Geological Modeling and Material Balance Study of Multilayer Heavy-Oil Reservoirs in Dalimo Field

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Abstract: Dalimo Field is a heavy oil field, situated on Sumatera Island, Indonesia, operated by an operator on behalf of the Indonesia government. Although the field has been in production since 1976, the recovery factor is low, with significant recoverable reserves remaining unproduced. Current production is coming from 62 wells with total of 11 productive sands. In this case there will be inter-reservoir allocation factor issue due to this field is produced from multilayers sand (commingle production). Consequently, a systematic geological and reservoir engineering investigation is extremely important to be performed to get insight information of the geological and reservoir models. This paper discusses the geological modeling which includes structural modeling, property modeling, and volumetric calculation to obtain original oil inplace (OOIP). Material balance analysis is performed to analyze the reservoir drive mechanism and to obtain the reservoir model which matches to the actual reservoir condition by conducting history matching analysis. Having performed geological modeling and material balance analysis, subsequently, the remaining reserve is calculated. Based on the volumetric calculation, the total of original oil inplace in the Dalimo Field is about 153.30 MMSTB. From production allocation with the permeability-thickness (kh) method, there are five major oil sands which are Sand 1, Sand 2, Sand 3, Sand 4, and Sand 6. Based on the result of material balance analysis, the reservoir drive mechanism in the Dalimo Field is Water Drive mechanism. According to the recovery efficiency (RE) calculation with J.J. Arps et. al. method for water drive reservoir, the total of remaining oil reserve in the Dalimo Field is about 12.79 MMSTB (RE = 19.95%).

Key-Words: Inter-reservoir allocation, Geological modeling, Original oil inplace, Material balance, Reservoir drive mechanism, History matching, Remaining reserve, Recovery efficiency.

1 Introduction

Original Oil In Place (OOIP) and reserve estimation are highly important to be identified in order to decide whether the reservoir is economically viable or not. In addition, by knowing the reservoir drive mechanism could help in reservoir performance analysis. If a large amount of oil inplace is present and the reservoir performance is also good, then the reservoir is going to be on production and profitable.

Dalimo Field is a heavy oil field which is located in the Sumatera Island, Indonesia. Geologically, it is located in Central Sumatera Basin. Although the field has been in production since 1976, the recovery factor is low, with significant recoverable reserves remaining unproduced. According to this condition, a plan for further development is highly needed to maximize the oil recovery factor in the Dalimo Field.

This study will focus on the estimation of OOIP by using Volumetric method from Geological Modeling and Material Balance method. The estimation will be performed for each layers and compartments in the Dalimo Field. In addition, the reservoir drive mechanism is also analyzed with Material Balance as well as the the remaining reserve is identified for each layers and compartments in the Dalimo Field.

2 Methodology

Methods implemented for the identification of original oil inplace and reservoir drive mechanism include the following sequential steps:

2.1 Geological Modeling

3D Geological Modeling in the Dalimo Field consists three main phases; Structural Modeling, Property Modeling, and Volumetric Calculation. Structural modeling was performed to produce the reservoir's framework in 3D. Analysis of fault orientation from seismic interpretation was conducted in order to obtain the number of segments or compartments within the field. This is important as the result of segmentation will determine number and distribution of the reservoir tank models that will be used in Material Balance analysis. Then, property modeling was performed in order to fill in the 3D framework with properties from the wells, i.e. facies, effective porosity, permeability, and water saturation. Having performed 3D structural and property modeling, these data were used to calculate the OOIP with using Volumetric Method. The OOIP will be calculated for each sands per segments in the Dalimo Field.

2.2 Material Balance Analysis

The material balance (MBAL) method is used to estimate the original hydrocarbon in place and reservoir drive mechanism. At the initial stage, inter-reservoir allocation which is production allocation was performed by using the permeability-thickness (kh) method. It was aimed to allocate the cummulative oil production (Np) for each productive sand per segments due to the field being produced from multilayers reservoir with commingle production method. Then, MBAL analysis was undertaken by defining the tank model (reservoir fluid); then, fluid properties (PVT) modeling; subsequently, construction of the tank model by inputing reservoir parameter, volumetric data, special core analysis (SCAL) data, production history, and aquifer modeling if there is aquifer influx from the analysis. Finally, history matching analysis was performed by using Graphical and Analytical methods, and the Energy Plot for drive mechanism analysis.

2.3 Reserve Estimation

Having performed geological modeling and material balance analysis, the OOIP and Np were then compared. The OOIP differences from volumetric method and material balance, and Np differences from production allocation and material balance should be less than 5%. Subsequently, the recovery efficiency was calculated based on the reservoir drive mechanism in order to calculate the ultimate recovery (UR). Eventually, the remaining reserve was estimated from ultimate recovery minus cummulative oil production.

3 Results and Discussion

3.1 Geological Modeling

3D geological modeling was performed in all of 11 reservoir zones in the Dalimo Field. Structural modeling is the initial step in geological modeling. This process includes mapping marker, pillar gridding, fault modeling, segmentation, make horizons, and layering process. The Dalimo Field is an anticline which has a main the fault with NW-SE (major) orientation, and also some minor faults with N-S and S-W orientation. The fault structure pattern in the Dalimo Field was obtained from seismic interpretation. **Fig. 1** shows the fault model in the Dalimo Field. The major fault orientation was used to conduct segmentation analysis. The segmentation in the Dalimo Field was resulted into two segments. The two segments were named as Segment 1 and Segment 2 (**Fig. 2**). These results justified for producing the reservoir tank models for further anaylsis in application of material balance method. All the sands in the Dalimo Field will be divided into two main compartments or segments. It will give impact the calculation of the distribution of original oil inplace, cummulative oil production, and remaining reserve in the field.

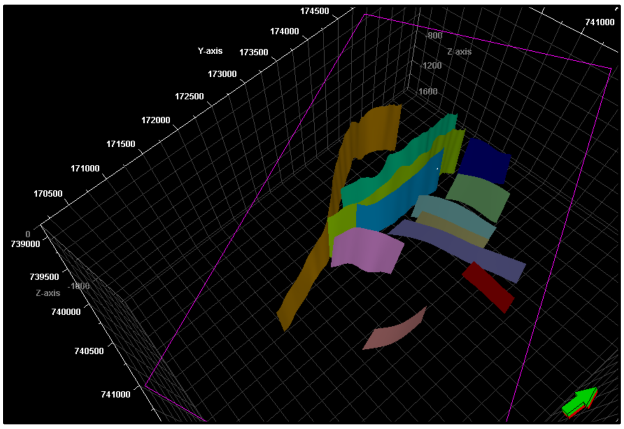

Fig. 1 The fault pattern in the Dalimo Field

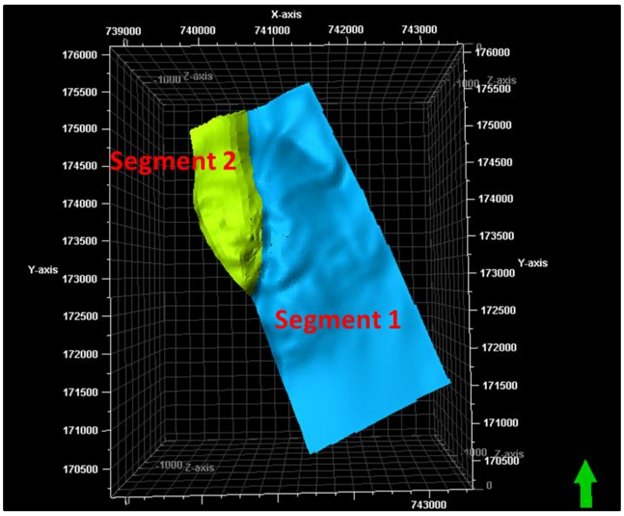

Fig. 2 The segmentation in the Dalimo Field

Making horizons was then performed based on the wells correlation in the Dalimo Field. The process used horizon - fault lines for each horizons.

Having performed the horizons for each zones, layering process was then conducted to produce the thin layers and detail for each reservoir zones.

The property modeling was then performed by firstly, scale up well logs. It includes scale up for facies, shale volume, and effective porosity. It is important to scale-up properties from well log interpretation before distribute in the geological framework model. This process was aimed to fill in the cells in well position by averaging properties from log interpretation results. Then, data analysis was carried out to analyze the tend of data distribution orientation as spatially, whether lateral or vertical orientation. This analysis was needed as inputing data to do property distribution. Distribution of the facies model was performed uses the SIS method (Sequential Indicator Simulation) and controlled by the results of variogram analysis from well logs scale up. **Fig. 3** shows the facies distribution model in the Dalimo Field. While petrophysical modeling, i.e. shale volume (Vsh) and effective porosity (PHIE), was performed uses the SGS method (Sequential Gaussian Simulation). The results of Vsh modeling and PHIE modeling are shown in **Fig. 4** and **Fig. 5**, respectively. Net To Gross (NTG) modeling was then derived from Vsh model uses property calculator.

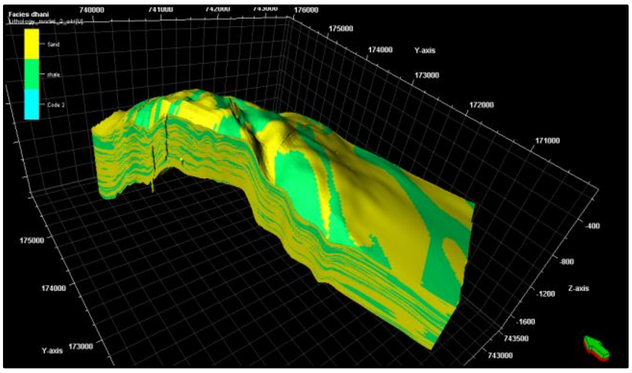

Fig. 3 Facies distribution model in the Dalimo Field

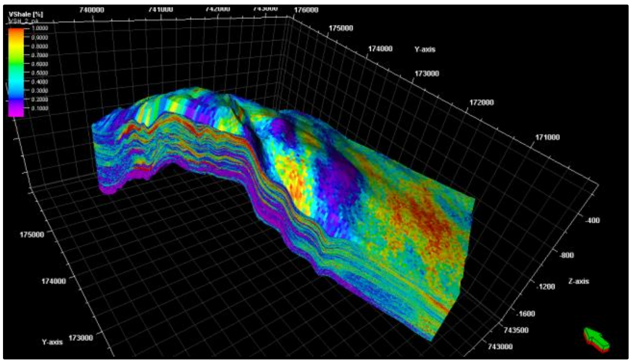

Fig. 4 Vsh distribution model in the Dalimo Field

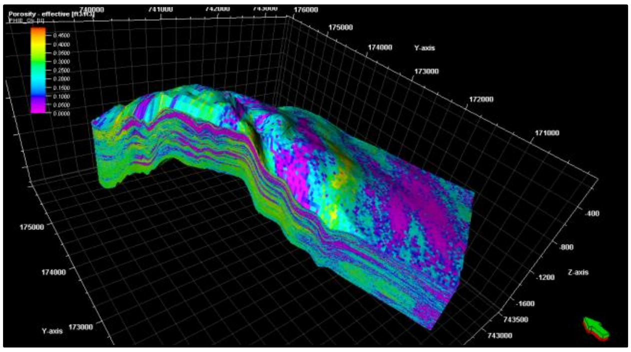

Fig. 5 PHIE distribution model in the Dalimo Field

Permeability modeling was derived from the result of porosity modeling. Permeability transform was carried out based on the empirical equation from the result of permeability – porosity crossplot from the core data. The permeability distribution model in the Dalimo Field is shown in **Fig. 6**. For determining water saturation (Sw), the J-Function method was applied. Basically, the J-Function method is performed by determining Sw correction from capillary pressure analysis of the core data which then it is implemented in the wells which have no core data. Calculation of Sw using J-Function approach includes capillary pressure analysis based on core data and well log data. The Sw model was distributed from the J-Function equation results. Then, the synthetic Sw logs from model were extracted and compared to Sw from well log data. The validate Sw model was then used for calculating OOIP.

Determination of Oil-Water Contact (OWC) was performed for each reservoir zones per compartments. It was done by selecting the well reference. Determination of well reference based on the deeper well and the well has perforation data, it has been proven in producing oil. **Fig. 7** shows the fluid contacts map above oil-water contact for reservoir zones in the Dalimo Field.

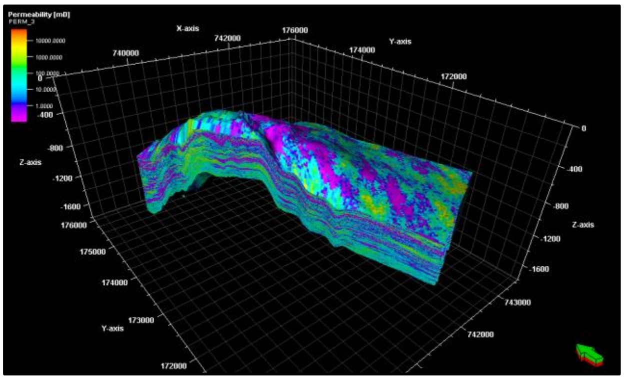

Fig. 6 Permeability model in the Dalimo Field

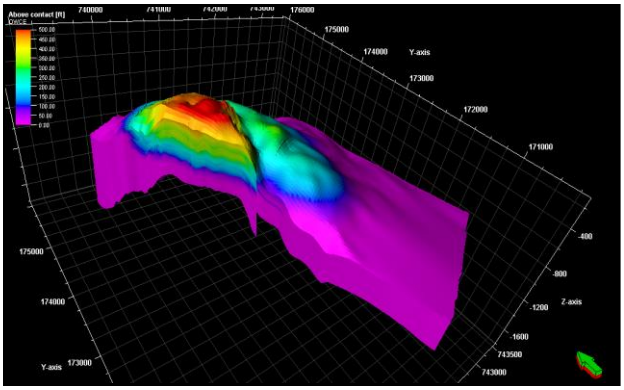

Fig. 7 Fluid contact map in the Dalimo Field

The required geological data to calculate OOIP with volumetric method are porosity (PHIE), Net to Gross (NTG), water saturation (Sw) and fluid contact data (OWC), and fluid property which is intial oil formation volume factor (Boi). The OOIP calculation was performed for each zones per segments. Sand 9, Sand 10 and Sand 11 in the Segment 1 were identified as water zone due to absent of oil water contact in these zones. The total OOIP for Segment 1 is about 77.66 MMSTB and Segment 2 is about 75.64 MMSTB, thus, the total of OOIP in the field is about 153.30 MMSTB. Based on the percentage of OOIP distribution in the Dalimo Field, it can be identified that there are five reservoir zones or sands which have OOIP more than 8 MMSTB (≥ 8% of total OOIP). These are Sand 1, Sand 2, Sand 3, Sand 4 and Sand 6 (**Fig. 8**).

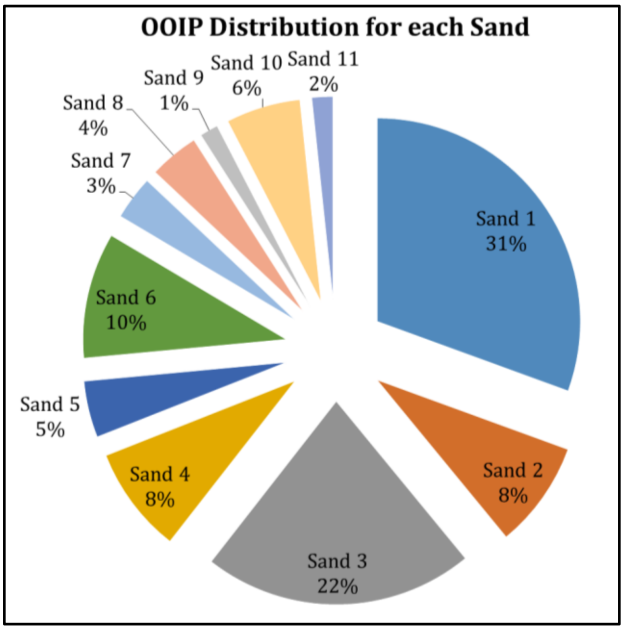

Fig. 8 Percentage of OOIP distribution for each sand in the Dalimo Field

3.2 Material Balance Analysis

Dalimo Field is multilayer reservoir consisting of 11 reservoir zones. In addition, related to the results of compartment analysis from major fault interpretation, the reservoir zones in the field was divided into two (2) segments. In this case there will be inter-reservoir allocation factor issue due to the field being produced from multilayers sand (commingle production). Construction of reservoir tank modes in the Dalimo Field needs original oil inplace (OOIP) data from the results of geological modeling, fluid properties (PVT data), routine core analysis (RCAL) and special core analysis (SCAL) data, production and reservoir pressure data.

According to production data history (**Fig. 9**), Dalimo Field began production on 01/31/1976 till 08/31/2014, with cummulative oil production of about 17.54 MMSTB with Water Cut of 88.25%. Total wells in Dalimo Field is 81 wells of which 62 are active wells and 19 are non-active wells, production comes from 11 productive sands.

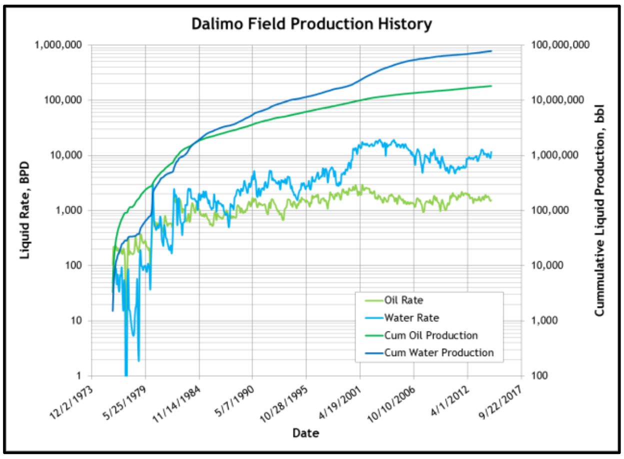

Fig. 9 Dalimo Field's Production rate and cummulative

The production allocation is highly needed to allocate the production performance for each reservoir zones. The permeability – thickness (kh) method was applied to allocate the production data for each reservoir zone. The allocation of production data was performed based on completion history data as the wells produced of hydrocarbon from certain productive sands per time step. **Fig. 10** shows an example of production allocation in Dalimo-5 well. According to the production history data, Dalimo-5 well has been producing from nine (9) productive sands. These are Sand 1, Sand 3, Sand 4, Sand 5, Sand 6, Sand 7, Sand 8, Sand 9 and Sand 10. Then, production data was allocated for each productive sands based on the completion history by using the kh method. The production allocation for each productive sands was obtained by multiplying the oil production rate with permeability-thickness from each productive sands which are produced per time step.

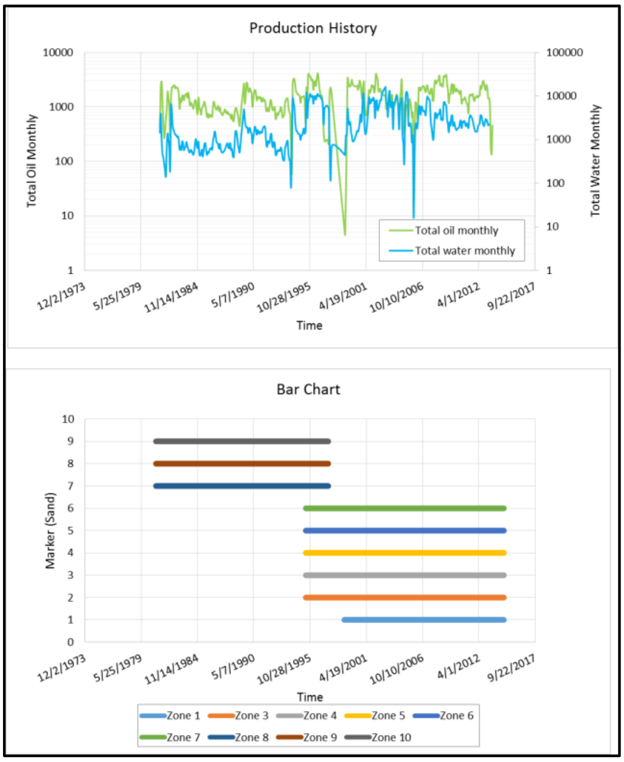

Fig. 10 Production allocation for each productive sands in Dalimo-5 well based on completion history

Having performed the production allocation for all of the wells in the Dalimo Field, then the cummulative oil production was calculated for each productive sands per segments. From the resuts, the current cummulative oil production obtained is 17.54 MMSTB, thus, giving the oil recovery factor (RF) of about 11.44%. Based on the percentage of cummulative oil production for each productive sands in the Dalimo Field (**Fig. 11**), it can be identified that there are five major oil sands which are Sand 1, Sand 2, Sand 3, Sand 4, and Sand 6. These sands have produced oil with cummulative oil production of around 1.48 – 5.70 MMSTB with the oil recovery factor of around 10.51% - 15.92%. Sand 1 has the largest cummulative oil production with total from Segment 1 and Segment 2 of about 5.70 MMSTB with recovery factor of about 12.17%. It represents 33% from total of cummulative oil production in the Dalimo Field. On the other hand, Sand 11 has the lowest cummulative oil production which comes from Segment 2 of about 0.01 MMSTB with represents 0.08% from total of cummulative oil production in the Dalimo Field.

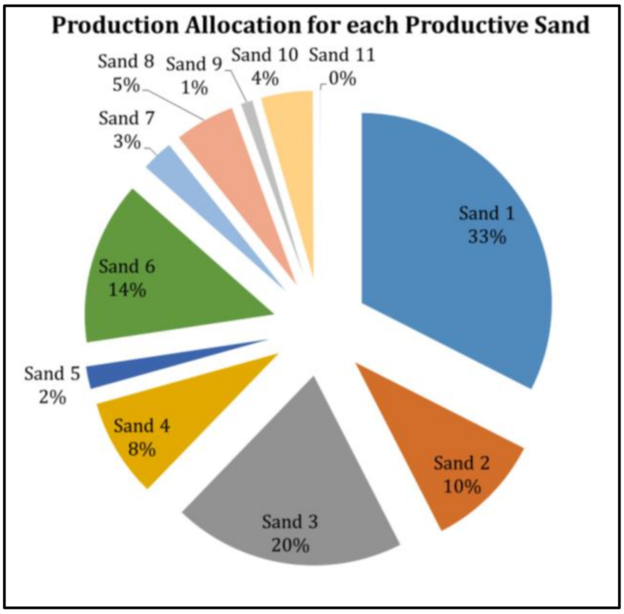

Fig. 11 The percentage of production allocation for each productive sand in the Dalimo Field

On pressure data, there are only a very limited data recorded in this field. The field has reservoir pressure data from Repeat Formation Test (RFT). All of the pressure data from all of the wells for each productive sands were constructed at the same datum, then plotted versus time. To determine the initial reservoir pressure (Pi) for each reservoir layers, it was taken from Dalimo Reservoir Pressure measurement at the same datum depth with RFT Pressure Data for each productive sands.

According to fluid properties (PVT) data in the Dalimo Field, the field has oil gravity of about 16.5 – 22 ^{o}API. This number indicate that the oil type belongs to heavy oil due to the low oil gravity value. The oil viscosity value also indicates that high oil viscosity of more than 87 centipoise (cp). The available PVT data includes Oil gravity (γ_o), Gas gravity (γ_g), Oil viscosity (μ_o), Reservoir temperature (T_R), Formation Gas-Oil ratio (GOR), Initial Oil Formation Volume Factor (Boi), and gas compositions.

In order to initialize the reservoir simulation with material balance (MBAL) method, we generated the series of oil relative permeability (Kro) and water relative permeability (Krw) based on the core samples data from some of the wells in the Dalimo Field. For sand which has only one sample of relative permeability data, it was plotted directly on the graph of oil-water relative permeability versus water saturation (Kro & Krw vs Sw). While for the sand which has more than one of sample number of core data, normalisation process was performed in order to obtain a representative oil-water relative permeability curve. **Fig. 12** shows an example of core samples in the Sand 3 which has five core samples data. In order to obtain the representative relative permeability data, the normalisation process was performed. **Fig. 13** shows the result of normalisation process of the relative permeability data in Sand 3. From the result, it is obtain the initial water saturation (Swi) of 0.15 and residual oil saturation (Sor) of 0.36, and water relative permeability at residual oil saturation (Krw@Sor) of 0.09 while oil relative permeability at initial water saturation (Kro@Swi) of 0.37.

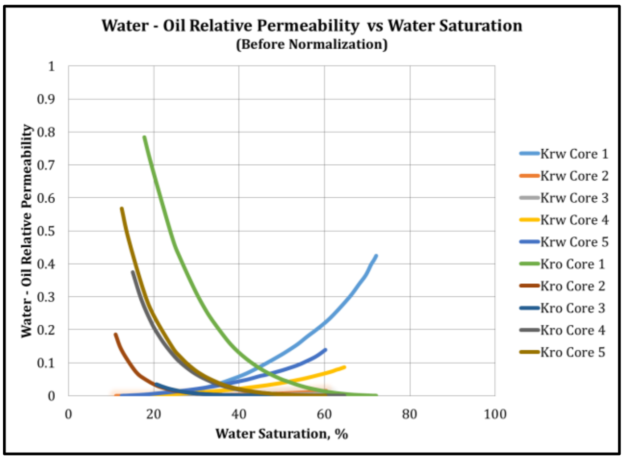

Fig. 12 Oil-Water relative permeability (Kro & Krw) data (before normalization) in Sand 3

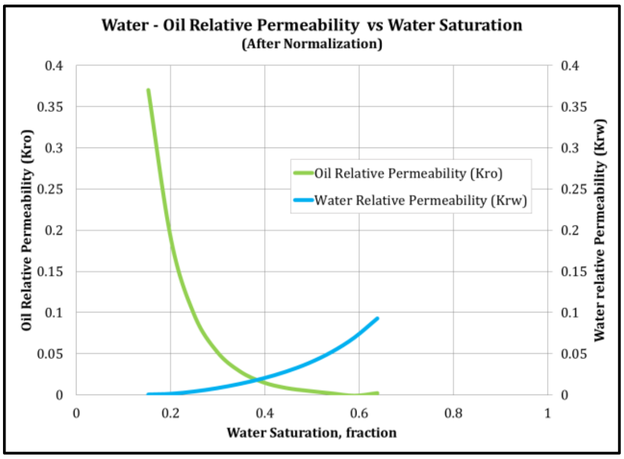

Fig. 13 Oil-Water relative permeability (Kro & Krw) after normalization process in Sand 3

Identification of original oil inplace (OOIP) and reservoir drive mechanism used Campbell Plot method (F/Et vs F). To identify the aquifer influx, analytical method was performed, which is the cross-plot between reservoir tank pressure versus calculated oil production from tank model and actual data. From all of productive sands per segments which were analyzed, the results show that the reservoir tank models have not been validated yet due to the results of cross-plot not matched. Thus, it is required to model the aquifer in Dalimo Field in order to obtain a valid tank model which matches to the actual reservoir condition.

The Hurst-Van Everdingen Modified was used to modeling the aquifer with radial system model. This method was applied as it is more accurate compared to other methods, such as Fetkovich, Carter-Tracy, Schiltuis, Wogt-Wang, etc. From the results of aquifer modeling, it was obtained that the reservoir tank models matched with actual data. **Fig. 14** shows an example of reservoir tank model validation with aquifer influx in Sand 2, Segment 1. Identification of reservoir drive mechanism was performed by the Energy Plot to see the drive index value. From all of sands per segments which were analyzed, the results show that the reservoir drive mechanism is Water Drive. **Fig. 15** shows an example of the result of Energy Plot in Sand 2, segment 1. The result shows that drive mechanism is dominated by Water Drive, it could be seen clearly that effect of the water influx from the initial production.

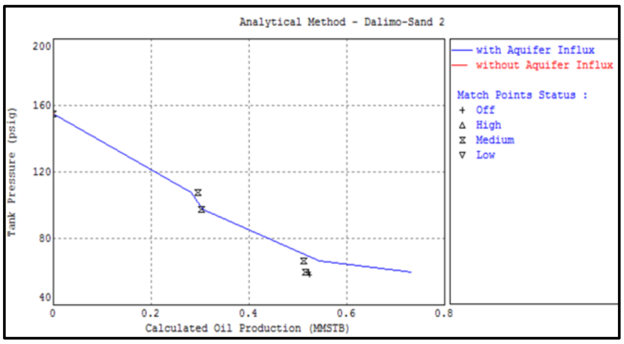

Fig. 14 Analytical method in Sand 2, Segment 1

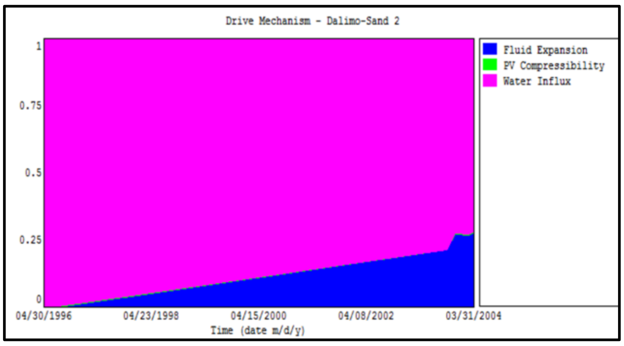

Fig. 15 Energy plot in Sand 2, Segment 1

History matching analysis was performed to match reservoir performance of the tank model with actual reservoir performance. **Fig. 16** shows an example of history matching in Sand 2 - Segment 1, the main parameters to be matched are reservoir pressure and production data. Reservoir pressure and cummulative fluid production were obtained from simulation matched to actual reservoir pressure and production data. Thus, the reservoir models have represented the actual reservoir condition. Cumulative fluid production from this field is very large, while the observed pressure depletion is relatively low. This would also indicate that the reservoir has a strong water drive mechanism. History matching analysis was conducted in all of productive sands per segments in the Dalimo Field, thus the results of material balance analysis will be valid and match to actual reservoir condition.

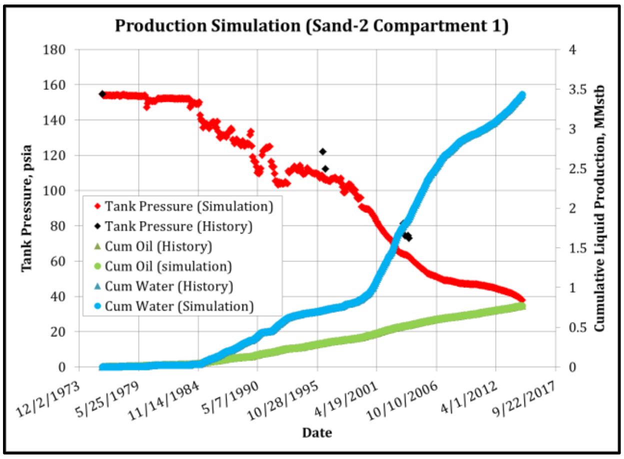

Fig. 16 History matching in Sand 2, Segment 1

From the results of material balance analysis in all of productive sands in Dalimo Field, total original oil inplace is 151.69 MMSTB with cummulative oil production of 17.59 MMSTB. This result did not include Sand 8 – Segment 1 as this sand does not have pressure data.

The result of material balance analysis was then compared to original oil inplace (OOIP) from volumetric result and cummulative oil production (Np) from production allocation. **Fig. 17** shows a comparison of OOIP from material balance and volumetric results. The differences of material balance and volumetric methods for all of sands in the Dalimo Field are less than 5%, that is about 0% - 1.88%. For comparison of cummulative oil production, the differences of material balance and actual production data from production allocation also are less than 5%, of about 0% - 2.34% (**Fig. 18**). These results indicate that the reservoir tank models in all of productive sands in the Dalimo Field matched the actual reservoir condition. The result of material balance analysis is valid and it will be used then for estimating the recovery efficiency (RE) in order to calculate the remaining reserve (RR) in the Dalimo Field.

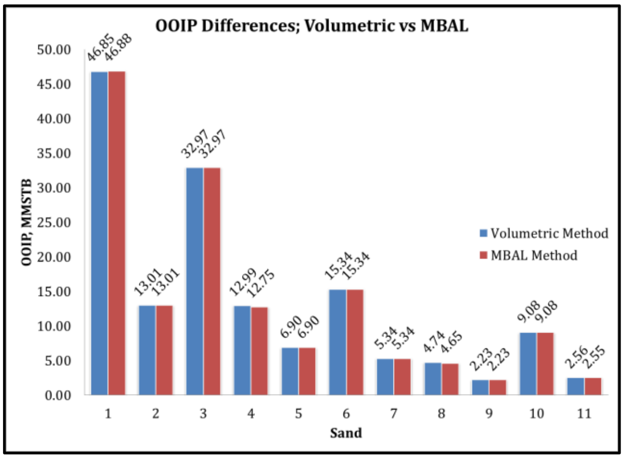

Fig. 17 A comparison of OOIP differences from Volumetric and MBAL calculations

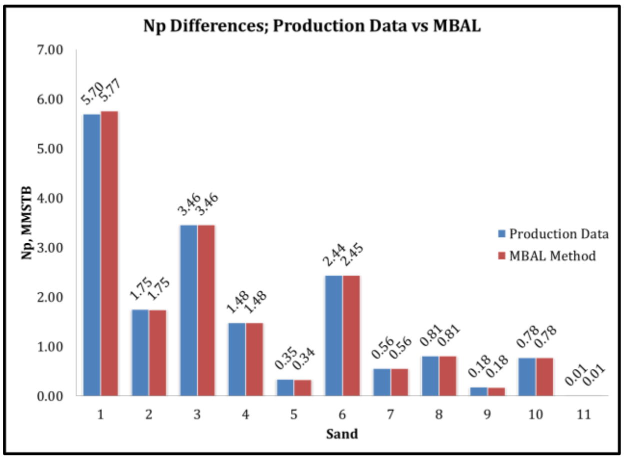

Fig. 18 A comparison of Np differences from Actual Production data and MBAL method

3.3. Reserve Estimation

Recovery efficiency (RE) was estimated by using Arps et al. method for water drive reservoir in order to estimate remaining reserves for each reservoir layers in the Dalimo Field. The total recovery efficiency obtained is about 19.95%, with ultimate estimated ultimate recovery (EUR) of about 30.33 MMSTB. **Fig. 19** shows the remaining reserve for each productive sands per segments in the Dalimo Field. The total remaning reserve in Dalimo Field of about 12.79 MMSTB, with recovery effiency of 19.95%. Sand 3 – Segment 1 has the larger remaning reserve is about 3.37 MMSTB. Total remaning reserve in Sand 3 is about 3.83 MMSTB, with 30% of total remaning reserve in the Dalimo Field. **Fig. 20** shows the percentage of remaining reserve distribution for each productive sands in the Dalimo Field. It will help in further development strategy in oder to maximize the oil recovery factor in the Dalimo Field. Steam flooding as tertiary recovery is recommended to be applied in this field due to the heavy oil type.

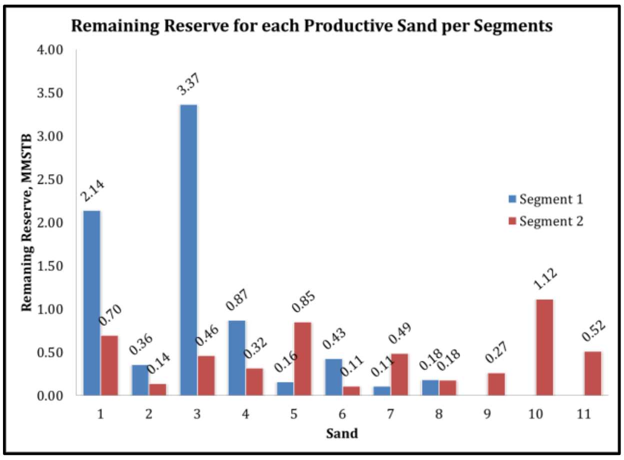

Fig. 19 Remaining reserve for each productive sand per segments in the Dalimo Field

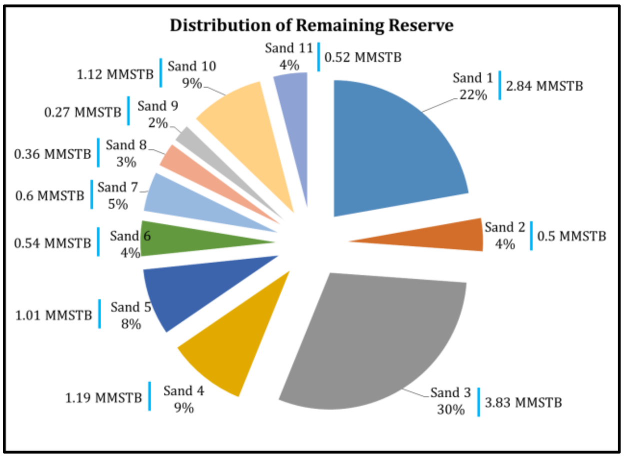

Fig. 20 Distribution of the remaining reserve for each productive sand in the Dalimo Field

4 Conclusion

From this study, the following sumarizes the major conclusions:

- Compartment analysis based on the interpretation of major fault orientation is important to be performed as the justification to produce the reservoir tank models for Material Balance analysis.
- Based on the volumetric calculation fom geological modeling, the total original oil inplace (OOIP) in the Dalimo Field is about 153.30 MMSTB.
- Based on the allocation of cummulative oil production (Np) for each productive sands in the Dalimo Field, it can be identified that there are five major oil sands which are Sand 1, Sand 2, Sand 3, Sand 4, and Sand 6.
- From the result of material balance analysis, the reservoir drive mechanism in the Dalimo Field is Water Drive mechanism.
- According to the recovery efficiency (RE) calculation with J.J. Arps et. al. method, the total remaining reserve in the Dalimo Field is about 12.79 MMSTB (RE = 19.95%).

5 Acronyms and Nomenclature

OOIP	Original Oil Inplace, MMSTB
Np	Cumulative Oil Production, MMSTB
qo	Oil Production Rate, BOPD
qw	Water Production Rate, BWPD
WC	Water Cut, %
RF	Recovery Factor, %
RE	Recovery Efficiency, %
Pi	Initial reservoir pressure, psi
Ti	Initial reservoir temperature, °F
Bo	Oil Formation Vol Factor, bbl/STB
Rs	Gas Solubility, SCF/ STB
μo	Oil viscosity, cp
GOR	Gas-Oil Ratio
SG	Specific Gravity
RCAL	Routine core analysis
SCAL	Special Core analysis
Kro	Oil Relative Permeability
Krw	Water Relative Permeability
Sw	Water Saturation, fraction
Swi	Initial water saturation, fraction
Sor	Residual oil saturation, fraction
k	Permeability, mD
h	Thickness, ft
EUR	Estimated Ultimate Recovery, MMSTB
RR	Remaining Reserve, MMSTB

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