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Integrated Surveillance and Reservoir Characterization Evaluation for Preliminary Water Injection Optimization Strategy of Carbonate Reservoir

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ABSTRACT

The RS field is a green oil field that is in development stage with a carbonate reservoir as the interest zone. A Zone is one of the reservoir zones of the field with the highest oil reserve and has been produced since October 2019. A water injection program has been applied through one injection well since November 2020. The significant pressure decline is an indicator that the injection program in A Zone is not optimum in maintaining the reservoir pressure. There is no dynamic model for reservoir performance forecasting. Therefore, a further detail and comprehensive analysis through monitoring surveillance and reservoir characterization is required. The objective is to optimize the pressure maintenance program and to increase the oil recovery of A Zone in RS field. This study consists of three steps of analysis: the evaluation of existing water injection (pressure maintenance) surveillance; reservoir characterization evaluation; and 1-D reservoir simulation study. Surveillance analysis includes production and injection performance analysis; pressure performance analysis; voidage replacement ratio (VRR) analysis; Hall's Plot analysis and Chan's Diagnostic Plot analysis. Reservoir characterization evaluation includes remaining reserve evaluation; drive mechanism analysis; reservoir displacement profile phase based on fractional flow analysis (Buckley-Leverett); quality and reservoir heterogeneity; and reservoir pressure condition analysis. Material balance modelling is used as an initial simulation for optimization of injection wells and production performance prediction. Based on production prediction model material balance, if produced with VRR = 1, until the end of the contract (October 2039), the A Zone reservoir is capable of producing oil with a flow rate of 3038.36 BOPD; capable of maintaining reservoir pressure up to 1679.28 psig; water cut reservoir reached 77.82%; and cumulative oil production is 31.14MMSTB or equivalent to 12.50% of recovery factor.

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1. Introduction

The RS field is a green oil field located in the southeastern part of the Arabian Peninsula with a carbonate reservoir type as the play zone (Fig. **1**). The development of the RS field has focused on A Zone since October 2019. From the production data obtained, it is known that there has been a decrease in pressure from 3,400 psig of initial pressure to 2,647 psig in December 2022. This significant pressure decline is an indication that the application of water injection has not been optimal in maintaining reservoir pressure.

This paper discusses the evaluation of water injections as pressure maintenance to determine the effectiveness and success ratio of implementing water injection in A Zone. The evaluation results will be used as a reference in planning large-scale waterflooding as part of long-term field development plan. Surveillance analysis includes analysis of production and injection performance; pressure performance analysis; voidage replacement ratio (VRR) analysis; Hall Plot [1]; and Chan's Diagnostic Plot analysis [2]. Apart from that, analysis related to reservoir characterization in relation to water injection as optimal pressure maintenance. The analysis of drive mechanism; displacement phase profile in the reservoir based on fractional flow analysis (Buckley-Leverett); the reservoir quality profile; reservoir heterogeneity; and reservoir saturation pressure conditions are parameters that play an important role in the success of the water injection development program and the implementation of waterflooding later in the RS field [3].

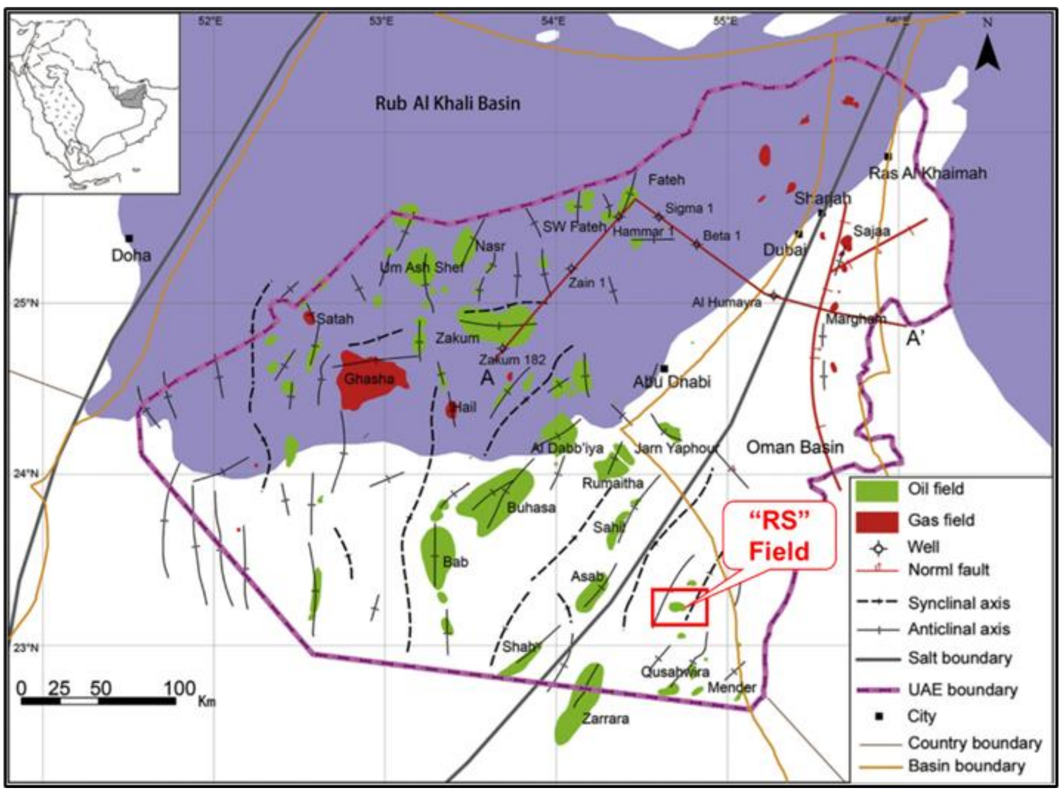

Figure 1: Location of RS Field [4].

2. Methodology

2.1. Data Inventory and Quality Control

Data preparation includes production data, reservoir fluid pressure volume and temperature (PVT) data, core data, well data, and geological data. Production data consists of production rate data, cumulative production, pressure data and water cut data. PVT data consists of data on the type and characteristics of the reservoir fluid. Core data consists of routine core analysis (RCAL) and special core analysis (SCAL). RCAL data includes porosity, permeability, shale volume and core thickness data. SCAL data includes end-point data, relative permeability curves, and capillary pressure. Well data includes well diagram data; well history data; well trajectory data; and well completion data (tubing and perforation). Geological data includes data on reservoir thickness, oil water contact (OWC), and reservoir area.

2.2. Surveillance Analysis of Existing Waterflooding

Waterflooding surveillance analysis includes production and injection analysis; voidage replacement ratio (VRR) and its effect on reservoir pressure trends; Hall Plot analysis to identify problems in injection wells; and Chan's Diagnostic Plot to identify problems in production wells.

2.3. Reservoir Characteristics Evaluation

SCAL data analysis is an integration of endpoint and relative permeability data analysis which is then combined with oil and water viscosity data to construct the fractional flow curve. The fractional flow curve will be used to analyze the displacement phase that occurs in the reservoir. The reservoir pressure analysis focuses on reservoir conditions regarding saturation pressure or Pb (bubble point pressure). RCAL data analysis includes conventional plot analysis between porosity and permeability and the reservoir heterogeneity coefficient in relation to the level of reservoir heterogeneity. Apart from that, the distribution of porosity and permeability values in the reservoir is also used to analyze reservoir quality.

2.4. 1-D Reservoir Simulation for Waterflood Optimization Program

Prediction of water injection performance as pressure maintenance is carried out numerically using one-dimensional material balance modeling. Validate the 1-D material balance model through the stages of pressure matching, in place matching, history matching, and fractional flow matching, before it can be used for production forecasts. The water injection optimization simulation includes 1-D modeling for water injection, streamline simulation, and production prediction to obtain a forecast profile of pilot waterflood optimization results in A Zone, RS Field.

A detailed research methodology flow diagram can be seen in Fig. (**2**).

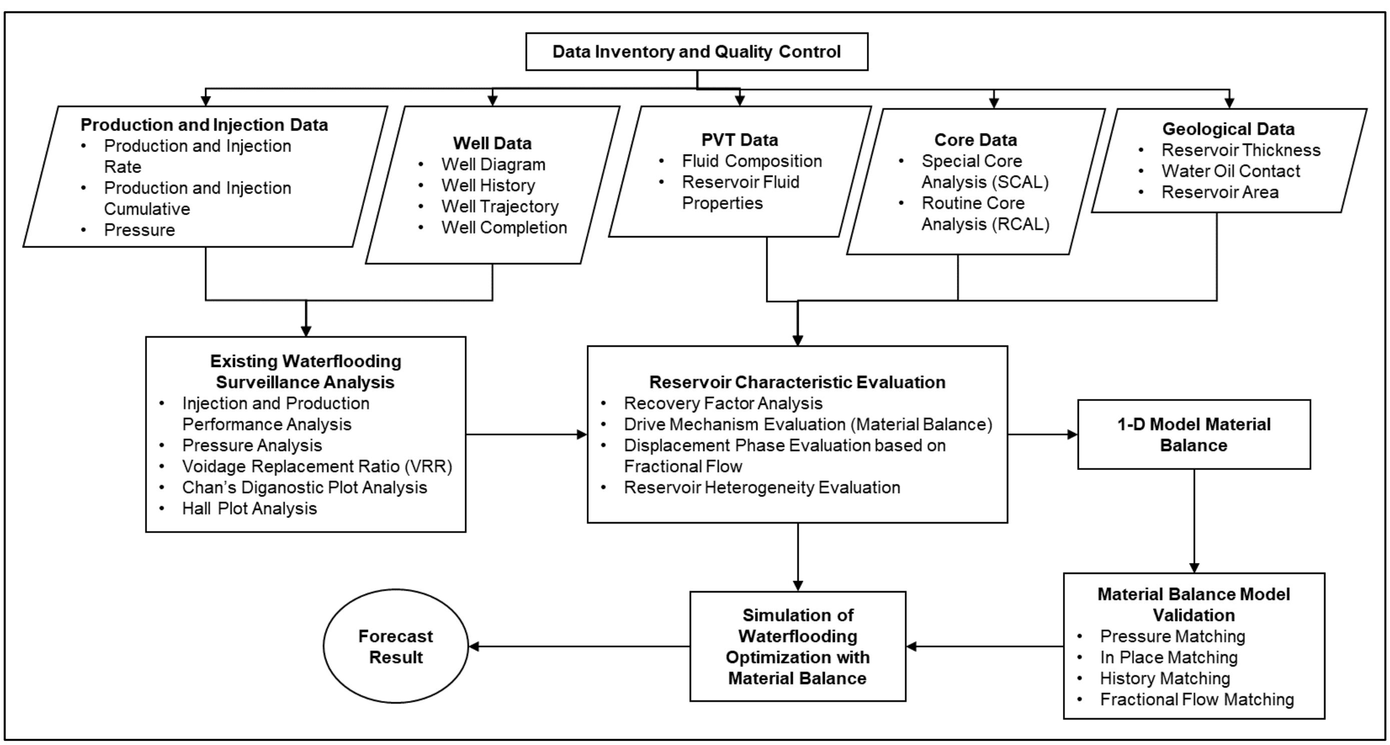

Figure 2: Methodology of analysis.

3. Results and Discussion

3.1. Surveillance Analysis of Existing Water Injection

3.1.1. Production and Injection Performance Analysis

A Zone in the RS Field started production in October 2019 through two production wells (RS-02 and RS-03) with an initial oil production rate (Qo) of 1,574 stock tank barrels per day (STBPD), 0% water cut (WC), and 245 SCF/STB gas oil ratio. The liquid production rate (Ql), which represents the total volume of produced fluids (oil and water), was recorded for each well. There were eight production wells and one injection well in A Zone of the RS Field. At the cut-off date of December 2022, two production wells were in shut-in status while the other six production wells were actively producing. The summary of production well status is on Table **1**.

Water injection as pressure maintenance was carried out in November 2020 through WI-01 with an injection flow rate of 200 BWPD. In December 2022, WI-01 was still operating with an injection rate of 1,375 BWPD. The A Zone reservoir production and injection performance graph can be seen in Fig. (**3**).

Table 1: Well summary of production well.

Well Name	First Prod.				Last Prod.					Status
	Date	Qi (BLPD)	Qo (STB/D)	WC (%)	Date	Qi (BLPD)	Qo (STB/D)	WC (%)	Np (MSTB)	
RS-01	Apr-22	1024	727	28.93	Oct-22	1375	200	85.4	58.7	Shut-In
RS-02	Oct-19	644	644		Dec-22	818	812	0.8	1099.2	**Active**
RS-03	Oct-19	1384	783	43.42	Dec-22	5751	2799	51.3	8146	**Active**
RS-04	Oct-21	1739	1730	0.49	Dec-22	755	748	1	519.6	**Active**
RS-05	Aug-21	714	689	3.5	Dec-22	2341	1421	39.3	467.4	**Active**
RS-06	Dec-21	1517	1516	0.07	Sep-22	1666	328	80.3	204.6	Shut-In
RS-07	Oct-21	1348	1290	4.34	Dec-22	2631	1232	53.2	291.2	**Active**
RS-08	Oct-21	658	653	0.76	Dec-22	967	710	26.6	185.2	**Active**

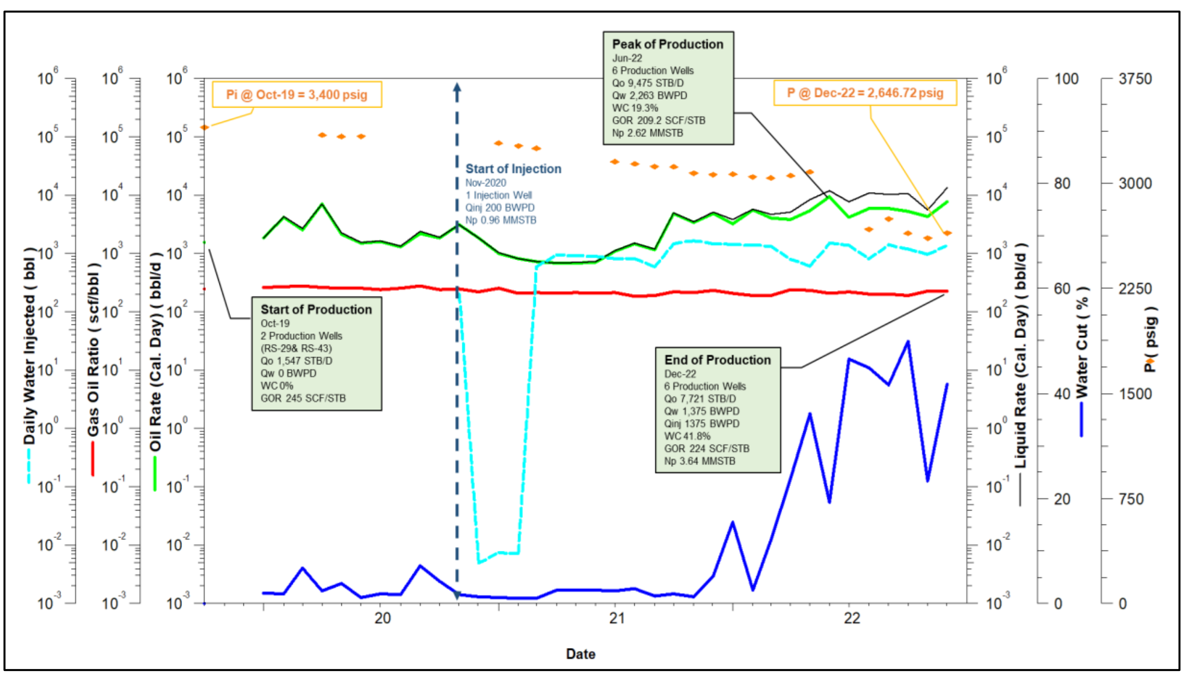

Figure 3: Production and injection performance of A zone.

3.1.2. Pressure Performance Analysis

The initial pressure in A Zone is 3,400 psig and when reservoir fluid begins to be produced, the reservoir pressure decreases. The decline in reservoir pressure before injection is not very significant because A Zone is produced only through 2 production wells. Reservoir pressure began to decrease significantly from 3,286.39 psig in January 2021 to 2,648.72 psig in December 2022; after the water injection was implemented. The significant pressure decline occurred because the number of production wells also increased. The decrease in pressure after injection is an indication that water injection is not optimal to maintain reservoir pressure.

In December 2022, A Zone reservoir pressure was 2648.72 psig. The pressure value is still far above bubble point pressure (Pb), 971.3 psig. This condition shows that on the cut-off date (December 2022), there is no dissolved gas released from the oil in the reservoir. Based on Rukmana *et al*. [3], optimizing waterflood under reservoir pressure conditions above Pb will provide optimal oil recovery.

3.1.3. Voidage Replacement Ratio Analysis

Voidage replacement ratio (VRR) analysis was carried out as validation of the decrease in reservoir pressure values in A Zone after water injection was implemented as pressure maintenance. The VRR target for optimal water injection is to maintain the VRR value close to 1, meaning that the volume of injected water matches the volume of produced fluids (oil, water, and gas). When VRR = 1, the reservoir pressure is theoretically maintained, ensuring stable production. The VRR value in A Zone of the RS Field is still below 1 suggesting that water injection is not optimal in maintaining the pressure decline in A Zone due to the amount of water required. Water injected into the reservoir is much less than the amount of fluid produced from the reservoir.

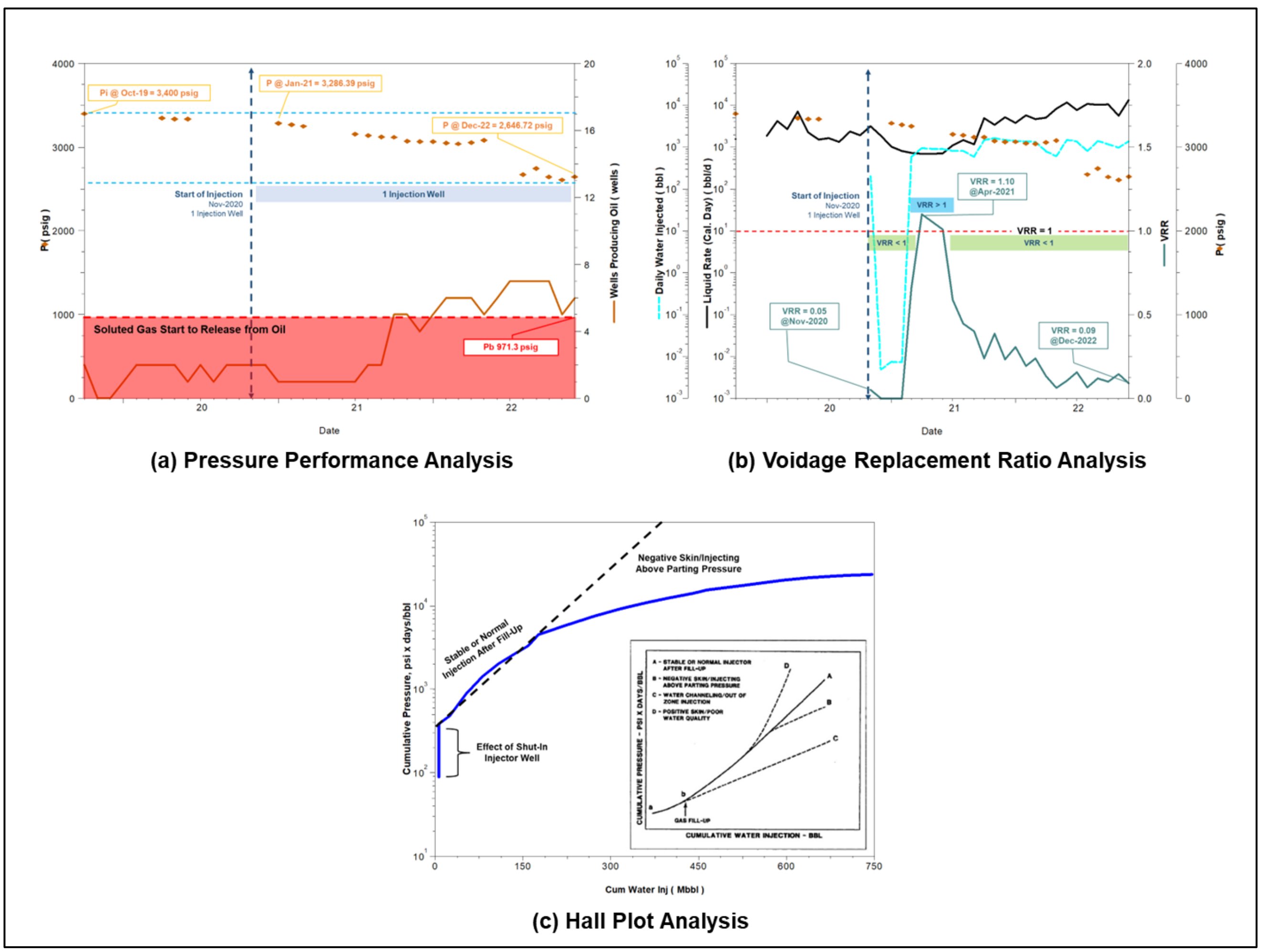

Figure 4: (**a**) Pressure, (**b**) VRR, and (**c**) Hall Plot Analysis of the A Zone.

3.1.4. Hall Plot Analysis

Hall Plot analysis is a plot between cumulative injection and cumulative pressure at the wellhead to provide an overview of the characteristics or condition of the reservoir around the injection well. Based on Hall Plot analysis (Fig. **4c**), it can be concluded that in the initial conditions of injection is normal injection after fill-up. The next trends indicate negative skin or injection exceeds fracturing pressure.

3.1.5. Chan's Plot Analysis

Water diagnostic plot or Chan's Plot analysis is carried out on production wells to determine problems in production wells [5]. The analysis acts as an initial indicator to determine the effect of water injection on production wells. Table **2** displays a summary of Chan's Plot analysis.

Table 2: Chan's plot summary of production wells on A zone.

Well	Date of First Production	Date of Last Production	Status	Chan's Plot Indication
RS-01	Apr-22	Oct-22	Shut-In	Channeling
RS-02	Oct-19	Dec-22	**Active**	Normal Displacement
RS-03	Oct-19	Dec-22	**Active**	Bottom Water Coning with Late Channeling
RS-04	Oct-21	Dec-22	**Active**	Normal Displacement
RS-05	Aug-21	Dec-22	**Active**	Bottom Water Coning
RS-06	Dec-21	Sep-22	Shut-In	Bottom Water Coning
RS-07	Oct-21	Dec-22	**Active**	Bottom Water Coning
RS-08	Oct-21	Dec-22	**Active**	Channeling

Based on Chan's Plot analysis which is in line with the trend of increasing water cut in production wells, there are indications of channeling problems in well RS-01 and well RS-08; indication of water coning with late channeling problem in the RS-03 well; as well as indications of bottom water coning problems in the RS-05 well, RS-06 well and RS-07 well. Normal displacement occurs in well RS-02 and well RS-04.

A summary of the key analyses performed in this study, along with their optimal criteria, is provided in Table **3** below.

Table 3: Chan's plot summary of production wells on A zone.

Analysis Type	Criteria/Range for Optimal Condition
Production and Injection Performance Analysis	Stable oil production, WC < 40%, GOR within limits.
Pressure Performance Analysis	Gradual pressure decline, above bubble point (Pb).
Voidage Replacement Ratio (VRR) Analysis	VRR ≈ 1.0 for pressure maintenance
Hall Plot Analysis	Linear trend; deviation suggests formation issues.
Chan Plot Analysis	Stable WOR for normal flow; increasing WOR indicates issues.

3.2. Reservoir Characteristics Evaluation

3.2.1. Fractional Flow Analysis

The fractional flow curve is determined using relative permeability data of the oil-water system and PVT (oil and water viscosity) data. The fractional flow shows the trend of water cut or an increase in water production in the reservoir along with changes in saturation due to the oil production process from the reservoir to the production well.

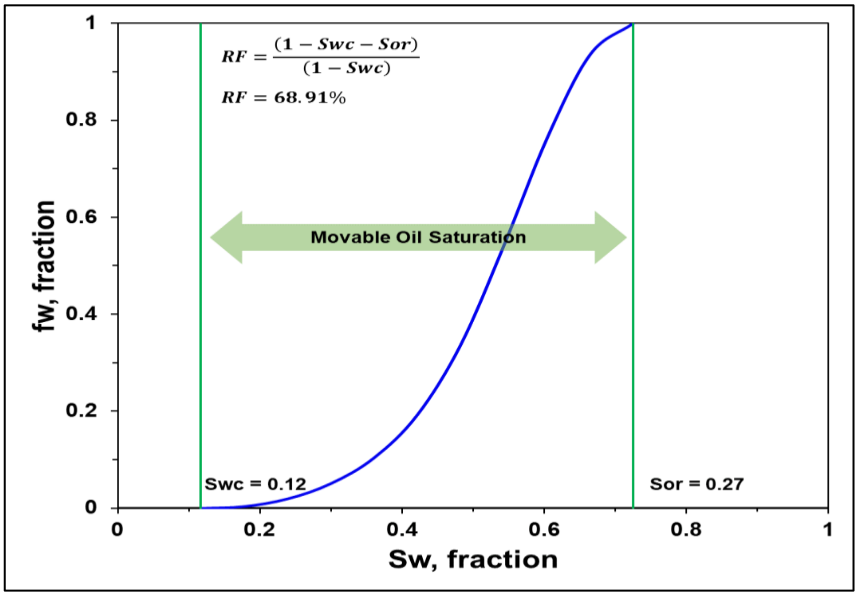

Figure 5: Recovery factor calculation from SCAL data of the A zone.

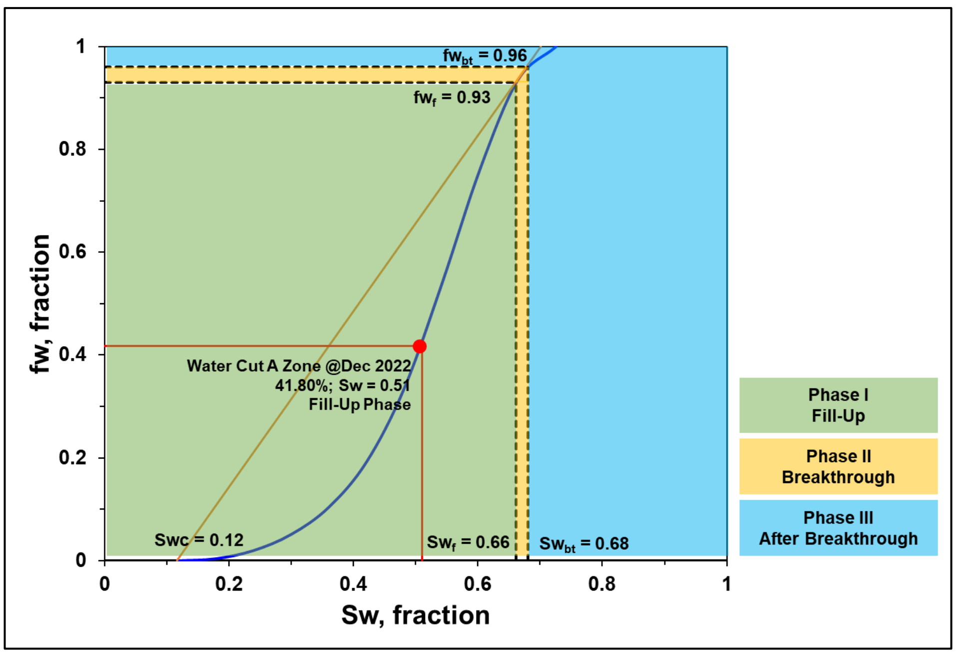

Figure 6: Displacement phase analysis of the A zone.

Fig. (**5**) shows the calculation of the maximum RF from SCAL data, 68.91%. The high RF value is consistent with typical carbonate reservoirs.

Analysis of the displacement phase in A Zone of RS Field uses the Buckley-Leverett displacement concept. Buckley-Leverett divides the displacement phase in the reservoir into 3 phases described by Rukmana *et al*. [3]:

1. The fill-up phase; is a condition where displacement occurs until the gas is completely produced. Waterflood production in this phase will be high.
2. The fill-up to breakthrough phase; is the process that takes place when water begins to be produced (water breakthrough). Waterflood production in this phase is lower than the fill-up phase.

3. The after-breakthrough phase; is the period where the injected water no longer displaces oil, but instead drags the oil towards the production well. Waterflood production in this phase will be low.

Analysis of the pilot waterflood displacement phase in A Zone can be seen in Fig. (**6**). The water cut value of A Zone in December 2022 is 41.80%. Based on the fractional flow curve, the displacement phase in A Zone, the RS Field is still in the fill-up phase. Therefore, the results of waterflood optimization will provide a higher recovery factor, compared to if the optimization is implemented after the displacement phase reaches the breakthrough or after-breakthrough phase.

3.2.2. Routine Core Analysis (RCAL)

Based on RCAL, there are several core data samples that show fracture conditions. The existence of fractures as a secondary porosity system is in accordance with the characteristics of the A Zone reservoir. Based on the distribution of fractures in the RCAL A Zone data, it can be seen that the fracture system is part of the matrix system. The indication of an even distribution of fractures with the matrix system is an indication that there are fractures in the WI-01 injection well, in line with the indications in the Hall Plot analysis (Fig. **4**).

Reservoir heterogeneity analysis was carried out using the Dykstra-Parson [6] method. The permeability values are sorted from the largest value and then plotted against the percentage of the cumulative thickness of each core sample. The Dykstra-Parson coefficient was calculated using the permeability value at a cumulative thickness of 50% and 84.1% and obtained a value of 0.7. This value shows that the A Zone reservoir in RS Field is a heterogeneous reservoir (Fig. **7**).

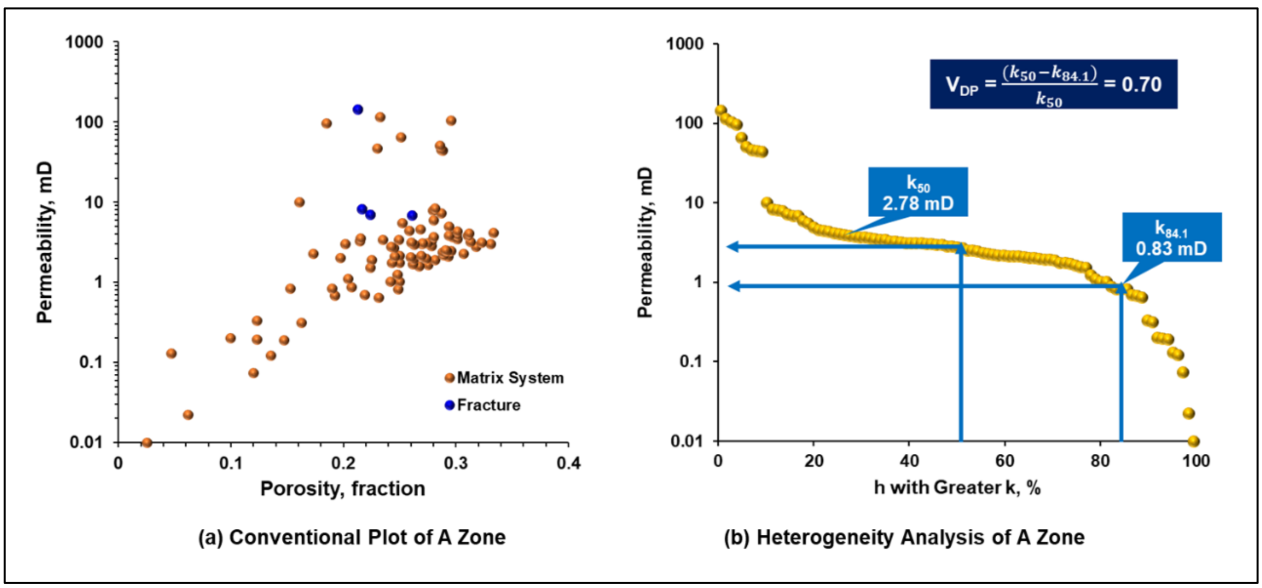

Figure 7: RCAL data analysis of the A zone.

3.2.3. 1-D Modelling of Water Injection in A Zone

Reservoir simulation for optimizing water injection and predicting production performance is performed using material balance modelling. In material balance modelling, the reservoir is considered as a homogeneous tank that has one porosity value and one permeability value. Reservoir heterogeneity is ignored but reservoir pressure is still considered as a function of production and injection in the reservoir (Fig. **8**).

3.2.4. Material Balance Model Validation

The initial stage of validating the material balance model before it can be used for production predictions is to match the reservoir pressure in place. Pressure and in place matching is carried out using analytical methods. Sensitivity to in place values, formation compressibility, and aquifer reservoir parameters are done to achieve matching results for pressure trends and cumulative reservoir production in A Zone (Fig. **9**).

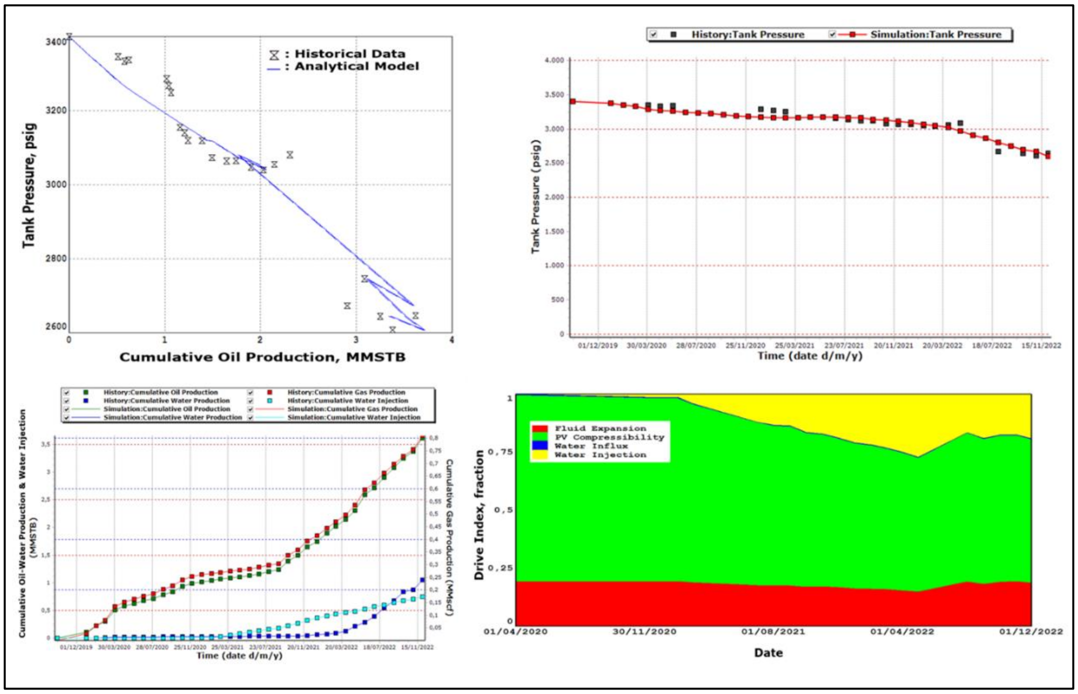

Figure 8: Validation result of material balance model.

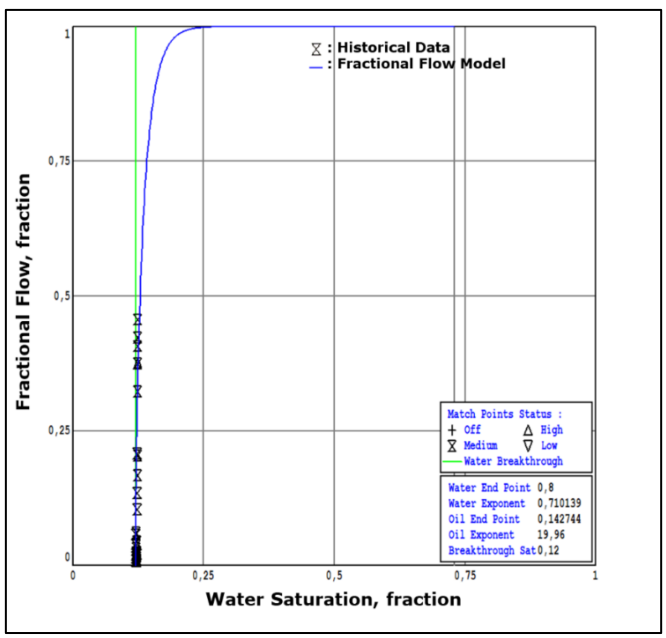

Figure 9: Fractional flow matching of the A zone.

Based on the results of matching pressure and in place, the OOIP value for A Zone is 249 MMSTB; the reservoir radius value is 15,483.6 ft (corresponding to the area above the contact); the formation compressibility value is 9.26 x 10-6 1/psi; and the aquifer model type is Fetkovich Semi Steady State (bottom drive aquifer) with an aquifer volume of 8.09 MMCF.

In contrast to analytical matching of in place and pressure trends, history matching of production and injection data in the material balance model is performed numerically. There is a combination of fluid expansion, pore volume compressibility, water influx (water drive), and water injection. The dominant drive mechanisms that work in the A Zone are the PV compressibility drive mechanism and fluid expansion, while the one that plays the smallest role is the water drive mechanism.

3.2.5. Production Prediction

Prediction of production performance and reservoir pressure using the material balance model is performed as a single reservoir unit. Production prediction is not influenced by the position and number of injection and production wells. The reservoir production is a function of the volume of fluid produced and injected into the A Zone. The scenario for production prediction in the A Zone reservoir, RS Field is to inject water with a volume that matches the volume of fluid produced.

Fig. (**10**) shows the forecast results of production, injection and pressure performance when the VRR value = 1. The injection flow rate is the same as the production rate, 16,304 BWPD. If produced with VRR = 1, until the end of the contract (October 2039), the A Zone reservoir is capable of producing oil with a flow rate of 3,038.36 BOPD. Reservoir pressure can be maintained up to 1,679.28 psig. In October 2039, the water cut value of the A Zone was 77.82% with a cumulative oil production value of 31.14 MMSTB or equivalent to a 12.50% of recovery factor (Fig. **11**). Table **4** displays a summary of the recovery of the water injection optimization program.

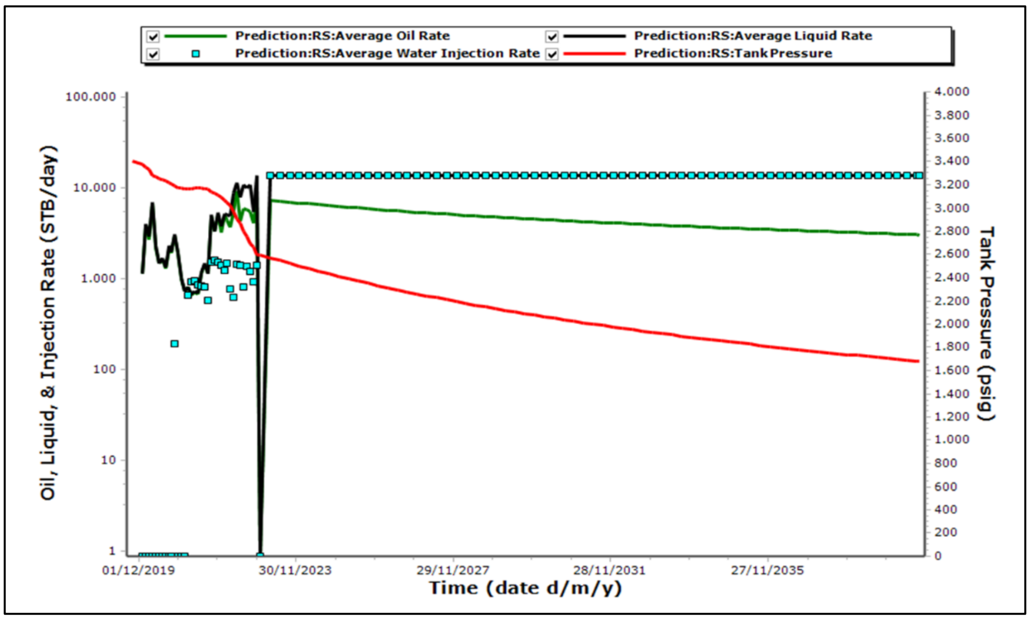

Figure 10: Production, injection, and pressure forecasting profile when VRR =1 for A zone.

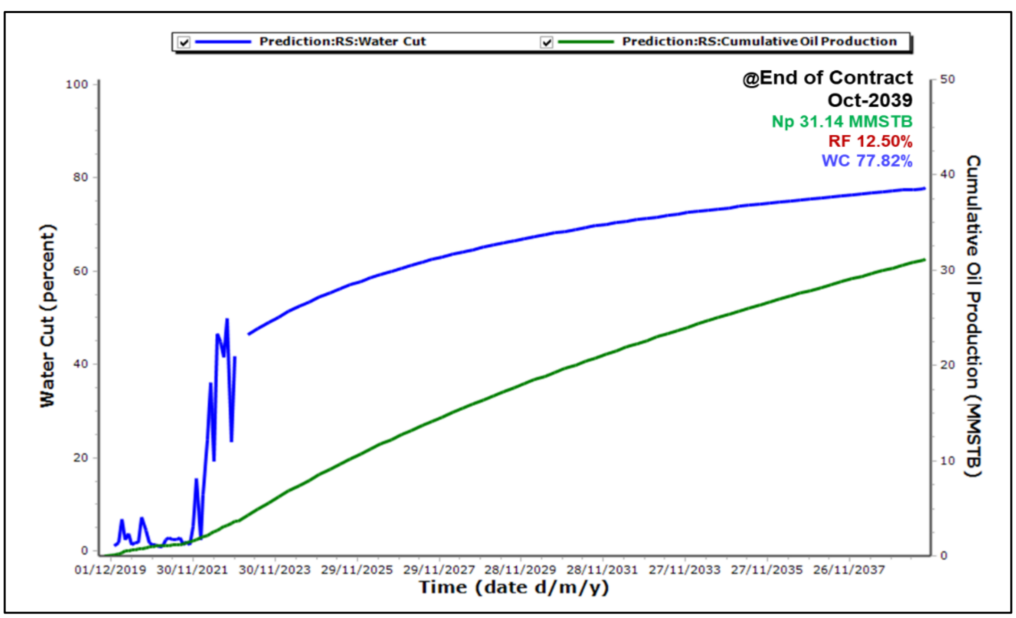

Figure 11: Water cut and cumulative oil production profile when VRR =1 for A zone.

Table 4: Summary recovery of waterflood optimization program for A zone.

OOIP (MMSTB)	Np @ End of PSC (Oct 2039, MMSTB)	RF @ End of PSC (Oct 2039, %)	RF JJ Arps (%)	EUR JJ Arps (MMSTB)	Remaining Reserve (MMSTB)
249	31.14	12.51	67.64	168.41	137.27

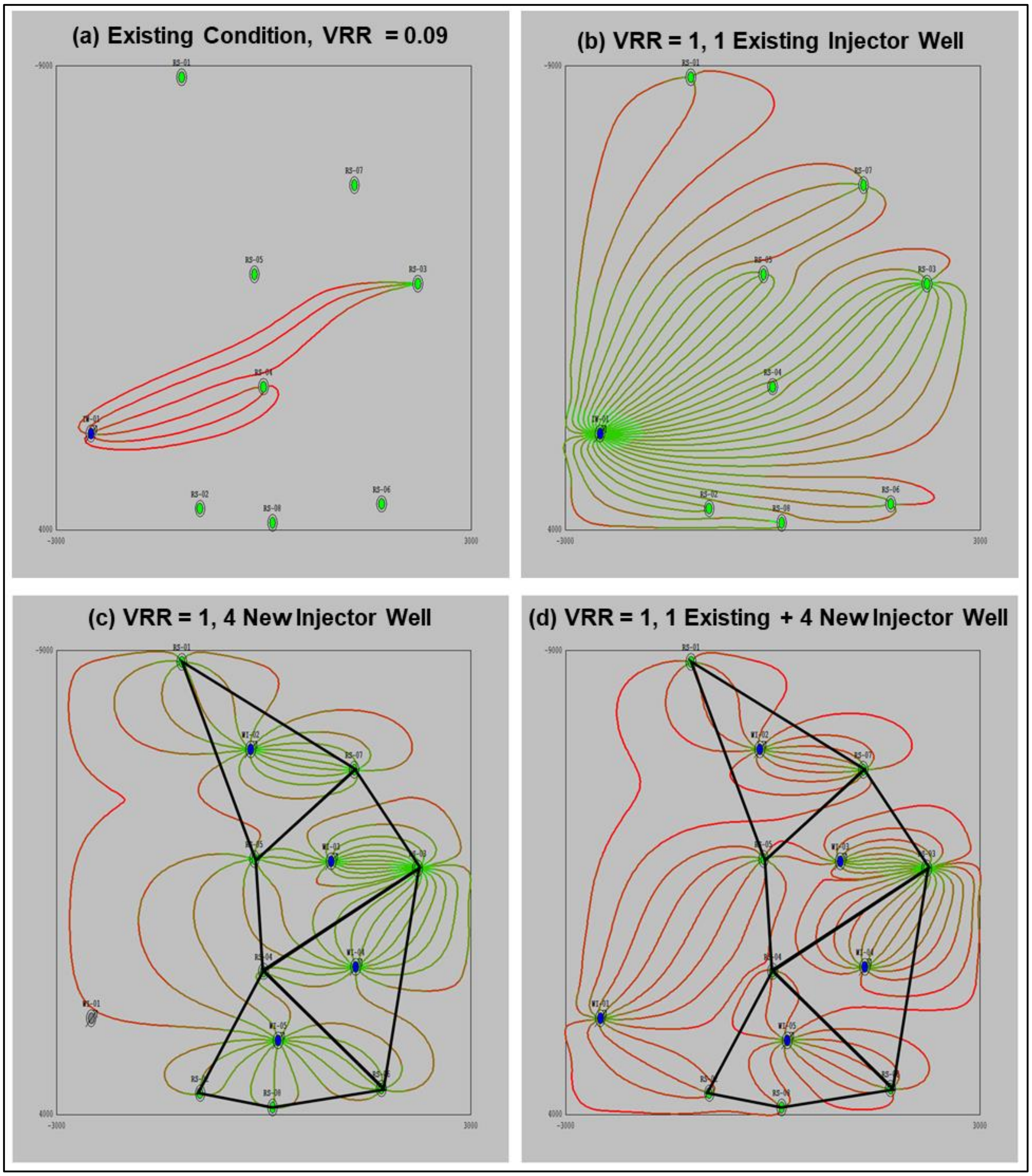

Figure 12: Streamline model of waterflood in A zone.

3.3. Discussion

3.3.1. Water Injection Surveillance Evaluation

Surveillance evaluation includes production and injection performance analysis; reservoir pressure performance analysis; voidage replacement ratio (VRR) analysis, and Hall Plot analysis for injection wells. A Zone in

RS Field was produced in October 2019 where the water injection as pressure maintenance was performed in November 2020. There has been water production since the start of production and continues to rise as an indicator of reservoir water drive effect, the water injection effect, or excessive water production problems in the production well. The gas oil ratio (GOR) is relatively constant and shows that the reservoir pressure is still above the Pb (972.1 psig).

Based on the Hall Plot analysis, there are indications of negative skin or injection exceeding the fracturing pressure. As supporting data, the results of Chan's Plot analysis on production wells indicate problems such as channeling and bottom water conning in production wells, which is one of the factors for the increased water cut in several production wells. The problem of conditions in the production wells should be investigated later. Based on the results of the surveillance analysis, the application of water injection in the RS field is not yet in the optimal phase because the reservoir pressure begins to decrease significantly after water injection is carried out. From the analysis, it was found that the average VRR value in A Zone of the RS Field is 0.3 and it is one of the justifications that water injection is not optimal in maintaining the rate of pressure decrease in A Zone.

3.3.2. Reservoir Characteristic Evaluation

Evaluation of reservoir characteristics was done to determine the correlation between reservoir characteristics to the surveillance water injection evaluation and reservoir compatibility of A Zone in the water injection optimization program. Based on the fractional flow curve, the displacement phase in A Zone is still in the fill-up phase. Theoretically, the application of water injection will not increase the recovery factor value, but if the optimization is done properly, the reservoir pressure drop can be minimized. With the ability to maintain reservoir pressure above the bubble point pressure, later if there is a plan to apply waterflooding to the reservoir A Zone, it will be more effective to increase the recovery factor supported by the reservoir condition which is currently still in the fill-up phase. Waterflood optimization under reservoir pressure conditions above Pb will provide optimal oil recovery [3].

Based on RCAL, several core data samples show fracture conditions as a secondary porosity system. The indication of an even distribution of fractures with a matrix system is in line with the indication in the Hall Plot analysis. Based on these indications, further analysis of the fracture distribution map is required so that the water injection optimization design will provide optimal results, where we can map the injection flow direction in the fractured reservoir later.

The reservoir heterogeneity constant value using the Dykstra-Parson shows that the A Zone reservoir in RS Field is a heterogeneous reservoir. The permeability values above 100 mD are less than 5%, suggesting that the A Zone can be categorized as a low-quality reservoir. This fairly low reservoir quality needs to be considered, especially in the design of injection water quality to prevent reservoir plugging. Based on the evaluation of reservoir characteristics, A Zone is compatible with water injection optimization by considering reservoir heterogeneity and injection water quality.

3.3.3. Material Balance Modeling

Based on the material balance modeling, it is known that the dominant drive mechanism working in A Zone is PV compressibility drive mechanism and fluid expansion. The reservoir drive mechanism is compatible for water injection optimization (waterflooding). Fractional flow matching is required for the forecasting stage so that the oil rate trend of the production prediction results matches the reservoir capacity.

Streamline modeling (Fig. **12**) is performed to see the flow of water injection in a homogeneous reservoir. In this model, all reservoirs are assumed to have the same thickness; the same reservoir physical properties (rock and fluid); and the same reservoir fluid mobility between oil and water (mobility ratio = 1). Based on the injection and production flow from each production well, with streamline modeling in homogeneous reservoirs, it is found that the flow from injection well WI-01 only flows to wells RS-03 and RS-04 in December 2022 with VRR = 0.09. When VRR = 1, the flow from injection well WI-01 flows to all production wells.

Production prediction is carried out with a material balance model as a single reservoir unit with a value of VRR = 1. Production prediction is not affected by the position and number of injection wells and production wells. Production results are a function of the volume of fluid produced and injected in the A Zone reservoir, RS Field. If produced with VRR = 1, until the end of the contract (October 2039), the A Zone reservoir is able to produce oil with a flow rate of 3038.36 BOPD with reservoir pressure can be maintained up to 1679.28 psig. By October 2039, the water cut value of the A Zone reservoir is predicted to reach 77.82% with a cumulative oil production value of 31.14 MMSTB or equivalent to a 12.50% recovery factor with 249 MMSTB OOIP.

Further evaluation of indications of problems in production and injection wells integrated with petrophysical evaluation and well history is vital. Analysis of reservoir quality and heterogeneity based on RCAL data needs to be integrated with petrophysical analysis and reservoir connectivity analysis using static model data. 3-Dimensional reservoir simulation is needed to predict breakthrough time, reservoir performance, and sensitivity of various water injection optimization scenarios by considering reservoir heterogeneity for more optimal and reliable results

4. Conclusions

1. Optimization program of the water injection in A Zone has the potential to be performed by considering the results of the evaluation of reservoir characteristics as follows:

    - The recovery factor from special core analysis (SCAL) data is 68.91%. With a current recovery factor 1.45%, there are 67.46% remaining reserves of OOIP that can be produced through waterflood optimization program.
    - The A Zone is still in the fill-up phase, so the optimization of waterflooding will be more optimal.
    - The reservoir pressure is above the bubble point pressure, where there is no dissolved gas released from the oil in the reservoir so that oil production can be optimized.
    - Water injection optimization needs to consider reservoir connectivity and injection water quality to minimize the risk of reservoir plugging.

2. Material balance modeling of A Zone shows that:

    - The dominant drive mechanisms acting in A Zone are PV compressibility and fluid expansion – compatible with waterflood program.
    - Streamline simulation shows that if VRR = 1, there is flow from injection wells to all production wells.

3. Based on the production prediction of the material balance model, if produced with VRR = 1, the estimated time until the end of the contract (October 2039), the A Zone reservoir can produce oil with a flow rate of 3038.36 BOPD; with a reservoir pressure of 1679.28 psig; the water cut value reaches 77.82%; and the cumulative oil production value is 31.14MMSTB or equivalent to a 12.50% recovery factor.

Further evaluation of indications of problems in production and injection wells integrated with petrophysical evaluation and well history is vital. Analysis of reservoir quality and heterogeneity based on RCAL data needs to be integrated with petrophysical analysis and reservoir connectivity analysis using static model data. 3-Dimensional reservoir simulation is needed to predict breakthrough time, reservoir performance, and sensitivity of various water injection optimization scenarios by considering reservoir heterogeneity for more optimal and reliable results.

Conflict of Interest

The corresponding author declared no conflicts of interest in this work on behalf of all the authors.

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