	15	1.5	1	6
ES3	60	15	1.5	1	6

Table 4. Probabilities of occurrence.

Geological Model	Partial Probability (P_i)	Economic Scenario	Partial Probability (P_j)	Total Probability (P_T)
H1	0.25	ES1	0.25	0.0625
		ES2	0.5	0.125
		ES3	0.25	0.0625
H2	0.5	ES1	0.25	0.125
		ES2	0.5	0.25
		ES3	0.25	0.125
H3	0.25	ES1	0.25	0.0625
		ES2	0.5	0.125
		ES3	0.25	0.0625

The polymer parameters were based on literature data (Lamas, 2017) (Cheng et al., 2015) (Lamas, 2012) (Botechia, Correia & Schiozer 2016) (Zampieri, 2012). It was selected an HPAM polymer, because this polymer type is usually recommended for these kinds of projects (Standnes & Skjevrak, 2014). Laboratory experiments using rheometer were realized to retrieve dependence of polymer viscosity on concentration (Table 5), shear rate (Table 6) and salinity (Table 7). Also, there were obtained a degradation half-life of 540 days and an adsorption value of 50µg/g$_{rock}$. Through sensibility analysis of the polymer injection process, it was determined to inject a slug of 0.3007 pore volumes with 2,000 ppm. Adsorption and permeability reduction demand core flooding experiment.

Table 5. Viscosity vs polymer concentration.

Polymer Content (ppm)	Viscosity (cP)
0	0.5
500	1.32
1,000	3.78
1,500	10.00

Table 6. Viscosity vs shear rate.

Shear rate (day^{-1})	Viscosity (cP)
864	10
1,861	10
4,010	9.9998
8,640	9.9992
18,614	9.9963
40,103	9.9831
86,400	9.924
186,143	9.6912
401,033	9.0494
864,000	8.0302
1,861,431	6.9581
4,010,333	5.9991
8,639,999	5.1773
18,614,314	4.4797
40,103,324	3.8889
86,399,995	3.3888

Table 7. Viscosity vs salinity.

Added NaCl (wt%)	Viscosity (cP)
1.00	10.33
2.00	7.28
3.00	6.36
4.00	5.87
5.00	5.54

There was implemented a five-spot (four injection wells in each corner and one production well in the center of the reservoir) pattern with waterflooding as initial production strategy, and the wells constraints were optimized improving the performance of the base case (Table 8).

Table 8. Wells optimized constraints.

Constraints	Well Type	
	Injectors	Producer
Max. BHP (psi)	3,400	—
Min. BHP (psi)	—	1,000
Max. STL (bbl/day)	—	9,450

Once built the base case, the simulation file was modified again to add the IWT and polymer flooding to evaluate their combined effect. Therefore, this study presents the following cases:

- **Case 1:** waterflooding with conventional producer.
- **Case 2:** waterflooding with intelligent producer.
- **Case 3:** polymer flooding with conventional producer.
- **Case 4:** polymer flooding with intelligent producer.

Results and discussions

The information showed below presents the following considerations:

1. There are exposed data of cumulative oil produced (Np), cumulative water produced (Wp), cumulative water injected (Winj), polymer injected amount and NPV; pursuant of each case.

2. The results of the cases 2, 3 and 4, are presented as a comparison with the base case (case 1), and the exact values are presented using tables.
3. The production time is different for each case, the project is finished upon the NPV turns negative.

Stage 1. The cases presented at this stage were evaluated using the first production strategy (water flooding with conventional producer well) and Table 9 shows the detailed results.

Table 9. Case 1 results.

	H1			H2			H3		
	ES1	ES2	ES3	ES1	ES2	ES3	ES1	ES2	ES3
Np (Mbbl)	14.6	16.1	17.3	12.4	14.7	15.9	12.3	14.5	16.2
Wp (Mbbl)	29	44.7	64.2	32.4	57.7	77.1	36	61.3	87.2
Winj (Mbbl)	42.5	59.7	80.4	43.9	71.5	92.1	47.4	75	102.6
NPV (MUSD)	-4.07	87.17	177.39	-34.3	47.33	125.95	-41.07	40.32	118.59

Stage 2. The implementation of intelligent completion allowed mostly an increase of Np, offering a good water managing as following:

*   Np average variation: +13%
*   Wp average variation: 0%

*   Winj average variation: +3%

Also, all cases achieved an improvement on NPV, with a minimum increase of 4.64 MUSD and a maximum of 41.69 MUSD. Table 10 shows detailed data obtained at this stage.

Table 10. Case 2 results.

	H1			H2			H3		
	ES1	ES2	ES3	ES1	ES2	ES3	ES1	ES2	ES3
Np (Mbbl)	15.8	17.5	18.7	15.1	16.5	18.4	16.3	16.3	16.3
Wp (Mbbl)	32.4	50.7	71.3	33.9	49.7	82.3	47.8	47.8	47.8
Winj (Mbbl)	47.3	67.2	89.1	48.1	65.3	99.9	63.4	63.4	63.4
NPV (MUSD)	0.57	94.34	186.43	-8.81	80	167.64	-11.36	75.17	157.95

Stage 3. The polymer flooding process showed higher Np and NVP values, but now with a notable decrease of managed water (Wp and Wi) even with a conventional completion for the producer well. The variations in comparison with the case 1, were obtained as follows:

*   Np average variation: +15%

*   Wp average variation: -23%
*   Winj average variation: -40%
*   NPV increase: min. of 13.96 MUSD and max. of 60.93 MUSD

Table 11 presents the results of the case

Table 11. Case 3 results.

	H1			H2			H3		
	ES1	ES2	ES3	ES1	ES2	ES3	ES1	ES2	ES3
Np (MBl)	17.1	18.3	18.9	15.8	16.4	17.2	15.4	16.5	17.3
Wp (MBl)	28.3	40.9	50.6	29	35.3	48.3	29.4	42.1	55.1
Winj (MBl)	29.5	42.3	52.5	28.7	34.8	48	28.7	41.3	54.8
Polymer. (Mkg)	60.5	60.5	60.5	65	65	65	64.8	64.8	64.8
NPV (MUSD)	9.89	109.33	206.58	-3.79	92.38	186.88	-8.15	85.45	177.5

Stage 4. The combination of both technologies results in the highest increases on NPV and Np values, but lower reductions on water volumes managed than in the previous stage. Variations presented as follows:

- Np average variation: +22%
- Wp average variation: -16%
- Winj average variation: -34%
- NPV increase: min. of 12.34 MUSD and max. of

80.11 MUSD

Table 12 shows the results of the last case.

Table 12. Case 4 results.

	H1			H2			H3		
	ES1	ES2	ES3	ES1	ES2	ES3	ES1	ES2	ES3
Np (MBl)	19	19	19	17.2	17.2	17.2	16.6	17.7	20
Wp (MBl)	46	46	46	29.8	29.8	29.8	28	40.6	83.1
Winj (MBl)	47.9	47.9	47.9	30.5	30.5	30.5	28.6	41.1	85.6
Polymer. (Mkg)	60.3	60.3	60.3	61.5	61.5	61.5	64.7	64.7	64.7
NPV (MUSD)	8.27	110.26	207.67	8.05	106.26	202.4	2.62	102.36	198.7

Stage 5. The implementation of IWT and PF generate large alterations about the project profitability from increasing the cumulative oil produced, reducing cumulative water produced and changing the productive life time of the field. Figure 6 shows these changes for the geological model H2 and economic scenario ES2, and presents cases 2 and 4 reaching higher NPV/EMV than cases 1 and 3 respectively. Also, there is presented the acceleration of oil production rate due to IWT effects and the highest efficiency from both technologies application (case 4) to mitigate the issues by high mobility ratio and reservoir heterogeneity.
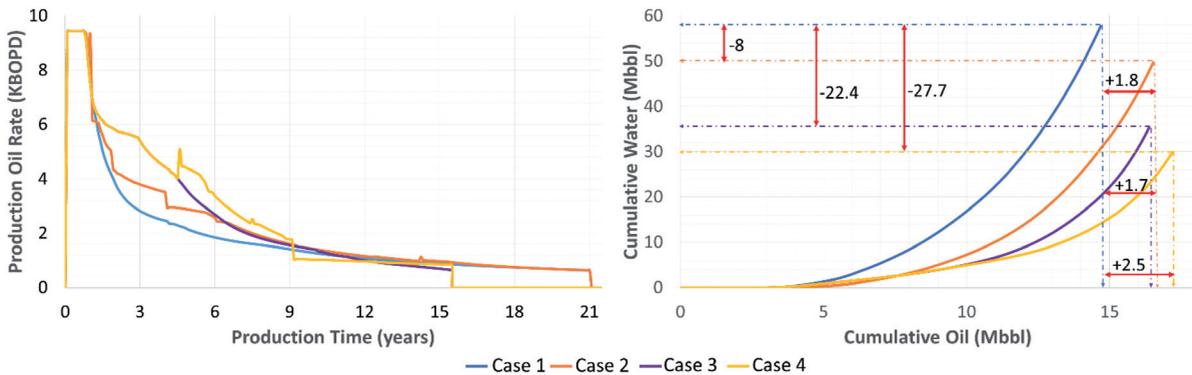

Figure 6. Production behavior (H2-ES2).

The case 4 shows itself as a project development without probability to obtain a negative NPV. However, cases 1 and 2 presents a probability around of 20% to obtain it, and approximately 15% for the case 3. The cases 2, 3 and 4 present a lower risk than base case because of higher NPV averages and lower variation coefficients. Table 13 shows the analysis of economic values and Figure 7 the risk curve for the cases performances. Also, there is a probability around of 5% to achieve the highest NPV.

Table 13. General economic analysis.

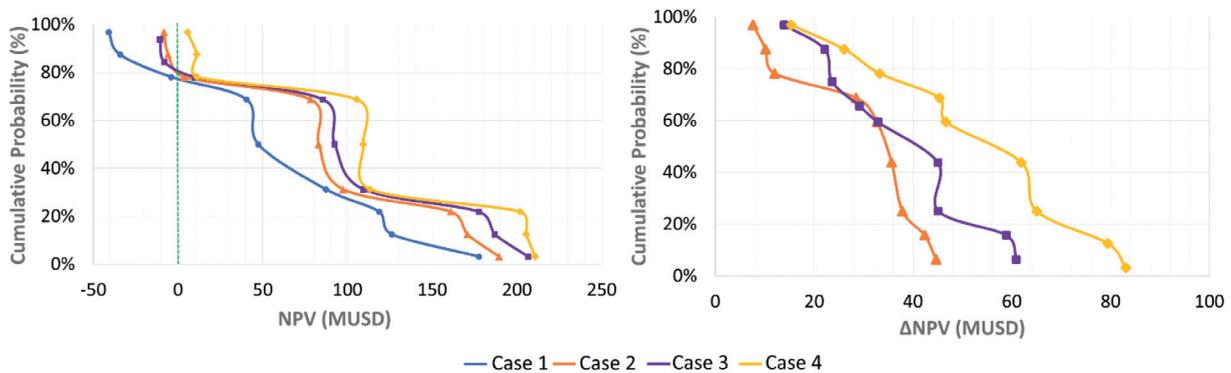| Production Cases	Average NPV (MUSD)	Standard Deviation	Variation Coefficient	EMV (MUSD)
1	57.48	75.83	132%	54.90
2	82.44	77.3	94%	81.89
3	95.11	83.4	88%	94.44
4	105.18	85.2	81%	105.53

Figure 7. Risk curve for the cases.

Conclusions

The potential of two technologies can be exploited at the same time to maximize results; nevertheless, the combined use must be analyzed under different real conditions. Therefore, there were calculated Dykstra-Parsons coefficients which corroborated that presented models represent cases with low, medium, and high heterogeneity, to study the showed technologies under geological uncertainty.

The IWT implementation improved the project profitability by itself, increasing the cumulative oil production and reducing the cumulative water production due to its fluids control capability. This technology led an increase of the cumulative water production in some cases. However, it rises the cumulative oil production even more, with an increment of the productive life time of the field.

Also, polymer flooding achieved the highest water volumes reduction maintaining an increase for the cumulative oil production. Furthermore, implementing the intelligent completion to the producer well, allowed to obtain the highest cumulative oil production values with larger increase that the water managed reduction.

Furthermore, the combined implementation of both technologies results in the best production strategy, increasing the NPV for each conditions environment compared to the base case, and thus achieving a higher EMV (nearly 100% more). Therefore, it means that the IWT applied to the producer wells, can enhance the production efficiency even more despite of implementing previously a polymer flooding process.

Finally, for further studies it is recommendable to use IWT also for the injection wells, considering mechanical degradation of the polymer due to valves. Therefore, an analysis for injectors and its comparison with this initial approach, will allow to determine the main advantages and disadvantages for different levels of integration of both technologies.

Nomenclature

BHP:	Bottom Hole Pressure
Bo:	Oil Formation Volume Factor
EMV:	Expected Monetary Value
ES:	Economic Scenario
ICV:	Inflow Control Valve
IWT:	Intelligent Well Technology
Np:	Cumulative Oil Produced
NPV:	Net Present Value
Pb:	Bubble Pressure
PF:	Polymer Flooding
Pi:	Initial Pressure
STL:	Surface Total Liquids
Tres:	Reservoir Temperature
WF:	Waterflooding
Winj:	Cumulative Water Injected
Wp:	Cumulative Water Produced

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