Optimization of a Water Alternating Gas Injection Scheme

Evaluation of a Miscible LPG Injection with Compositional Fluid Flow Simulation in a Kazakhstan Field

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Abstract

In modern society, energy fossil fuels resources are essential for keeping the standards of living we have today. Considering that nowadays the oil and gas reserves replacement is not keeping pace with the growing energy demand, the industry is turning its investments in the optimization of the existing oil and gas fields and using Enhanced Oil Recovery (EOR) methods to recover more of the residual oil. The main goal of this thesis was to maximize the oil recovery of the EOR pilot sector of a field in Kazakhstan, of an Aptian age reservoir. The miscible Water Alternating Gas (WAG) injection scheme was the production technique evaluated on this sector, where LPG and water are injected alternately through a central injector well of a 5-spot pattern with producers in the corners. LPG is a by-product of processing the associated gas in the field. However, since there is no local market to sell or consume the gas, it was also the aim of this work to demonstrate the benefits of injecting this gas in the reservoir to achieve maximum oil recoveries instead of using it for power generation or any other use.

For this purpose, a compositional model of the EOR sector was built to forecast the production until the end of the field's production license in 2024. First, a fluid model with a tuned equation of state was built using PVTi and used to predict how the fluids behave within the reservoir. The compositional sector model was built using and converting a previous full field black model, incorporating the history of production data and the fluid model. In the second part of this thesis, an optimization study of the LPG and water injection rates was performed using PSO, a stochastic optimization method based on the social behavior of some groups of animals. The optimum injection rate values obtained were then used to simulate different scenarios of WAG cycle and low, mid and high scenarios of permeability.

The results of the simulations demonstrate that LPG flood shows a faster production and incremental recovery over water flood or any other WAG scenario, until the end of license. However, despite the higher recoveries obtained with continuous LPG injection, the WAG scenarios help to sustain the

production rate for much longer because of better pressure support and higher macroscopic sweep efficiency of water injection, which might translate in higher oil recoveries for extended production license. It was also revealed that sole LPG injection is not very effective after some years of production as most of the recoverable oil between the injector and the producers is displaced and the gas has a breakthrough in the producer wells. On the other hand, some WAG scenarios, such as the 4x8, make a more efficient use of the LPG, avoiding its waste and enabling the injection of the spare LPG in more 5-spot patterns in the field, maximizing the total field oil recovery.

Keywords: Reservoir simulation, compositional simulation, EOR, WAG scheme, Particle Swarm Optimization.

1. Introduction

Energy resources are essential to mankind. For the last 60 years, oil and gas have played a very important role in the worldwide energy consumption and will continue to do so for many years to come. Each year, new production is needed to compensate the natural decline of existing wells. For this growth to be sustainable, a strong focus will have to be placed on finding new discoveries and/or optimizing oil production from current resources. Considering that the reserves replacement is not keeping pace with the growing energy demand, the industry is also turning its investments in EOR (Enhanced Oil Recovery) methods, a group of techniques usually applied after both primary and secondary recoveries have reached their economic limit with the aim to achieve ultimate oil recovery (Sarkar, 2012).

Within the framework of this thesis, miscible WAG injection was technique evaluated in an EOR pilot sector of a reservoir field in Kazakhstan, where water and gas are injected alternately to combine the benefits of the increased microscopic displacement by gas and macroscopic sweep efficiency by water. LPG is the gas injected into the reservoir to mix with the residual oil and enhance recovery. This miscibility process is facilitated by the first contact miscibility between both products, which means the LPG will be miscible from the first contact with the crude oil (Nwidee *et al*, 2016).

In general industry WAG applications, LPG is not mainly injected because of its high demand as a marketable commodity. However, LPG is a by-product of processing the associated gas in the Kazakhstan field (due to confidential agreement it will be referred simply as ‘Kazakhstan field’). Since there is no local market for the LPG and it is not desired to flare the LPG from an environmental standpoint, it was made a simulation study in this thesis with the objective of maximizing the oil recovery of the pilot sector using the WAG technique. This way, it was intended to demonstrate the benefits of LPG injection and suggest this production strategy to expand to other sectors of the field. For this purpose, a dynamic compositional model was created using Eclipse300 and used to simulate the flow of fluids and predict future reservoir performance (Alargoni *et al*, 2015).

2. Methodology and Workflow

To maximize the oil recovery in the EOR pilot sector of the Kazakhstan field, an optimization study of some of the most influential variables in WAG design was conducted. The LPG and water injection rates were optimized using the PSO (particle swarm optimization) algorithm, a stochastic optimization method based on the social behavior of some groups of animals. The optimum injection rate values obtained were then used to simulate different scenarios of WAG cycle in order to find an optimum production strategy that maximizes oil recovery. In the end of the project, low, mid and high scenarios of permeability were simulated for the final WAG cycle cases to account for this very important factor

The main references used as a basis of information for the methodology and workflow of this thesis, were the Field Development Plan (FDP) from 2014 and the Report for the Evaluation of the LPG Injection (Miscible Flood) in the Kazakhstan reservoir from 2012. The original names of the wells, companies and some reservoir characteristics are not presented in this abstract due to a confidential agreement between Partex and the author.

2.1. Kazakhstan Field Overview and EOR Sector Model

The field in Kazakhstan is an onshore oil producing field situated close to the coast of the Caspian Sea in the Mangistau Oblast, western Kazakhstan (Figure 1). Unlike most reservoirs in this region, the field is a Cretaceous oil reservoir in a province of mainly Jurassic oil and gas reservoirs, making it unique. The main reservoir of the field and the subject of this study is the Lower Cretaceous Aptian sandstone, a heterogeneous shallow marine with varying deltaic influence formation which is further divided in two sections: Aptian A (on top) and Aptian B (on the bottom). The Aptian reservoir consists of thin, very fine-grained, argillaceous sandstone beds interbedded with shale heteroliths and intervals of calcite cemented sandstones. As a result, the vertical permeability is about 10% of the total horizontal permeability. On a reservoir scale, the horizontal permeability is controlled by the continuity of the different sand layers (Cazier *et al*, 2011). The oil is a light 42 ºAPI paraffinic live oil (oil with dissolved gas).

The field was first discovered in February 1966 and the first commercial oil flow from the Aptian reservoir started in June 1968. The peak total production from the field is expected to be around 35 000 bopd (barrels of oil per day). The Kazakhstan field is currently operated under the terms of a production sharing agreement (PSA) and the production license is valid until 2024.

In order to capture an adequate level of heterogeneity, a 3D sector static model of a full 5-spot pattern located near the crest of the field was used. Figure 1 shows the EOR pilot sector model ‘cut-out’ of the full field static model (provided by Partex). The static EOR model was built using Petrel and it was used as an input for Eclipse 300. The EOR pilot corresponds to a 5-spot pattern with Well-X as the central injector and wells Well-A, Well-B, Well-C and Well-D as the producing wells.

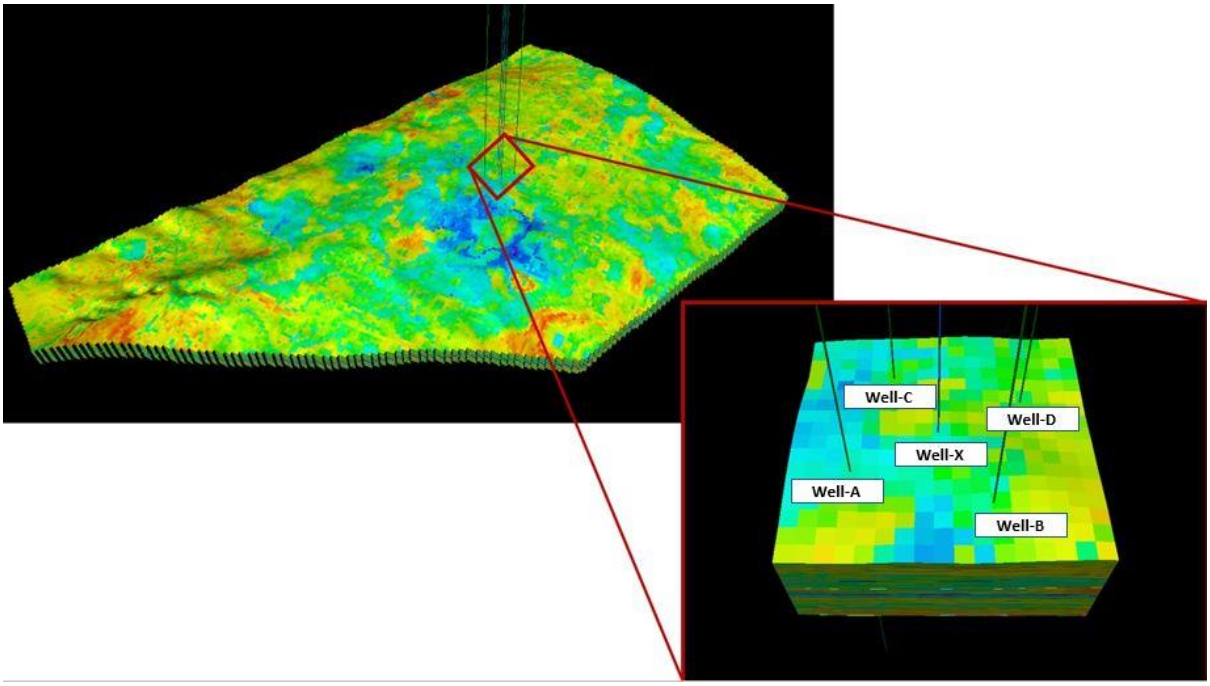

Figure 1 – Porosity values of the Kazakhstan field static model (at the left) and EOR pilot sector model (at the right): 5-spot pattern with Well-X as the central injector well and Well-A, Well-B, Well-C and Well-D as the producing wells (exported from Petrel).

2.2. LPG Composition

LPG volume is almost 20% of the daily natural gas volume production and it is rich in mid components (Table 1). After December 2009, the total produced LPG volume of the field has been continuously injected into Well-X to date. The under saturated oil of the Aptian reservoir is ideal for LPG injection due to the full miscibility between the reservoir oil and because the LPG is injected above the bubble point pressure at 945 psia, pressure at which the first bubble of gas comes out of the oil solution. This is also the value of the MMP (miscibility minimum pressure), essential factor for the miscibility WAG process.

Table 1 – Composition of produced LPG.

Composition	Mole (%)
C_1	8.0
C_2	14.0
C_3	39.0
C_4	33.0
C_5	6.0

2.3. Fluid System Model

A complete fluid model description and a regression of an equation of state to fit the model to the Aptian reservoir fluid behavior were done using PVTi by Schlumberger. A comprehensive PVT fluid analysis of the field was used to improve the quality of the equation of state regression.

The reservoir fluid composition used as an input for PVTi was a mixture of 50% Aptian A oil and 50% Aptian B oil. Therefore, the molar fraction used for each component was an average between both samples. Since there are more than 45 components identified in the reservoir composition of the PVT report, the components of the mixture sample were grouped to reduce the computation time and memory requirements of reservoir simulations. Table 2 indicates the reservoir oil composition after grouping operation, showing a total of 8 group of components. The butane, propane and pentane components were left as individual groups due to their importance in the LPG miscible displacement and because they have significant mole fractions alone. The C_{30+} represents an average weight of the components larger than C_{30}.

Table 2 – Reservoir oil composition after grouping operation (mixture sample).

Components	Mixture (%)
$C_1 + N_2$	18.22
$C_2 + CO_2$	7.475
C_3	6.535
C_4	5.155
C_5	3.34
C_{6-10}	20.105
C_{11-29}	31.905
C_{30+}	7.265

The selected equation of state for this study was the three parameter Peng-Robinson equation of state as it is one of the most common equations used to describe the flow of under saturated oils, providing as well a more accurate calculation of phase density (Pinto, 2014). Observations (viscosity, GOR, oil formation volume factor, Bubble Point Pressure, liquid density and relative oil volume) from four different laboratory experiments were used to adjust the equation of state and to simulate the changes in oil properties of the Aptian reservoir as pressure drops during production. After a significant amount of trial and error regression experiments, a successful tuning of the equation of state to the experimental data was achieved with the adjustment of critical pressures for each component and critical temperatures for the mid oil components (C_4 and C_5).

2.4. Dynamic Compositional Model

The grid block size of the static sector model is 100 ft x 100 ft x 1ft. It has a very fine grid in order to improve our understanding of the vertical flow of fluids within the EOR pilot. The average porosity value is around 23% and the average horizontal permeability is around 1 mD. The influence of the area surrounding the sector model was not taken into consideration, and so, no boundary effects were added to the dynamic model. The cells coordinates, the rock properties and special cores analysis were all exported from Petrel and were introduced in the Eclipse300 code as include files. The fluid model with the equation of state description was exported from PVTi in a compatible format to be used in Eclipse300 compositional runs. The initial average reservoir pressure is 2320 psia and the reservoir temperature is 79°C. The initial reservoir volume of oil is 60,5 MM reservoir barrels and the average initial oil saturation is of 49,7% of the rock pore volume.

The production schedule section of the dynamic model includes a first part with the history of production from May 2008 to July 2016 and a forecast simulation part from August 2016 until the end of license in August 2024. An attempt to history match the production was made by multiplying permeabilities. However, they were found to be unrealistic (10x multiplier needed to reproduce history data) and since this study was made on a sector field where the pore volumes and the pressures values in the rest of the field are not accounted for in the simulations, the simulated oil production is always less than the original field production. The objective of this work was to know the influence of different optimization variables in the increase of oil recovery in relative terms and not absolute terms. Therefore, a reduction of the original production was made to match production, as all the variables are in the same set of conditions of optimization.

In the second part, the LPG and water injection rates were simultaneously and automatically optimized using the PSO algorithm by Raven, for each WAG cycle scenario. The PSO algorithm is expected to assign random values to both variables of Well-X, according to a uniform distribution with an interval between 300 and 2000 stb/d. The maximum value of 2000 stb/d was defined as an upper limit to ensure that the injection pressure does not go beyond the fracking pressure of 3232 psia. For each iteration, a new random number is given until a meaningful trend can be observed. The rates that maximize the oil recovery were then used to forecast six different production scenarios, namely 6x6, 8x4, 12x12 and 4x8 WAG cycles, LPG continuous injection and water continuous injection. After all simulations were done, the three best WAG cycle scenarios with the optimized injection rates were picked and for each one of them, a low, mid and high case permeability scenario (-25%, 0% and +25% permeability values variations) were simulated to account for the big uncertainty of this very important factor.

3. Results and Discussion

3.1. LPG and Water Injection Rates

The aim of the simulations made in this section was to understand how these different injection rates affect our objective function by increasing the total oil production. Figure 2 to Figure 10 show the optimization trend for the total oil production versus the LPG and water injection rates. For each WAG cycle scenario, around 100 iterations were made in order to get a meaningful trend for the optimum LPG and water injection rate values. The left column shows the field oil production total (FOPT) versus LPG injection rate plots and the right column shows the FOPT versus water injection rate plots, for each WAG scenario.

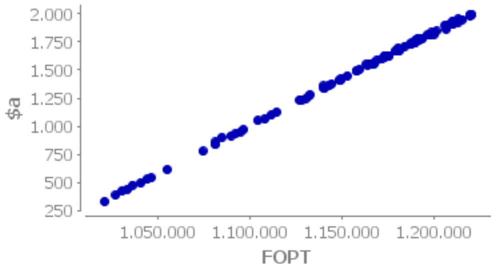

Figure 2 – FOPT vs LPG injection rate ($a) – 4x8 WAG cycle (Raven).

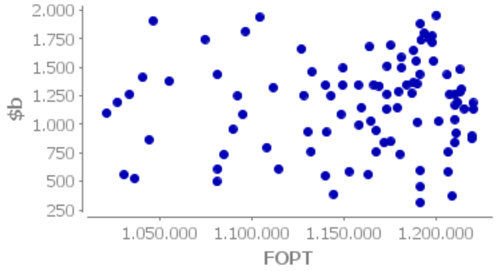

Figure 3 – FOPT vs Water injection rate ($b) – 4x8 WAG cycle (Raven).

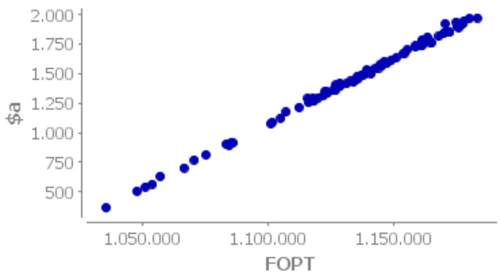

Figure 4 – FOPT vs LPG injection rate ($a) – 6x6 WAG cycle (Raven).

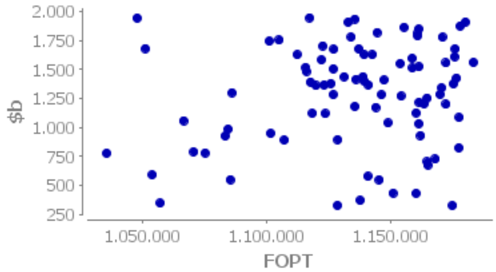

Figure 5 – FOPT vs Water injection rate ($b) – 6x6 WAG cycle (Raven).

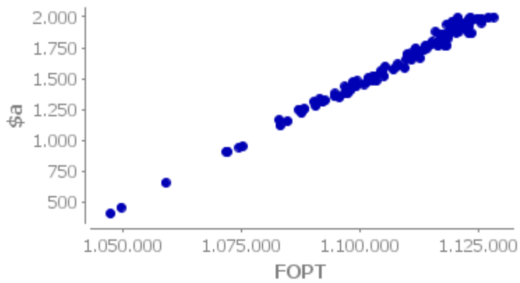

Figure 6 – FOPT vs LPG injection rate ($a) – 8x4 WAG cycle (Raven).

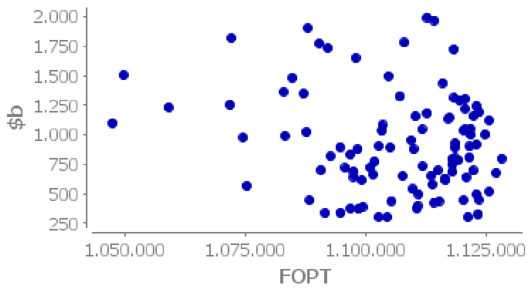

Figure 7 – FOPT vs Water injection rate ($b) – 8x4 WAG cycle (Raven).

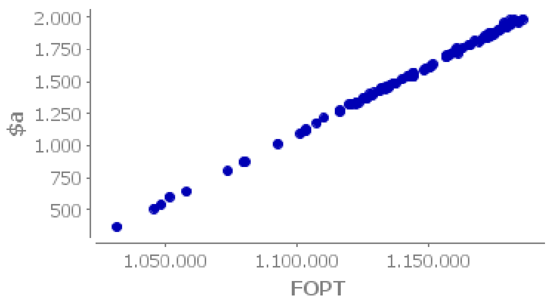

Figure 8 – FOPT vs LPG injection rate ($a) – 12x12 WAG cycle (Raven).

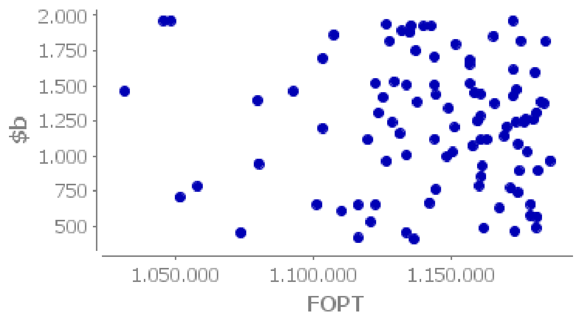

Figure 8 – FOPT vs Water injection rate ($b) – 12x12 WAG cycle (Raven).

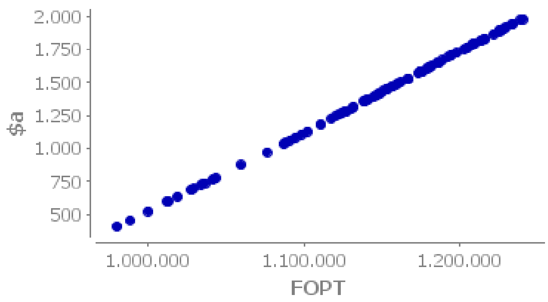

Figure 9 – FOPT vs LPG injection rate ($a) – sole LPG injection (Raven).

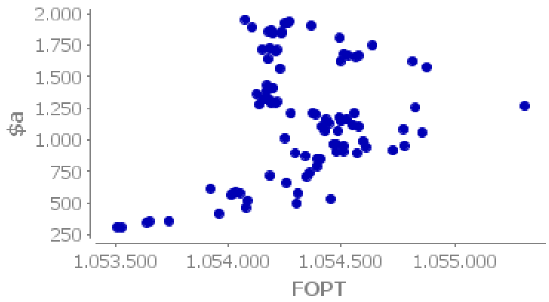

Figure 10 – FOPT vs Water injection rate ($b) – sole Water injection (Raven).

Plots on left indicate that as the LPG injection rate increases, the FOPT gradually increases, confirming the benefits of the miscibility displacement between LPG and the reservoir oil. Contrarily, no clear trend of the optimum water injection rate values is shown, for all the scenarios. This may be caused by the fine grained sized of the formation which effects the relative permeability of water and its ability to displace the oil effectively. Therefore, LPG injection rate has a much stronger effect in increasing the overall displacement efficiency than the water injection rate.

3.2. WAG Cycle Time

To determine the best WAG cycle time in the EOR pilot sector, a fixed LPG injection rate of 2000 stb/d (optimum value) and a fixed water injection rate of 1000 stb/d were considered for the 4x8, 6x6, 8x4 and 12x12 WAG cycles. For the sole LPG and water injection cases, an injection rate of 2000 stb/d was considered. Figure 11 and Figure 12 show the field oil production rate (FOPR) and FOPT, respectively, from the beginning of the forecast in 2016 until the end of license in 2024.

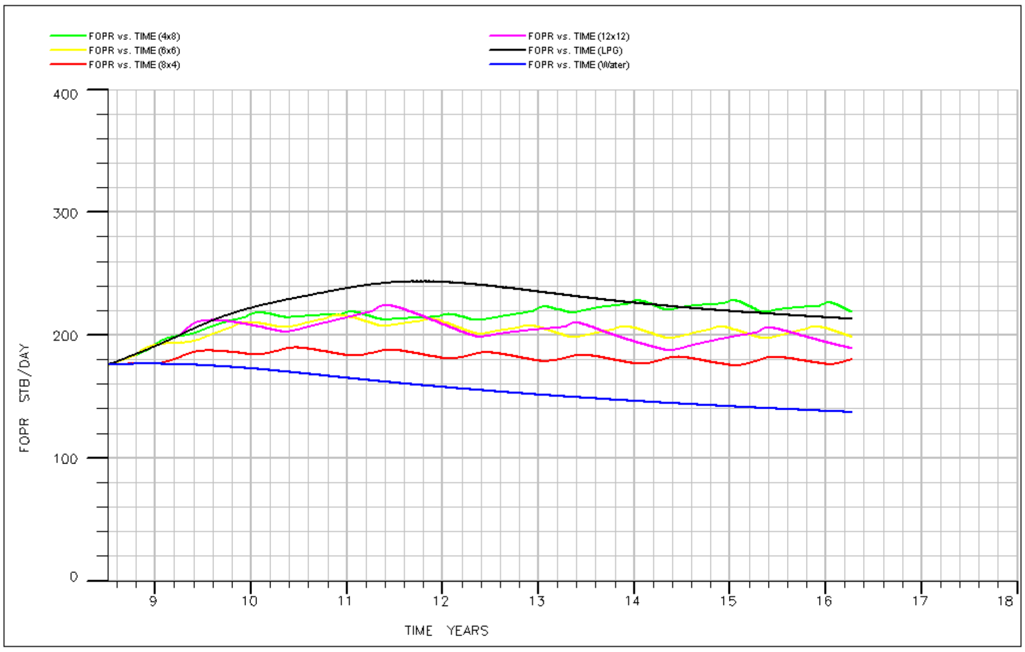

Figure 11 – Field oil production rate from August 2016 to August 2024 for each production scenario: 4x8 WAG cycle (green), 6x6 WAG cycle (yellow), 8x4 WAG cycle (red), 12x12 WAG cycle (purple), sole LPG injection (black) and sole water injection (blue).

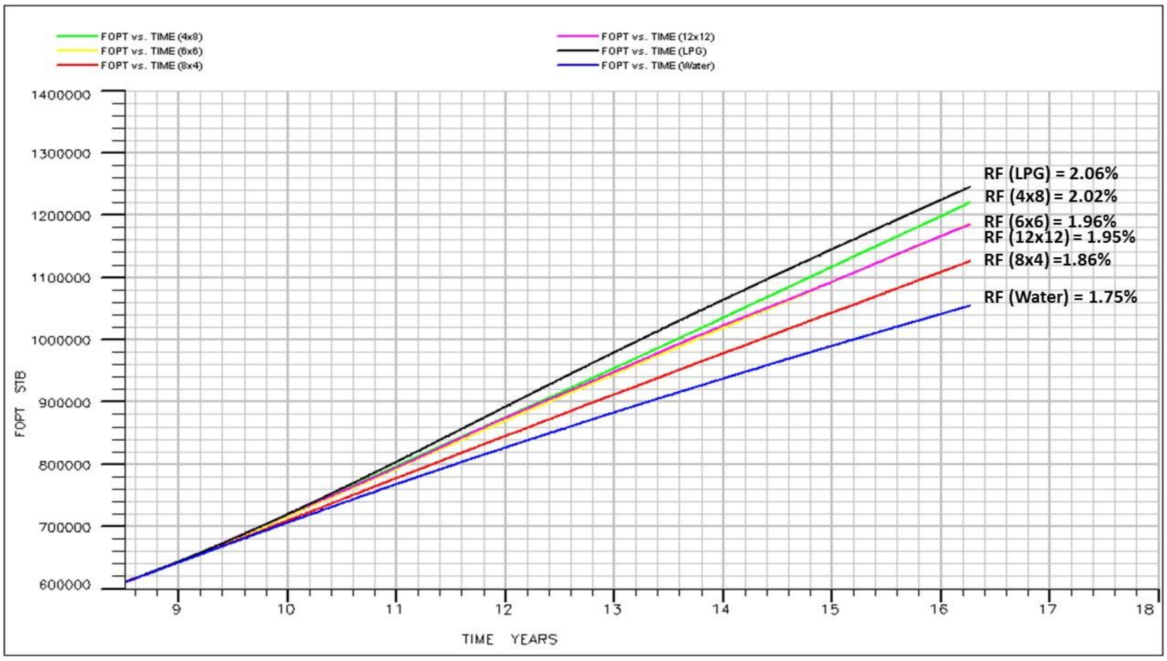

Figure 12 – Field oil production total from August 2016 to August 2024 for each production scenario and their correspondent recovery factors: 4x8 WAG cycle (green), 6x6 WAG cycle (yellow), 8x4 WAG cycle (red), 12x12 WAG cycle (purple), sole LPG injection (black) and sole water injection (blue).

Sole LPG injection is the scenario with the highest oil recovery (RF = 2.06%). However, the oil is produced fast in the early years and reaches the peak of production only around 3 years after the start of simulation. The WAG scenarios do not show a clear sign of a production decline until the end of license in 2024 and the sole water injection case only shows a steady decrease in oil production through the whole forecast and represents the lowest oil recovery scenario. This suggests that injection of water alternated with LPG helps to sustain the production for much longer through the benefits of microscopic and macroscopic sweep efficiencies, which might translate in higher oil recoveries if the production license is extended. Further analysis gave a noticeable increase of the main LPG components around only 2.5 years after the start of the forecast. This means that the sole LPG injection is not very effective after some years of production, as most of the recoverable oil between the injector and producer wells is already swept, and consequently, the pressure support gets weaker and the LPG starts being produced to the surface. On the other hand, the other WAG cases show a much less significant amount of C_3 and C_4 in the production stream at the end of the forecast, having a more noticeable increase around 5 years after the forecast simulation start.

3.3. Permeability Values

A low and high scenarios of permeability values were simulated in the end and compared with the base case for each of the WAG cycle. As expected, higher permeability values lead to a higher recovery of oil for all production scenarios. It was also observed that the flow of the injected water is affected by the lower permeability values, slowing down its flow through the reservoir and taking longer to provide an effective pressure support until the end of license. Since this is a very influential parameter on the success of the WAG operation, a better estimation of the permeability values of the field should be performed to reduce its very high uncertainty and, therefore, help the operator to make the best decisions when choosing between different WAG and other production scenarios to maximize oil recovery.

3.4. Final Considerations

Despite showing lower oil recoveries, WAG injection makes a more efficient use of the LPG, preventing its waste and achieving a better pressure support until the end of license due to water injection, extending the production plateau for much longer than the sole LPG injection. Some WAG cycle scenarios, such as the 4x8 (or even 6x6), may represent a good cost-effective solution because, in spite of giving slightly lower incremental recovery than the LPG flood case, the incremental gain over the water flood is substantial and there is spare LPG that could be used in more 5-spot patterns to fully maximize the oil recovery by gradual and systematic expansion field wide. An economic analysis should be performed to ascertain the real profits of selecting some of the WAG options presented in this thesis. It is suggested to make a better history matching procedure with boundary effects incorporated to have a more accurate model of the reservoir. Also, this work also shows that there are more optimization opportunities that got potentially reaffirm the benefits of WAG injection and maximize the oil recovery.

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