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Production Optimization In Peripheral Waterflood Field Using Capacitive Resistance Model (CRM) with Clustering Approach, Pandhawa Field Case Study

Muhammad Hasto Nugroho[1,2], Billal Maydika Aslam [1], Taufan Marhaendrajana[1]
[1]Petroleum Engineering Department, Institut Teknologi Bandung, Indonesia, [2]Medco E&P Indonesia

Abstract
Waterflooding is one of the most effective methods to improve oil recovery in mature fields because of its high success ratio, easy in application and cost efficiency. Development until now has shown that Capacitance Resistance Model (CRM) can be used as alternative from reservoir model and simulation studies. CRM can be used as model to predict reservoir characterization and reservoir performance quickly and accurately with only require historical production and injection data. CRM characterizes the reservoir by calculating the connectivity value and the response delay between the injections well and the production well as unknown parameters. Pandhawa Field is a heterogeneous carbonate reservoir with an average permeability of 65 mD with peripheral waterflood since 20 years ago. By knowing the injection efficiency, the optimization process can be carried out by increasing the water injection rate in injection wells that have high efficiency and vice versa. In this study, the performance of waterflood is analyzed using the Capacitance-Resistance Injection-Production Model (CRM-IP) to determine the connectivity of each injection and production well. This study also discuss CRM-IP implementation on MATLAB programming language and optimization of injection rate allocation for the most optimum cumulative oil production. Result of this study indicate total additional oil 505 MBO will be obtained during 120 months period by conduct redistribution water injection management for each injector. By using CRMIP methodology, waterflood management in this field can be done much faster, therefore decision taken for this field will be more effective. Some proposed solution to reduce dimensionality of field data and improve CRM-IP history match quality is also discussed such as influence radius and clustering producers.

Introduction

One of proven strategy to increase oil recovery in mature field is waterflooding. Water is the most injected fluid to maintain reservoir pressure and push oil from injectors to producers because of it is availability, low cost compared to other techniques and easier to inject.

Reservoir characterization and simulation are the important activities in order to evaluate reservoir performance. Evaluation reservoir performance can be conducted by many methods such as material balance, streamline simulation, numerical simulation, etc. Currently reservoir simulation is one on the methods that is commonly used by petroleum engineers. Reservoir simulation has limitation such as require long time consuming and processing, data uncertainty (geological, petrophysical, reservoir engineering), furthermore to long term response of reservoir management.

Effective reservoir management in waterflooding field needs rapid action regarding injected fluid distribution to improve areal and vertical sweep efficiency during secondary process. Therefore, simpler method that deliver rapid results to counterpart reservoir simulation are important for reservoir management. Capacitance Resistance Model (CRM) is one of verified method to solve the above challenges.

Nowadays CRM arrest various attention because of its ability of rapid evaluation in reservoir performance. Common benefits of CRM application are the low execution time, high level of accuracy adapted to available input data quality, can determine inter-well connectivity, needs no geologic information and fluid flow modelling and can be adapted for an excel spreadsheet (Kansao et al, 2017). Changes in the sweep area will happen along with the injection process. Therefore, it is necessary to re-optimize and even re-modify it to get the optimum oil recovery.

Capacitance Resistance Model Injector-Producer (CRM-IP) was selected because it provides a better insight into the well-to-well connectivity (Yousef et al, 2006) and depending on the heterogeneity of the reservoir, different injectors can impact the production rates of a certain producer with different velocities (Holanda, Gildin, & Jensen, 2015). The CRMs use only production/injection history data to predict performance, which provides simplicity and speed of calculation (Sayarpour et al, 2009). The capacitance–resistance model (CRM) offers the promise of rapid evaluation of waterflood performance.

Noticeably, it will take long time if done manually. In this study, a computer program based on MATLAB was created with only the most recent input of production and injection history data to solve this problem. The program will semi-automatically provide a recommendation output for the optimization of the injection rate at certain wells.

The objective of water injection is to give energy support into reservoir, as well as to increase recovery factor. The water injection is expected to sweep oil that cannot be produced naturally (primary recovery). Furthermore, the water injection can be used to maintain the reservoir pressure.

Capacitance Resistance Model (CRM) is a predictive method that relies upon signal processing, in which water injection rates are treated as input signals and production rates as output signals. The name CRM is derived from its analogy to resistor-capacitor (RC) circuit (Thompson, 2006). Production rates response to a step-change in injection rate is analogous to the voltage change of capacitor in a parallel RC where battery potential is equivalent to the injection rate. CRM may also be viewed as a nonlinear multivariate regression analysis tool, which accounts for compressibility and fluid flow in the reservoir (Yousef et al, 2006). There are unknown parameters in CRM, which are inter-well connectivity as well as time response delay. These parameters reflect connectivity between injector and producer well based on historical injection and production data.

Data and Method

Capacitance resistance model (CRM) characterizes a flooded reservoir by estimating inter well connectivity, time constants and productivity index using production/injection rates for history matching. Figure 1 shows the flow of modeling using Capacitance resistance model (CRM). For this case using the CRMIP model and the figure 2 show the illustration of CRMIP. CRMIP was chosen because it provides a better insight into well to well connectivity (Yousef et al, 2006) and depending on the heterogeneity of the reservoir, different injectors can impact the production rate of a certain producer with different velocities (Holanda et al, 2015).

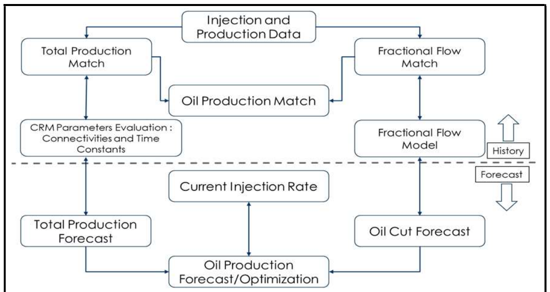

Figure 1. Workflow of CRM

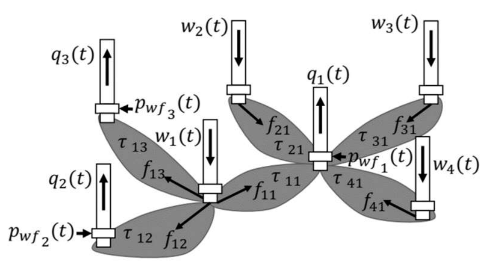

Figure 2. Injector–Producer Pair Based Control Volume, CRMIP (Holanda et. al, 2018)

Modeling using CRM begins with collecting field data such as injection and production rate history, and then predicting total production and oil production using the CRMIP model equation as follows (Sayarpour, 2008)

$$q_{ij}(t_k) = q_{ij}(t_{k-1})e^{\frac{-\Delta t_k}{\tau_{ij}}} + \left(1 - e^{\frac{-\Delta t_k}{\tau_{ij}}}\right)\left[f_{ij}I_i^{(k)} - J_{ij}\tau_{ij}\frac{\Delta p_{wf}^{(k)}}{\Delta t_k}\right] \quad (1)$$

Oil production can be calculated using the empirical oil-cut model. This model is presented by Gentil (2005). This model considering relationship between water oil ratio over time and cumulative injected water. Therefore, the fractional flow of oil can be written as below. Calculation of oil production rate is require evaluation of the value α and β from oil production history each producers.

$$f_o(t_k) = \frac{1}{1+\alpha W_i^{\beta}} \quad (2)$$

Estimation of oil production rate each injector could be calculated using this equation

$$qo_{ij}(t_k) = q_{ij}(t_k)\ f_o(t_k) \quad (3)$$

In CRMIP, for each injector/producer pair, four model parameters exist: $q_{ij(to)}$, τ_{ij}, f_{ij}, and J_{ij}. Make initial estimates for these parameters then this parameter will be optimized to produce the smallest error. The procedure for determining the initial guess of f_{ij} by looking at the distance of the injector to the producer, where the closer distance will have a greater f_{ij} value than those who have farther distance, the number of connectivity (f_{ij}) of one injector to each well must not exceed one or more, can be written as :

$$\sum_{i=1}^{Ni} f_{ij} \leq 1 \quad (4)$$

For this model we use some assumptions such as:

1. Constant Pwf, ΔPwf=0
2. Fluid density are constant and capillary pressure are neglected
3. Immiscible fluid water and oil only

After calculating the total liquid production and oil production, the calibration is carried out between the observed data and the predicted results by minimizing the error by optimizing time constant (τij), connectivity (fij), alpha (α) and beta (β). $fmincon$ function with interior-point algorithm, which already provided in MATLAB optimization toolbox is used to minimize the error. History Match Error can be written as

$$MSE = \frac{\sum_{n=1}^{n_{data}}(q_{act} - q_{est})^2}{n_{data}} \quad (5)$$

A suitable CRM model is obtained after the smallest error is obtained and it is also seen on the chart that the data observe with the estimation results are suitable, then this model will be used to predict oil production for the future. However, it is also important to note that history matching in CRM is an ill-posed problem which can lead to uncertainty of CRM model parameter. The uniqueness of CRM model parameter in history match will depend on the amount of historical rate data available, measurement noise, diffusivity constant, and number of producers per area (Kaviani et. al., 2014).

Result and Discussion

Pandhawa Field is an oilfield located in South Sumatra, Indonesia. Main oil production came from BRF reefal carbonates with minor contribution from TAF and TLS sandstone. Oil gravity produced in Pandhawa Field is considered as light oil with API gravity at 36° API. The reservoir is described as a single continuous zone with minor faults occurrence. The BRF carbonates have good reservoir quality except at several local areas where tight facies occurs and which provides a permeability barrier and stratigraphic entrapment exceeding the simple four-way structural closures. In contrast, the TAF and TLS reservoirs are rather tight.

The Pandhawa Field OOIP is estimated at 230 MMSTB and currently have implemented peripheral waterflood to improve its recovery. There are a total of 238 production wells in Pandhawa field which are divided into 61 clusters. However, for this study we will only consider well that produce from BRF that consist of 58 production wells and 36 injection wells. Production and injection rate history along with voidage replacement ratio (VRR) used in study are given in figure 3(a) and 3(b) respectively. The VRR plot indicates a good balance of injection and production as the values ranging between 1 – 1.2.

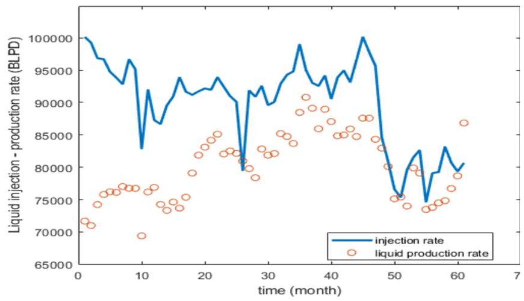

Figure 3(a). Field Production and Injection Rate History

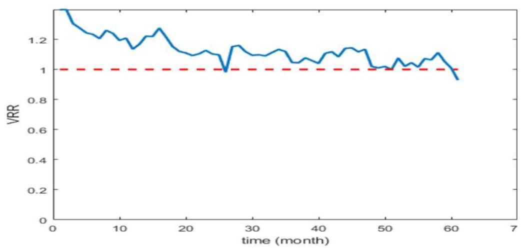

Figure 3(b). Voidage Replacement Ratio

History matching of liquid rates was successfully performed in this analysis. This is conducted to observe whether the liquid produced matches the simulation results. In figure 4 and figure 5, it can be seen that the total liquid rate field and each well generated from calibration of CRM is quite similar trend, however the quality is not yet satisfactory to the actual data. CPU time for history match took only 91.7 seconds on processor 4 core 2.1 GHz.

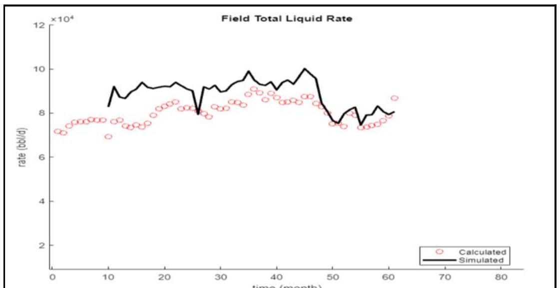

Figure 4. Field Total Liquid Rate History Matching Result

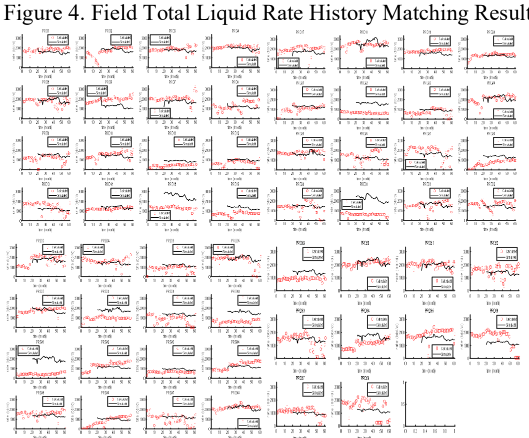

Figure 5. Well Liquid Rate History Matching Result

From the connectivity map in figure 6, it can be seen that due to the scattered distribution of injector the connectivity of injector to producer is quite disordered. However, as injector is intended to be peripheral, general connectivity trend showed that injection is directed to nearest producer. On the other hand, several injection wells show connectivity for producer that are located very far (> 10 km interwell distance) which could make the result unphysical.

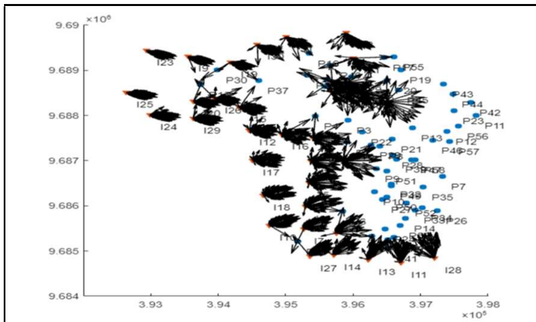

Figure 6. Well Connectivity Map from History Matching

Calculated allocation factor (fij) consistency check can also be done by comparing the values between allocation factor and distance. Generally, further well pairs will have weaker interwell connectivity. Scatter plot of fij versus interwell distance given on figure 7 confirmed this description.

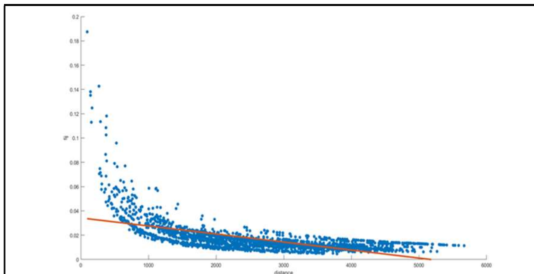

Figure 7. Allocation factor-well pair distance from CRM

In determining the oil rate match, empirical parameter in fractional flow model is calibrated by minimizing the mean square error between predicted oil rates and actual oil rates. Gentil (2005) fractional flow model is used to predict oil rates as it avoid implicit calculation of the fractional flow in each time step. It can be seen in figure 8 and figure 9 that the oil rate data field and each producers is sufficiently matched to the fractional oil flow model used. Calibrated fractional flow model is then used for oil rate forecast and injection allocation optimization.

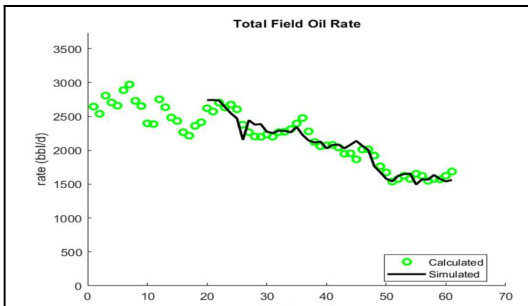

Figure 8. Field Total Oil Rate History Matching Result

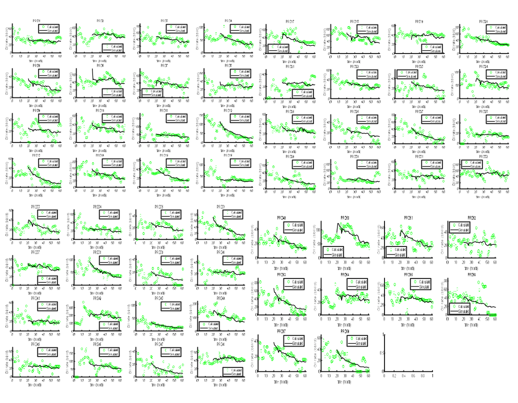

Figure 9. Well Oil Rate History Matching Result

Base case forecast scenario in which no change in allocation rate for injector is carried out to provide base estimate of future reservoir performance. Optimized scenario is then run by the same total injection capacity as in base case, however allocated injection rate will be optimized by interior-point algorithm to obtain maximum cumulative oil produced at the end of forecast period. Maximum injection rate constraint based on history injection rate per well is also imposed to observe achievable value of injection rate and avoid induced fracturing.

Field oil production profile and injection rate allocation for base and optimized scenario are given on figure 10 and figure 11 respectively. By optimizing injection rate allocation, additional 505 Mbbl oil is expected to be recovered, which is equivalent to 0.22% incremental oil recovery factor.

Figure 10. Pandhawa field base and optimized forecast scenario comparison for total oil production rate and oil production cumulative

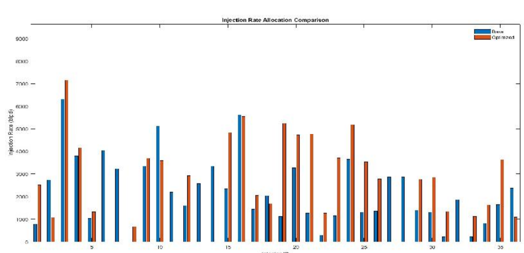

Figure 11. Injection rate allocation comparison between base and optimized case

From interwell connectivity standpoint, optimal allocation rate calculated by CRM can be interpreted as increasing injection support for production wells with the highest oil rate. Producers with the highest oil rate at the start of forecast, hence by CRM logic, the injectors with highest connectivity to these wells will be given priority to increase liquid throughput. Well by well comparison of base and optimized case scenario is provided in figure 12.

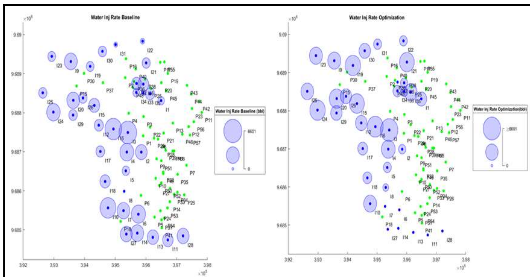

Figure 12. Injection rate allocation comparison between base and optimized case

CRM Improvement

Some workaround has been attempted such as by limiting connectivity only in "influence radius" and clustering well in order to solve CRM issue such as unstable well production data due to shut in period and to make calculation faster than current methodology.

Influence Radius

This method is using limiting connectivity for producers and injector pair that is the maximum distance of possible interwell connectivity. The history match result by implementing influence radius of 2 km is shown on figure 14. Note that influence radius cannot be too small such that a producer is left without injection support as shown in figure 13. The history match result from implementing influence radius did not improve significantly. However, sensitivity analysis of influence radius magnitude can be exercised to infer whether optimal influence radius exists that minimize history match error. Such exercise is planned for future phase.

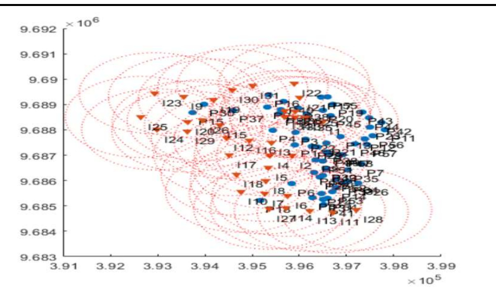

Figure 13. Well influence radius of 2 km

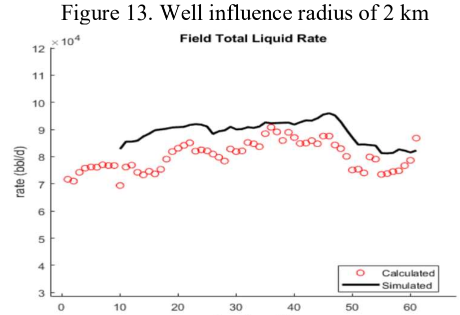

Figure 14. Field Total Liquid Rate HM

Clustering Producers

Clustering producers is conducted by merging producers into grouped of wells. It can be seen as compromise between single tank control volume as in CRMT and injector-producers control volume as in CRMIP. Benefit of this approach is that it can reduce unknown parameters significantly therefore give smaller computational cost. The premise is that, due to the waterflood is done in peripheral and producer wells are located non-uniformly, it is possible that once a producer well undergone shut-in, the nearby wells will take the injection support from the closed well. Hence, the production in nearby wells can be represented by single pseudo-well for each cluster. The cluster centers must also represent the major flow path that is happening in the reservoir, which most likely will be directed towards the key wells. Here the key wells are defined as the wells with highest productivity index, or simply can be approached as the well with highest liquid production rate.

This type of clustering scheme can be attempted using several unsupervised clustering algorithm. Weighted K-means is chosen as the most suitable algorithm proposed due to the nature of the clustering scheme. Example of implemented clustering using weighted k-means for six clusters in Pandhawa field is provided in figure 15. The choice of cluster number is an arbitrary input, but several metrics such as silhouette values can be used as guideline for determining the optimal number of cluster.

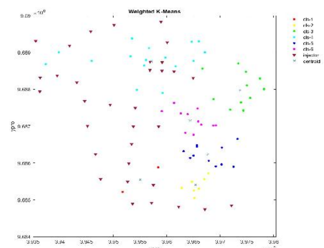

Figure 15. Clustering Producer (weighted k-means)

Result of this method can be seen in figure 16-21 start from liquid history field and well matching, oil history field and well matching, well connectivity map from injectors to clustering wells, baseline production scenario and optimization case. History matching quality of liquid and oil is acceptable and it can be conducted faster 16 time than previous method with similar result. Optimization result using clustering method give smaller number than without clustering, 352 MBO versus 505 MBO.

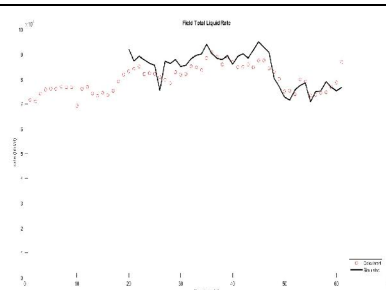

Figure 16. Field Total Liquid Rate HM Result Using Clustering

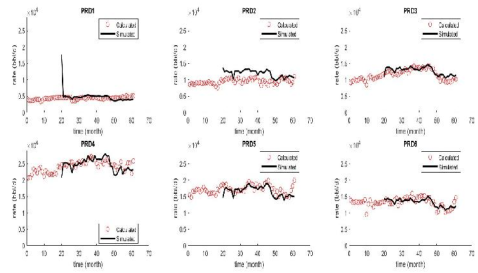

Figure 17. Well Total Liquid Rate HM Result Using Clustering

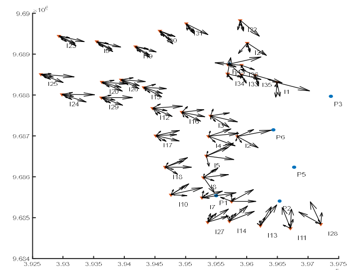

Figure 18. Well Connectivity Map from History Matching

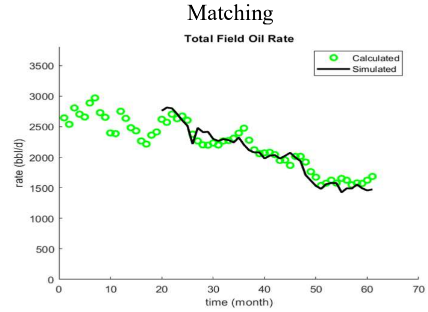

Figure 19. Field Total Oil Rate HM Result Using Clustering

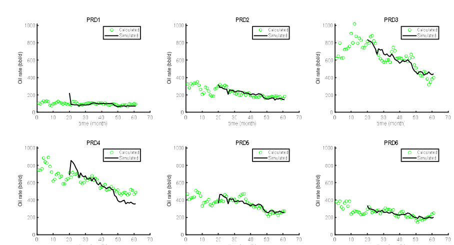

Figure 20. Well Total Oil Rate HM Result Using Clustering

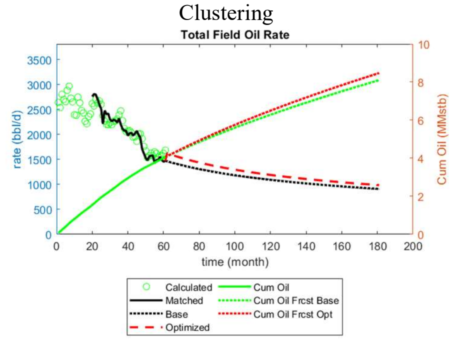

Figure 21. Pandhawa Field Base and Optimized Forecast Scenario Comparison using Clustering

Conclusions

Based on current study, we conclude that

- A computer program for CRM-IP implementation based on MATLAB has been successfully constructed and validated using Pandhawa field data.
- CRM-IP could be used to predict oil reservoir performance with simple and fast, in this study using actual data from Pandhawa field.
- CRM-IP has been shown to analysis injectors and producers performance (effective and ineffective well) in waterflood field by using interwell connectivity estimation.
- Clustering method is success implementing in this study to solve shut in well condition and accelerate time calculation with acceptable result.
- Optimization in Pandhawa field conducted by utilizing interwell connectivity to redistribute injection water with result 352-505 MBO.

Several works are planned to be exercised to further the research progress, such as :

- Optimization algorithm performance comparison for CRM Implementation in Matlab.
- Extension of CRM to include aquifer model such as Carter-Tracy analytical model to aid in uncertainty analysis

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