

THREE DIMENSIONAL NUMERICAL MODELING OF MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

The three-dimensional numerical model of Mindanao Geothermal Production Field developed to predict reservoir conditions under different exploitation schemes. The numerical model, consisting of 16,411 active blocks was calibrated using TOUGH2 against pre-exploitation state of the reservoir and 13 years production history of the field. Natural state modeling gave good matches to the measured temperatures and pressures, and showed good agreement with the major flow features of the conceptual model. Production history matching was also able to match the field discharge trend. The numerical model also reproduced observed physical properties, such as minor effects of injected fluids and expansion of two-phase region. With the current extraction strategy of the field and planned development of additional 50MWe generation, forecasting runs were also conducted to investigate the viability of the project.

INTRODUCTION

The Mindanao Geothermal Production Field (MGPF) lies within the watchful eye of Mt. Apo, the Philippines' highest peak at 2,954 mASL. It is located in the south-eastern part of the island of Mindanao, Philippines. Mt. Apo is one of the several Quaternary volcanoes that cap Mindanao's north-south trending Central Cordillera. It rises from the surrounding plain at 300-m elevation and coalesces with two adjoining volcanoes (Mt. Talomo and Mt. Sibulan) to form one contiguous volcanic complex of more than 700 square meters in area.

The geothermal field is geographically divided into three sectors from the northwest to southeast namely, Matingao-Kullay, Marbel and Sandawa (Figure 1). There are already 31 wells drilled in the field, 21 production and 10 wells for brine injection.

Power generation in MGPF was developed in two stages. The first stage, the Mindanao 1 (M1GP), was

commissioned last March 1997. The ten production wells of M1GP are situated in the Marbel Corridor and are supplying steam to a 52MWe power plant. The second stage development commenced with the commissioning of the second 52MWe double-flash turbine unit, the Mindanao 2 (M2GP) which started its commercial operation in June 1999. The steam supplied to this plant comes from nine production wells in the Sandawa sector, two wells in Marbel Corridor, and steam from the secondary flash of brine from M1GP wells. Of the ten injection wells in the area, 2 infield injection wells situated in Sandawa sector are dedicated for M2 brine injection. The eight other injection wells are located in Matingao-Kullay area where six wells are used for Mindanao 1 hot brine injection and two wells are for cold condensate injection. Shown also in Figure 1 is the location of the wells.

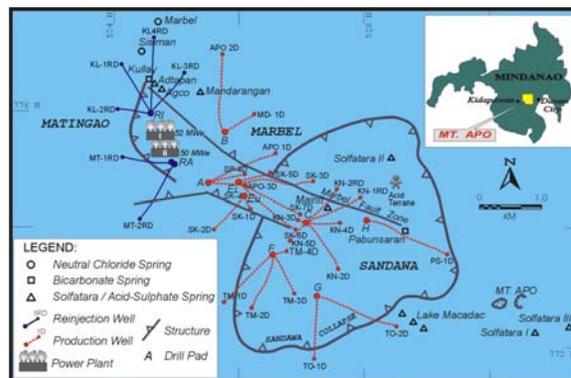


Figure 1: Location map of the showing the well tracks and major geological faults in the area.

There are two numerical simulation studies previously conducted in MGPF (Esberto 1995,2002). The first simulation was a 2D numerical model made using the simulator MULKOM and was completed in October 1995. The second study used a three dimensional model consisting of 1,122 blocks. It was completed in 2002 and employed TETRAD. Though both numerical models gave a reasonable match to actual field conditions, they were not able to clearly

define the injection effects to some production wells and did not include additional areas for expansion.

This study aims to provide an updated model of the Mindanao Geothermal Production Field that would best forecast its behavior in response to commercial exploitation. The study employed a larger three dimensional numerical model of MGPF and calibrated the 13 years exploitation data of the field using TOUGH2. The modeling process consisted of: 1) natural state modeling and simulation; 2) production history matching; and 3) forecasting run.

FIELD OVERVIEW

Below are brief description of the reservoir condition and characteristic of the Mindanao Geothermal Production Field (Mt. Apo geothermal resource). Reservoir characteristics of MGPF prior to the commissioning of the two plants in 1997 and 1999, respectively and assessment of the field after several years of commercial production is also briefly discussed. These are then used as basis in defining the model for the numerical simulation of the field.

Geology and Stratigraphy

Marbel, Matingao and Sandawa sectors are of almost the same stratigraphy. The upper sequence of the Older Apo Volcanic (oAVu) composed of hornblende andesite, dacite and pyroxene basaltic andesite lavas, tuff breccias and minor hyaloclastites make up the top unit of the area's stratigraphy. Beneath oAVu is the sequence consisting of basaltic andesite, grading to basalt and minor pyroxene andesite lavas, tuff breccias and hyaloclastites. This sequence is called oAVI or Lower sequence of Older Apo Volcanics. A lithologic break of hematized claystone layer marks the boundary between the oAVu and oAVI. This paleosol horizon somewhat thins out going towards the Sandawa vicinity. Contact Metamorphic Zone, which forms an aureole around the Sandawa Intrusive beneath the Sandawa Collapse, is conspicuously absent in the Matingao sector. Figure 2 is the illustration of the subsurface stratigraphy of the Mt Apo field looking north north east.

Temperature and Pressure

Contours of field temperature at different elevations (Figures 3 to 4) show similar distributions where temperatures are highest at the Sandawa sector and decrease towards the Marbel Corridor and Matingao Block. This area is the inferred upflow sector of the resource. Relatively lower temperatures were observed at the Kullay and Matingao injection wells which indicate outflow conditions towards lower elevation, and entry of cooler fluids at depth.

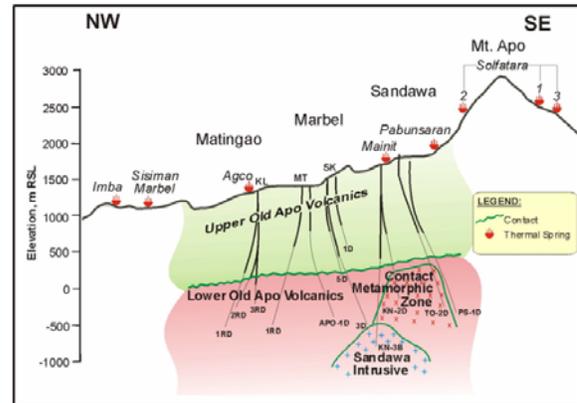


Figure 2: MGPF Sub-surface Stratigraphy along section looking NNE (after PNOC-EDC 1994).

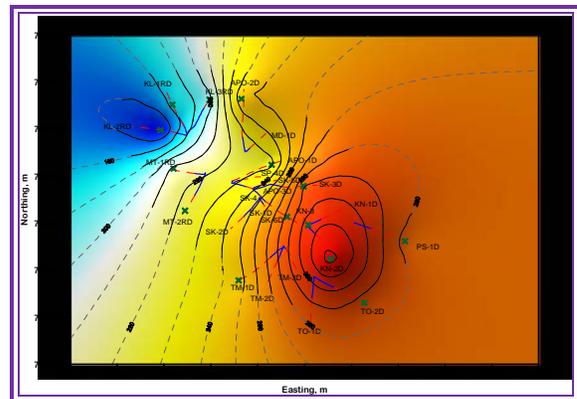


Figure 3: Isotherms at -200 mRSL (from PNOC-EDC, 1994; 2004).

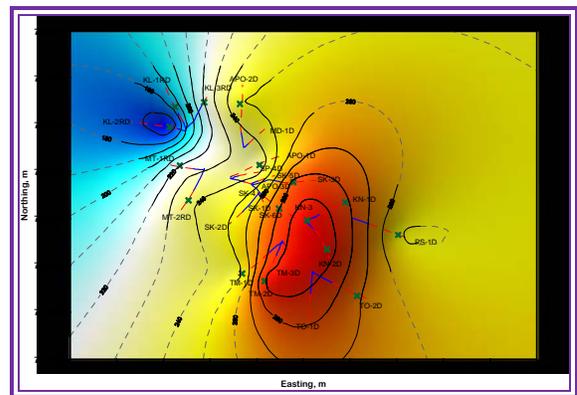


Figure 4: Isotherms at +390 mRSL (from PNOC-EDC, 1994; 2004).

Cross-section map of the temperature distribution from southeast to northwest (Figure 5) indicates also a lowering of temperatures towards the shallow depths from Sandawa collapse to the Matingao block.

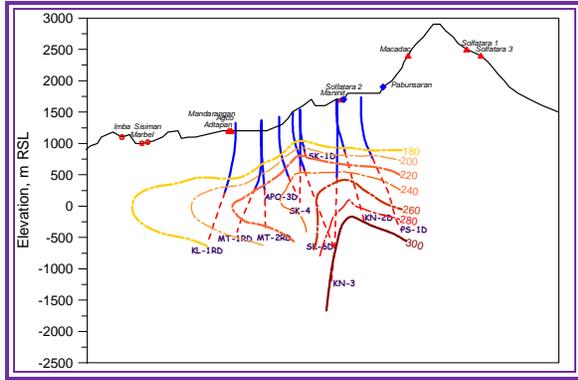


Figure 5: Cross-section map of the field showing temperature distribution from southeast to northwest (from PNOC-EDC, 1996)

Pressure contours across the field as shown in Figure 6 follow similar trends to that of the temperatures where the highest pressures are observed at the inferred upflow area within the Sandawa Collapse. Decreasing reservoir pressures are observed towards the injection sector (Matingao - Kullay Block).

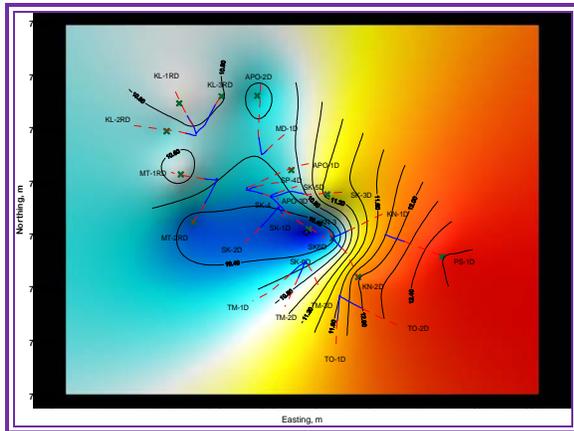


Figure 6: Pressure distribution across the MGPF showing similar trends with temperatures (from PNOC-EDC, 1994; 2004)

Permeability

Contours of permeability (Figure 7) based on the injectivity indices and transmissivity values obtained from well completion data shows relatively high permeability within the production area particularly at Mindanao 1, as indicated by the high injectivity indices i.e. up to 312 l/s-MPa in APO-1D. Only in the area of well KN-4D where a very low injectivity index (2.3 l/s-MPa) and positive wellhead pressures were monitored during the injectivity test.

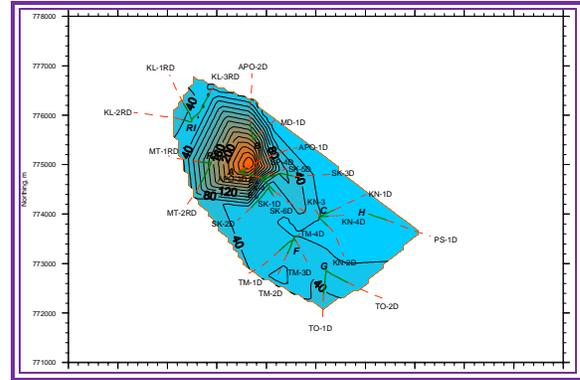


Figure 7: Injectivity index distribution (based on completion test data) across the field (after Sta. Ana et al., 2004)

Hydrological Flow Model

PNOC-EDC (1994) reported that the inferred upflow zone lies to the west of Mt. Apo beneath the Sandawa Collapse. This hot upflow with a temperature higher than 300 °C is diverted horizontally towards the northwest of the field. The likely outflow path of the fluid is through the numerous NW-SW trending faults across the field. The outflow then moves towards the north upon encountering an impermeable sector in the cold Matingao Block. The fluid outflow reaches the surface through the springs of Imba, Marbel and Sisiman. This flow regime is characterized by the temperature reversal at depth observed in the wells drilled in the area.

In the natural state, there also exists a steam zone at shallow levels beneath the Sandawa Collapse that extends above the outflow fluid in the Marbel Corridor. This two-phase zone covers most of the production sectors of Mt. Apo. Figure 8 shows the conceptual flow model of the field indicating the two-phase region at the production sector and the cold shallow region in the injection sector.

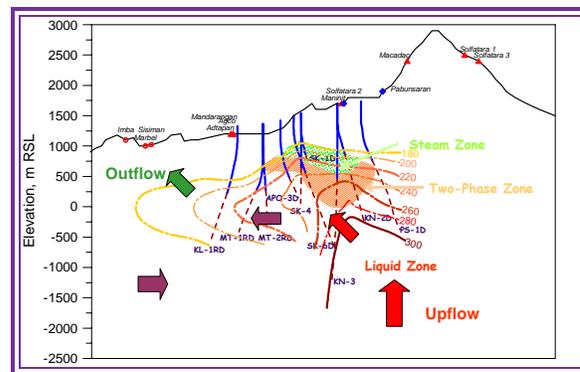


Figure 8: MGPF Hydrological flow model (after PNOC-EDC, 1996)

Reservoir Performance

Commercial production from Mindanao Geothermal Reservoir commenced after the commissioning of the M1GP Fluid Collection and Disposal System (FCDS) in October, 1996.

During the early stages of operation of the field, production is concentrated from the steam cap and the two-phase zones of the reservoir. The average enthalpy indicated an increasing trend during the first year of exploitation. With production coming from the shallow steam cap and two-phase zone, the available steam is more than enough to meet the plant requirements. Reservoir pressure drawdown was very minimal, with a drop of 0.50 MPa relative to the baseline value.

Injected fluids returning to the M1GP production sector was already recognized as a potential operational problem of the field even before the start of exploitation. Such a concern was raised because of: (1) the close proximity of injection sink to the production sector and (2) the presence of structural and lithologic flow paths connecting the two sectors.

By the second year of commercial exploitation in March 1998, the production field experienced a reduction in steam availability from the production wells because of two contributing factors: (a) calcite formation in some of production wells and (b) declining enthalpy. Initial field enthalpy of M1GPF ranging from 1250-1300 kJ/kg later declined to 1150-1200 kJ/kg. The decline in enthalpy is attributed to the injected fluid encroaching in the production area.

MGPF 3D NUMERICAL MODELING

The objectives of the three-dimensional modeling are to match the subsurface temperatures and to reproduce all the significant features of the conceptual model. That is to create a model calibrated by matching the thirteen-year production history of MGPF that would best represent the field for production forecasting.

The numerical simulation model of the Mt. Apo field considered a total area of 572 km² (22 km by 26 km) encompassing the 701 hectares geothermal reservation (Figure 9). It vertically extends from an average topographic surface of +1250 mRSL (reduced sea level) to -2000 mRSL. The model was oriented in the NW-SE direction, roughly parallel to the Marbel Fault Zone. It was divided into 31 by 47 blocks and 19 layers giving a total of 27,683 blocks of which 16,411 are active elements in the model. Larger grid blocks cover the areas outside the production sector.

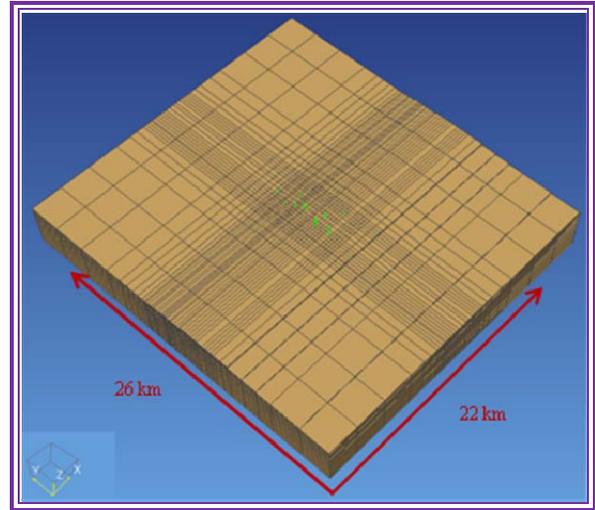


Figure 9: 3D grid block system used in the MGPF modeling

The top of the model is a constant pressure boundary that represents atmospheric pressure and is set at a constant temperature of 65 °C and pressure of 0.1 MPa. The sides of the model are closed boundaries with respect to heat and mass, with the exception of constant pressure sinks near Kullay area to represent subsurface discharge out of the system.

The initial permeability distribution was based on the previous MGPF simulation studies. The initial horizontal and vertical permeabilities assigned, ranged from 0.50 millidarcies to 75 millidarcies. The rock porosity was considered to be a function of permeability, based on the assumption that the rock matrix has very low porosity.

Numerical model was developed using a commercial pre and post processor linked to TOUGH2. The model was calibrated in two stages, first by matching the natural state of the reservoir and second by matching the production history of the field.

Natural State Modeling

Initial model calibration was conducted by matching the natural state of the field. The model was run up to 9.5×10^7 years of simulated time to be able to reach a pseudo steady state. Adjustments were made to the heat and mass flux and the thermodynamic conditions of the boundary blocks. Simulation results suggest that the upflowing source fluid has a rate of 145 kg/s at a temperature of 320 °C. The permeability distribution in the model was constantly adjusted until the calculated temperatures reasonably matched the measured temperatures.

Figure 10 is the vertical slice of the temperature of the model looking Northeast along Sandawa to Matingao block. The generated model matches the major of feature of the conceptual model of the field.

These are the upflowing fluids beneath the Sandawa Collapse and fluid outflowing along the Marbel Corridor. The temperature inversion or the cold barrier in the injection sector (Matingao) is likewise duplicated.

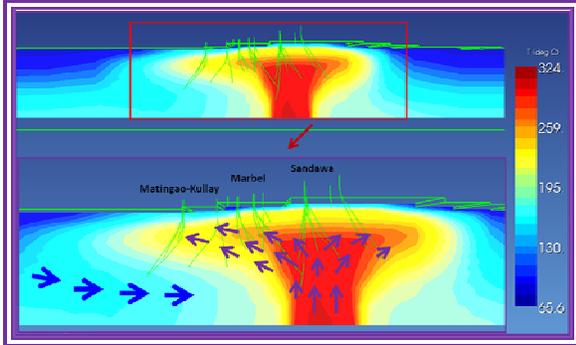


Figure 10: Vertical slice of temperature of the model along Sandawa to Matingao Sector

Figure 11 compares the calculated and measured temperature contours of the field. Result shows generally good matches to the actual data measured.

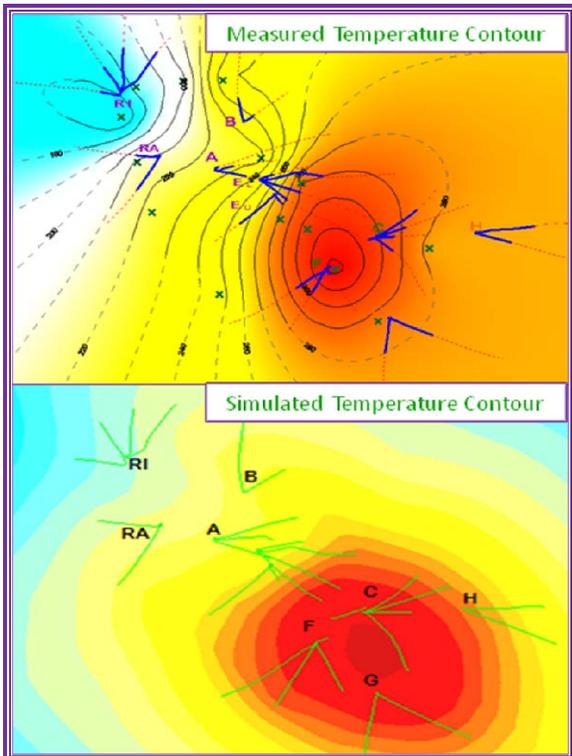


Figure 11: Simulated and measured temperature contour of MGPF

Production History Matching

The resulting initial state model was further calibrated by matching the discharge histories of the nineteen production wells in the field. The permeability structures and porosity were also further

adjusted. The numerical model results were compared with the actual production enthalpy.

After several adjustments made on the model, a reasonable match to the measured data was achieved. The rock porosities used in the final model range from 7 to 10 %.

As shown in Figure 12, the model result shows close agreement with the measured enthalpy on wells. The model also shows the effects of the injection to some of the MGPF production wells. This is illustrated in Figure 13. Figure 14 also illustrates the expansion of the two-phase region of the field.

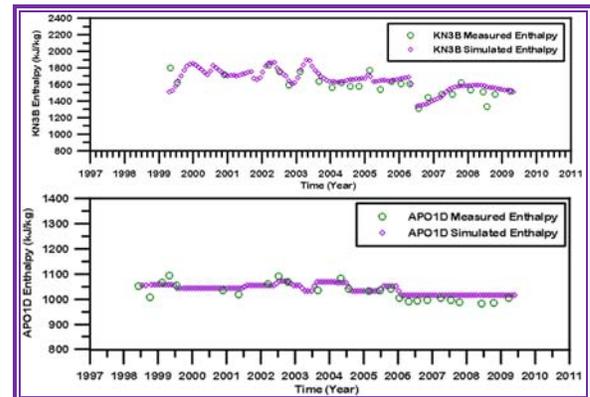


Figure 12: Simulated and measured enthalpy trend of wells KN3B and APO1D

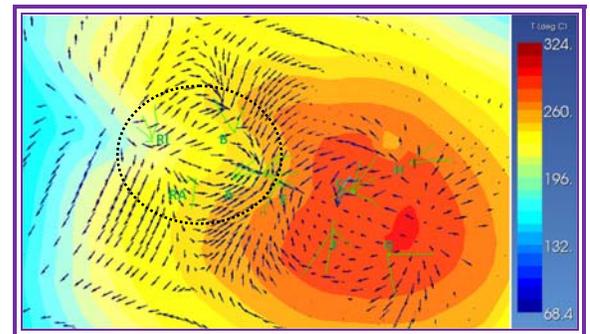


Figure 13: Simulation result showing effects of the injected fluid

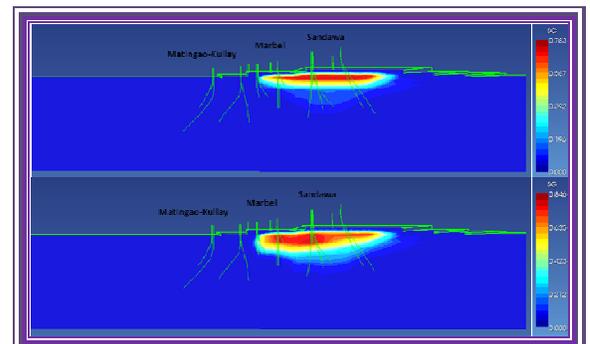


Figure 14: Simulated expansion of the two-phase region of the field.

Forecasting Run

With the planned Mindanao expansion, the calibrated model was used to determine reservoir response and viability of the project. Forecast was initially made using fixed massflow for each well rather than the rates dictated by productivity indices. Although the productivity indices of each well can be easily obtained by calibrating against the wellbore flow at certain period, a fixed mass flow is still a realistic estimate since the massflow of MGPF wells for 13 years extraction were relatively stable. In addition, forecast period of five (5) years will be conducted to evaluate the transient response of the reservoir thus the effect of pressure drawdown on the field should be minimal. The five (5) years forecast period was based on the duration similar to the evaluation of transient effect of commissioning M2GP on M1GP. For longer forecast, individual productivity index will be identified and used.

There are two initial short term prediction runs conducted: a) additional 50MWe generated from the southeast portion of the reservoir and b) extracting additional 50MWe from the southeast portion of the field and transfer of brine load (~150 kg/s) further north of the current injection sink.

Initial forecast result shows that with the existing extraction-injection scheme, additional 50MWe production has no significant effect on the performance of M1 and M2 production wells. Approximately ~1.5 MPa drawdown from the baseline pressure or an additional 0.3 MPa drawdown is predicted. This pressure drawdown is still very minimal given that the projected pressure drop of the field without the 50 MWe project is of similar range. Figure 15 is the plot of simulated and measured pressure trend of the field.

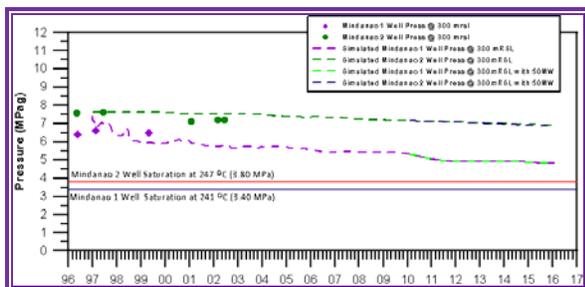


Figure 15: Measured and simulated pressure trend of representative wells showing the effect of the 50MW expansion project.

Scenario B initial forecast result shows that after 5 years from commissioning of the expansion project, there is no significant cooling of the reservoir temperature observed. Result however shows slower decline of field temperature as illustrated in Figure 16. Forecasted pressure drawdown is ~1.7 to 2.0

MPa from baseline. Pressure trend of the field with the additional 50 MWe generation and brine transfer is shown in Figure 17.

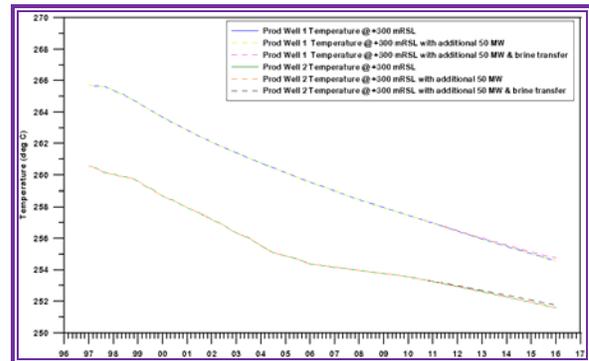


Figure 16: Simulated temperature trend of representative wells nearest the injection sink

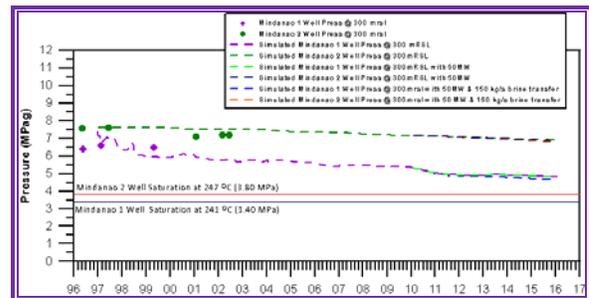


Figure 17: Measured and simulated pressure trend of representative MGPF wells showing the effect of the 50MWe expansion project and brine transfer.

CONCLUSION

- The numerical model closely adheres to all aspects of the conceptual model. The model also matched the measured steady state wellbore pressure and temperature data.
- Calibration of the numerical model based on the production history of the field produced reasonable matches with the discharge enthalpy of the wells. The simulated pressure trend of the field also matched the measured data. The model also simulated the effects of injection to some production wells.
- Initial forecast run shows that 50MWe field expansion proved to be viable as there has been no predicted significant effect (pressure drawdown) on the reservoir.

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