PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

NUMERICAL SIMULATION FOR DEVELOPMENT SCENARIOS OF NW-SABALAN GEOTHERMAL RESERVOIR, IRAN

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ABSTRACT

A numerical model of the NW-Sabalan geothermal field was developed. The model covers a total area of 96 km^2 and extends vertically from variable elevation of 2200-3600m a.s.l to 1,000m b.s.l. The model has 2,595 grid blocks in l4 horizontal layers. The boundary conditions and distributions of horizontal and vertical permeabilities were obtained by trial-and-error matching of the initial temperature and pressure distributions in the wells. Other hydraulic and thermal properties were obtained from exploration drilling and well testing. Observed and calculated temperature profiles and pressure were well-matched, confirming the validity of the conceptual model and providing the first stage of calibration of the numerical model. This effort yielded reliable estimates of the locations and rates of fluid recharge and discharge in the initial state. Performance prediction was made for required steam for 20MWe for three different reinjection scenarios. Assumed that the productivity of new wells to be drilled lies between that observed in Wells NWS1 and NWS4. The results show that the reinjection is required and the area of reinjection is preferable to be located in injection area B than area C. The field can sustain a power generation of 20MWe with six production and four reinjection wells. One make-up well is needed to be drilled of 5 years after operation start in full reinjection scenarios. Two make-up wells for no-reinjection scenario in years 2 and 5 are needed to maintain the required steam for 20 MWe.

INTRODUCTION

The NW-Sabalan geothermal project is located in the northwestern flank of the Sabalan trachyandesitic stratovolcano, in the province of Ardebil in the northwest of Iran where significant amount of geo-scientific studies have been performed by Iran Ministry of Energy since 1975. The project area is within the Moil Valley that is the dominant topographic feature and a major structural zone on the northwest slope of Mt. Sabalan.

Several warm and hot springs of neutral Cl-SO_4, acid Cl-SO_4 and acid SO_4 types are discharging in the valley. The isotopic composition of the spring waters and their seasonal variation in flow rates with little change in temperature or chemistry suggested that a large regional ground water aquifer overlies the potential geothermal reservoir.

An MT survey implied a presence of a large low resistivity zone (70 km^2) in the project area (Bromley et al. 2000). A low resistivity zone (<4Ωm) associated with the thermal features was initially selected for target area for exploratory drilling. Therefore, in order to identify the deep reservoir, a drilling program was adopted.

This simulation studies with the objective of natural state simulation and production performance of the resource was undertaken for the primary purpose of predicting and assessing the response of the reservoir to the planned developments by implementing TOUGH2 computer codes with EOS 1 (Pruess, et. al., 1999).

The work carried out for the numerical modeling has includes the following:

- Construction of conceptual model of the field
- Construction of grid blocks and assigning the rock types to the model
- Definition of initial and boundary conditions, based upon the conceptual model and measured data
- Validation of the model by matching available downhole temperature and pressure data from the existing wells with the simulated results. This requires running the models to steady state and comparing the simulated data with the known or interpreted conditions in the system. This is an iterative process that continues until a good match is obtained and requires changing model properties, such as permeability, rock density, specific heat capacity and inflow/outflow conditions.
- Predicting the reservoir response to the planned production and reinjection scenarios.

EXPLORATION DRILLING

Three exploration wells were drilled in the study area based on the result of geological, geochemical and geophysical studies. Table 1 shows the specifications of the exploration wells.

Table 1 Specification of three exploration wells

Well		NWS1	NWS3	NWS4
Elevation (m a.s.l)		2630	2277	2487
Well depth (m)		3197	3177	2266
Casing dep.(m)	Conductor 30"	27	24	26
	Surface 20"	110	113	105
	Anchor 13-3/8"	380	357	541
	Produc.ion 9-5/8"	1587	1599	1195
	Liner 7"	3197	3170	2265
Well permeable zones (m a.s.l)		1800-1400	No permeable zone	1050 - 900
		200 - 0		880-890
		-200- -350		
Maximum T (°C)		240	148	229

CONCEPTUAL MODEL

Before a simulation model of the given geothermal field can be setup, a conceptual model must be developed. A good understanding of the important aspects of the system leads to develop a conceptual model. The model is usually represented by two or three sketches showing a plan view and vertical sections of the geothermal system. Setting up a conceptual model requires the synthesis of information from a multi-disciplinary team composed of geologists, geophysicists, geochemists, reservoir engineers and project managers. Conceptual model of the study area along AB cross section in Figure 1 from north to south was developed. Three exploration wells were interpolated to the AB line and the intersection of the faults and cross section was defined as location of the faults in the model. The faults were assumed to be vertical or sub-vertical (Sinclair Knight Merz, 1998).

In central part of the study area, Dizu formation presents and extends to the depth of about 200 m. This formation consists of terrace deposits mainly conglomerates with sand intercalations. It is well exposed around the Site A (NWS1), Site C (NWS3) and throughout Moil Valley. The conglomerates consist predominantly of rounded clasts of andesite, trachyandesite and subordinate trachydacite. The Valhezir formation reaches to the surface near the Site B (NWS4) and it extends to the depth of about 700 m in study area. This formation consists of andesitic lava, tuft and tuff breccias. Pyroclastics predominate in the upper portions of the unit with lavas beneath.

A regional Miocene monzonite batholith was interpreted for deep reservoir on the basis of high gravity that extends from the area of the monzonite's surface exposure in the west into the project area (Sinclair Knight Merz, 1998).

Interpretation of MT resistivity data along AB line

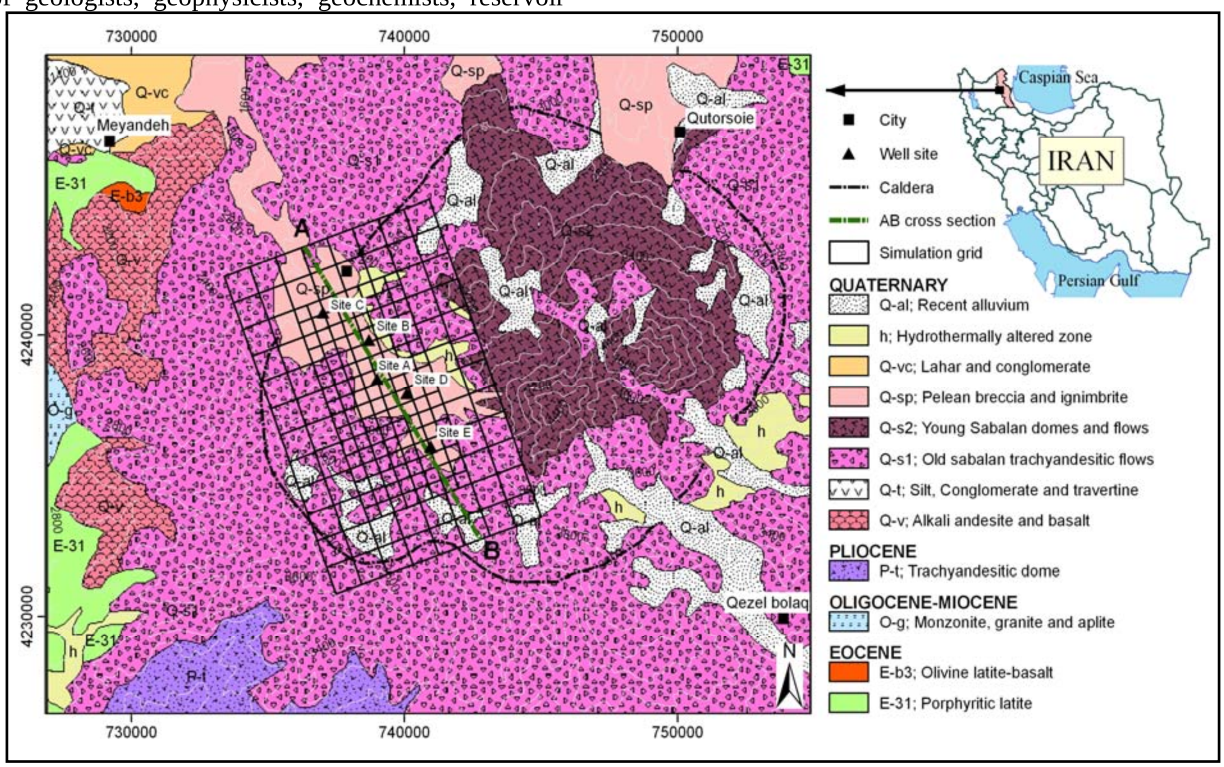

Figure. 1. Geological map of the NW Sabalan with main structures and AB cross section

showed that there are two low resistivity areas in the south and north of the cross section and a high resistivity in the central part of the model. The presence of the slightly high resistivity area below Well NWS4 can be represented by assuming the existence of a young diorite porphyry intrusive. In Well NWS1 on the elevation from 1368- 1284 m a.s.l (intermixed with Monzonite) and from 1221- 1179 m a.s.l which can be assumed an intrusive dike from this main body.

By integration of the subsurface geology of the wells with resistivity and temperature data, the conceptual model of NW-Sabalan geothermal filed is represented in Figure. 2. Subsurface geological conditions in Wells NWS4 and NWS3 are different and it can be interpreted by presence of the fault NE2, Also the temperature and pressure of these wells shows significant difference which can be interpreted by the presence of this fault. The NE2 fault appears to mark the northern boundary of the reservoir between NWS4 and NWS3.

Temperature distribution along AB cross section using data from wells shows that temperature decrease from south to north and implies the presence of upflow zone in the southern part of the field.

NUMERICAL SIMULATION

A three-dimensional numerical model of the NW-Sabalan geothermal field was developed on the base of conceptual model. The model was calibrated by repeating simulations until a good match was obtained with the natural state condition in the reservoir.

Grid blocks and layers

For modeling purposes, the NW-Sabalan geothermal field was assumed to be a rectangular prism of 12×8 km and 4.6 km deep in higher elevation area, giving a total area of 96 km^2(Figure. 1). The upper layer has variable thickness to represent the surface elevation which increasing elevation to the south.

The model has 14 horizontal layers ranging in thickness between 100 to 1000 m extending from a maximum of 3600 to -1000 m a.s.l. Each layer has 192 grid blocks in different size. Their horizontal dimensions are 500×500m and 1000×1000 m. The exploration drilling area is in the center of the model, covering an area of 3×6 km in which the grid blocks are at smaller horizontal size (i.e. 500×500m). Figure. 3 shows the 3D-view of the model and the location of upflow and surface discharge zones. To represent the shape of the system as closely as possible and to be consistent with the major flow direction in the system, the numerical grid was oriented to the NE-SW direction. The axes of the grid was oriented parallel to the major faults direction (i.e. fault NNW2) that eases to assign permeability values to the fault grid blocks. The computational mesh was designed so as to follow the main faults to facilitate representation of the flow paths.

The distribution of layer thicknesses in the vertical direction was primarily determined on the apparent locations of permeability in the exploration wells and temperature distribution in vertical cross section. Where the temperature gradient is higher, a thinner layer was assigned to easily match the simulated data with measured data. It is also important to ensure that sufficient shallow layers are included to adequately model the possible existence of two phase conditions within the reservoir, either due to natural conditions or as a consequence of production related pressure drawdown. Table 2 summarizes the layers elevation, thickness and block center elevation.

Rock type properties and assignment

Permeability values assigned to the model range from 1×10^{-17} to 0.5×10^{-13} m^2**,** with the maximum value in upflow zone and shallow permeable horizon between 1900 and 1400 m a.s.l. Porosity was specified to 10% to all rock types and rock density and thermal conductivity of 2500 kg/m^3 and 2.5 W/m^2°C were assigned to all rocks. Rock parameters corresponding to the final natural state model are summarized in Table 3.

Geological information obtained from drilling, and presence of the faults was used to assign the permeability and rock parameters of the grid blocks. Sixteen rock types were used in the model to assign different permeabilities on the basis of the conceptual model. As the data in blocks of the bottom, peripheral boundaries are not available, rocks parameters of these blocks are determined by trial-and-errors.

Table. 2. Horizontal layers used in grid model

Layer name	Elevation (m a.s.l)	Thickness (m a.s.l)	Block center elev.(m a.s.l)
Atmo.		Infinite	
AA	Vary	200-900	vary
BB	2600-2400	200	2500
CC	2400-2200	200	2300
DD	2200-2000	200	2100
EE	1900 -2000	100	1950
FF	1900 -1800	100	1850
GG	1800 -1650	150	1725
HH	1650-1550	100	1600
II	1550-1400	150	1475
JJ	1400-1300	100	1350
KK	1300-1000	300	1150
LL	1000-500	500	750
MM	500-0	500	250
PP	0--1000	1000	-500

Table. 3. Rock parameters of final natura state model

Rock type	Porosity (%)	Permeability (m^2)			Specific heat (J/kg°C)
		kx	ky	kz	
ATMOS	99	2.5×10^{-14}	2.5×10^{-14}	2.5×10^{-14}	9.0×10^{5}
TOP00	10	5.0×10^{-17}	5.0×10^{-17}	1.0×10^{-17}	1.0×10^{3}
BASE1	10	1.0×10^{-16}	1.0×10^{-16}	1.0×10^{-17}	1.0×10^{3}
BOND1	10	9.5×10^{-16}	9.5×10^{-16}	6.6×10^{-16}	1.0×10^{3}
TOP01	10	1.0×10^{-16}	1.0×10^{-16}	5.0×10^{-17}	1.0×10^{3}
TOP04	10	4.0×10^{-16}	4.0×10^{-16}	8.0×10^{-17}	1.0×10^{3}
BASE3	10	1.0×10^{-16}	1.0×10^{-16}	8.0×10^{-17}	1.0×10^{3}
LOW01	10	8.0×10^{-16}	8.0×10^{-16}	3.0×10^{-16}	1.0×10^{3}
MAKH3	10	1.0×10^{-15}	1.0×10^{-15}	5.0×10^{-16}	1.0×10^{3}
MATRX	10	1.0×10^{-15}	1.0×10^{-15}	7.0×10^{-16}	1.0×10^{3}
TOP02	10	2.0×10^{-15}	2.0×10^{-15}	8.0×10^{-16}	1.0×10^{3}
MAKH0	10	5.0×10^{-15}	5.0×10^{-15}	1.5×10^{-15}	1.0×10^{3}
TOP03	10	4.0×10^{-15}	4.0×10^{-15}	1.8×10^{-15}	1.0×10^{3}
LOW02	10	6.0×10^{-15}	6.0×10^{-15}	2.5×10^{-15}	1.0×10^{3}
MAKH1	10	3.4×10^{-14}	3.4×10^{-14}	1.5×10^{-14}	1.0×10^{3}
MAKH2	10	5.0×10^{-14}	5.0×10^{-14}	2.5×10^{-14}	1.0×10^{3}
UPFLO	10	5.0×10^{-14}	5.0×10^{-14}	1.0×10^{-14}	1.0×10^{3}

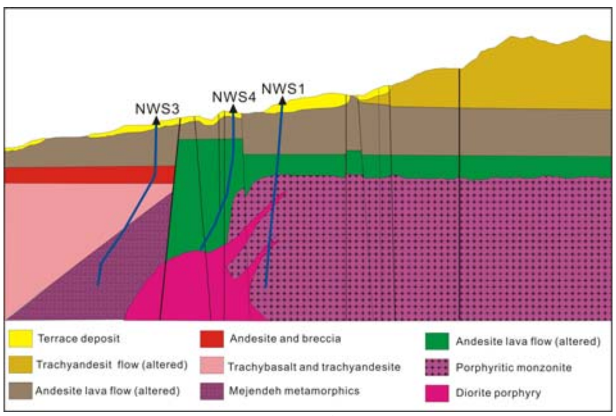

Figure. 2. Conceptual model of the NW-Sabalan geothermal field

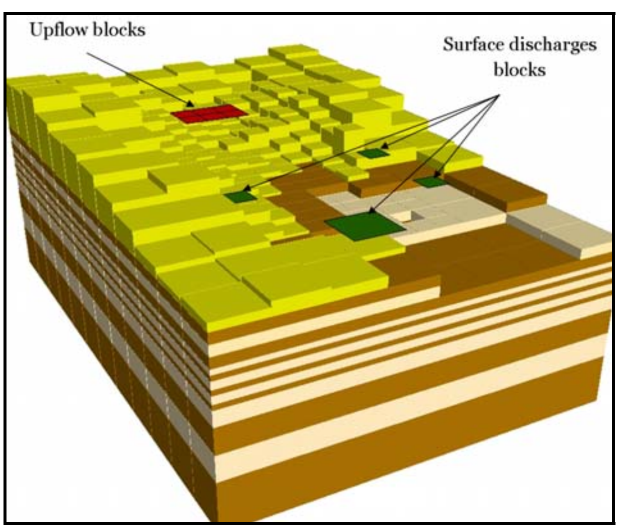

Figure. 3. 3D-view of the simulated area and the location of upflow and surface discharges

The rock types TOP00, TOP01 and TOP04 with lowest permeability were assigned to layers AA, BB, CC and DD which represent the cap rock of the system. The TOP02 and TOP03 rock types were assigned to the area B (Figure. 4) for representing the conductive temperature profile observed in Well NWS4.

LOW01 and LOW02 were used to the rocks in the layers LL, KK and JJ in southern and central part of the model and represent a low permeability layers between two high permeable layers in shallow and deep zones. The rock types of BASE1 and BASE3 denote the base layer (PP) of the system with low permeability. The UPFLO rock type indicates the upflow zone. Six grid blocks (500×500 m) in southern part of the reservoir were assigned to this high permeable rock type.

For the outer part of the assumed area for geothermal reservoir and unknown areas the rock type of MARTX with moderate permeability was assigned. The rock types of MAKH1, MAKH2 and MAKH3 stand for high permeable layers and assigned to small grids (500×500m) of the model for layers MM, II, HH, GG, FF and EE.

According to the information from two wells (NWS1 and NWS4), there are two main permeable horizons in the reservoir: a shallow zone between 1800 and 1400 m a.s.l. in southern part, and a deeper zone between 500 m a.s.l and sea level in both wells. Both wells encountered lost circulation zones in the deep zone. In the computational grid, the uppermost high permeable horizon in the reservoir was therefore subdivided into four layers (FF, GG, HH and II). The layer MM denotes the deep high permeable horizon.
Layer AA represents the "surface blocks" of the system, whose surface elevations range between 2800 and 3600 ma.s.l. The layers BB and CC also represent surface blocks in southern part which the elevation is from 2200 to 2800 m a.s.l.
Grant curve was used for relative permeability (Grant, 1977).

Initial and boundary conditions

The boundary conditions at the top of the model are specified using an infinitely large block saturated with water at 0.788 bar and 15 °C. In this model, there are no inflow and outflow from peripheral boundaries. High temperature fluid recharges at a rate of 90 kg/s of 1135 kJ/kg from the bottom layer, PP, is given through regional faults in the southwest region. This enthalpy corresponds to saturated water of 260°C. According to vertical temperature distribution on AB cross section, upflow zone may locate about 2.5 km to the southeast of Well NWS1. The recharge was assigned to the grid blocks of 88, 92, 103, 105, 109 and 111 in PP layer (Figure. 4). The location and temperature of recharge were determined by trial and error manner by iterative process.

There is several natural discharge of geothermal fluid through hot springs and in river bed mostly in northern part of the area. The surface discharge temperatures are from 25 to 86°C and the flow rate of hot springs are about 25-30 kg/s but there are several discharges in river bed and banks which unable to measure the flow rates. Thus, we assumed that the total outflow from the system is about 40-50 kg/s.

In order to reproduce the hot spring activity in the numerical model, fluid production based on deliverability (Pruess et al., 1999) was utilized in three blocks in layers FF (51, 78, and 130) and one block in layer II (183) below the location corresponding to these surface manifestations. The productivity index (PI) is calculated on deliverability model and well bottom pressures (P_{wb}) are obtained by trial and errors.

Peripheral boundaries of the model are adiabatic for heat. Heat flux was given to the blocks in the bottom layer (PP) of the model as a conductive heat supply. A heat flux of 90mW/m^2 was used to each block in southern and central part where the rock type of BASE1 is assigned. Heat flux from northern part (Area C) specified 50mW/m^2. Conductive heat is losses from the top layers (AA, BB and CC) to the atmosphere.

Model validation and well data matching

The validation process normally involves matching of the natural state conditions in the syetm, as defined by available subsurface information. The temperature distribution and surface outflows of heat and mass in the model are also compared with measured field data and the permeability structure of the model is adjusted to achieve a satisfactory match. The magnitude and location of the deep hot upflow may also need to be adjusted.

During the natural state simulation of NW-Sabalan reservoir, the computed results were compared against temperature and pressure measured in three wells. The matches between the measured and computed parameters were improved primarily by adjusting the permeability, fluid flow rate and enthalpy of the high-temperature recharge assigned to the bottom six grid blocks.

The grid blocks 59 and 49 of the model were used for Well NWS3. The well is deviated and the corresponding temperature and pressure of layers CC to EE of grid block 59 and layers FF to PP of grid block 49 from "best model" were used to match the measured and simulated data. For Well NWS4 the grid blocks of 166 for layers BB to GG and 165 for layers HH to PP were used. Well NWS1 is a vertical and grid block of 150 was used for whole well depth for matching. In Figure. 5 the measured and computed natural state temperature profiles of three wells were compared.

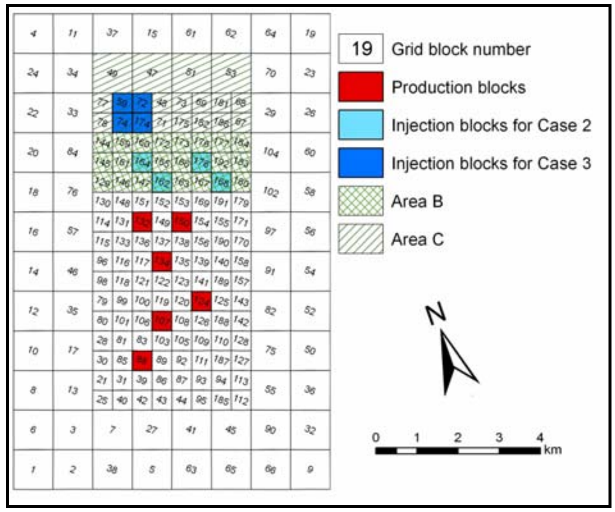

Figure. 4. Grid blocks layout with production, reinjection, monitoring and upflow blocks

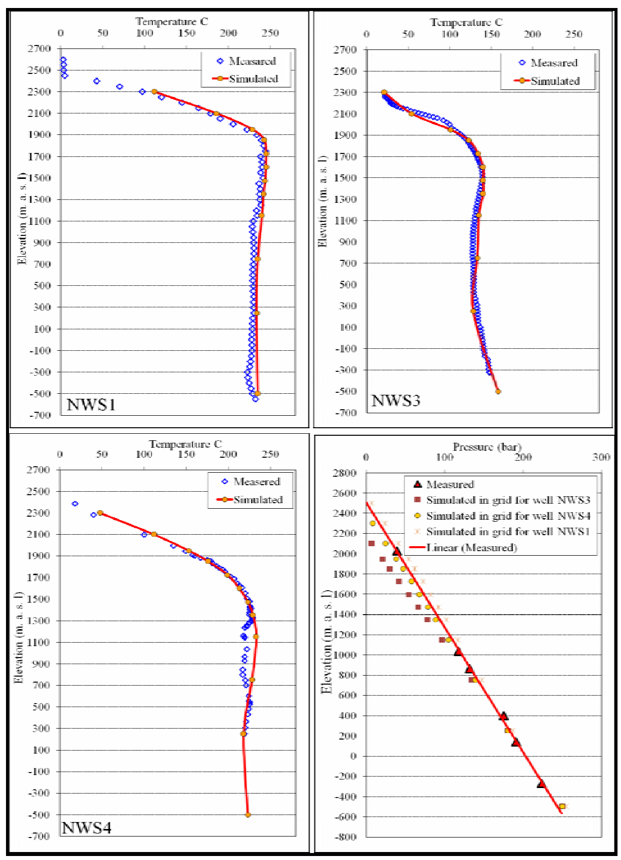

Figure. 5. Measured and simulated natural state temperature and pressure

Wells NWS1 and NWS4 are believed to be located close to the upflow zone in the southern part of the field. Well NWS3 in the northern part, however, is out of the assumed geothermal reservoir. Fault NE2 acts as northern boundary of the field and its presence may cause differences of temperature in Wells NWS3 and NWS4. Measured and computed natural state pressure profiles were compared in Figure. 5**.** The simulated pressure in model was adjusted by changing the permeability of grid blocks, productivity index and well bottom pressure on well in deliverability grid blocks.

The model developed for natural state was used to evaluate the response of the system to the production and reinjection scenarios.

PRODUCTION PERFORMANCE

Numerical simulations were conducted for predicting reservoir performances by assigning production and reinjection wells. As for production zones, we first examined distributions of permeable zones. Figure. 4 shows location of the production and reinjection grid blocks for all scenarios. The production zones were located in the southern area where Sites A, D and E are located. This area is junction of several faults including NNW2, NNW3, NNW5, NE5, NE6, NW3, NW4 and NW5 where high permeable fractured zone may be developed along the faults.

The northern part of the field with lower elevations was recommended for reinjection. Reinjecting of geothermal brine to these localities with different arrangement was examined on different production scenarios.

The simulation was run for 30 years of production using TOUGH2 simulator (Pruess et al., 1999). During production simulation the original surface discharge and inflow of the system were kept constant same as natural state.

The production of 20MWe in the first phase of NW-Sabalan project was purposed. Three kinds of production and reinjection schemes for 30 years were simulated;

- **Case 1:** production without reinjection
- **Case 2:** production with reinjection at Site B
- **Case 3**: production with reinjection on Site C

The response of field to above cases was examined and optimum case was suggested. Based on discharge evaluation data from Well NWS4, for a proposed single flashed power plant, required geothermal fluid was calculated by programming in Engineering Equation Solver (EES) (Beckman and Klein, 2007). The input parameters are; produced fluid enthalpy 945 kJ/kg, separation pressure 5.5 bar, condenser pressure, 0.1 bar, outlet temperature 46°C and isentropic efficiency of the turbine 0.78. By assigning these inputs and output information, required production rate of geothermal fluid for 20 MWe of power output is 311 kg/s which was used for reservoir simulation and production performances.

By assuming that the productivity of new wells to be drilled lies between that observed in Wells NWS1 and NWS4, for production of 311 kg/s geothermal fluid, drilling of six geothermal wells is planned for all cases. Production wells are proposed to drill in Sites A, D, and E in southern part of the field in grid blocks 88, 107, 124, 132, 134, and 150 (Figure. 4).

In Cases 2 and 3 the produced brine is reinjected into the reservoir. About 87% (272 kg/s) of produced fluid was reinjected from four wells in Site B and Site C into the reservoir. The reinjection wells were assigned on layer MM into the grid blocks of 162, 164, 168 and 178 for Case 2 and blocks 59, 72, 74 and 172 for Case 3 (Figure. 4).

Four grid blocks 163, 149, 122 and 126 were chosen to monitor and compare the pressure and temperature data with depth in natural state and production scenarios.

In all cases a small temperature drop in layers DD, EE and FF (elevation from 1900-1600 m. a.s.l) is shown in southern and central part of the reservoir where the production wells are located.

Pressure drop from initial state at main production layer (layer MM) was calculated and distribution model is shown in Figure. 6. In Case 1 pressure drop (up to 50 bars) expands in whole area but the magnitude was higher in production area than northern part of the field. In Case 2 pressure drops is lower than that in Case 1. In the area of reinjection in northern part, pressure increases because of reinjection.

Same as the last two cases pressure drop was monitored in the production area in Case 3 but magnitude is higher than Case 2 and lower than Case 1. In the area of reinjection where the grid block of 163 is located pressure increases but its magnitude is lower than Case 2. In monitoring grid blocks 149, 122 and 126 the highest pressure drop was observed at layer MM (main producing layer). This grid blocks are located in central part of the production area and the pressure drop is unavoidable.

The result of time history data for mass flow shows that total mass flow during 30 years of production was decreased by 86, 50 and 58 kg/s for Cases 1, 2 and 3, respectively. Figure. 7 shows the total produced mass flow from 6 wells over 30 years of production.

As a result, Case 1 shows the largest drop in flow rate in 30 years. The amount of mass flow reduction in Case 3 was less than the amount in Case 1 but it is higher than Case 2 and it is because of the location of reinjection wells, the effect of permeability structure of the model in reinjection area and presence of the fault NE2. In Cases 2 and 3 according to the amount of mass flow reduction one makeup well in year five need to be drilled to maintain the total production rate. Two make-up wells for no-reinjection scenario in years 2 and 5 are needed to maintain the required steam rate for a 20 MWe.

The pressure drop in all cases in production area around producing grid blocks is much higher than other parts of the reservoir. The pressure in reinjection area was increased due to reinjection.

DISCUSSION

The simulated scenarios were analyzed to select the best development scenario among three cases. The factors which are analyzed are temperature and pressure drop and mass flow rate.

By the comparison of the pressure drop in main production area in Figure. 6 can be seen that the pressure drop in production area in Case 1 is higher than Case 2 and Case 3. Also pressure drop in Case 3 is higher than Case 2. Also total mass flow reduction in Case 2 is lower than other cases. As a result the Case 2 can be the best development scenario for this reservoir.

The production scenario Case 2 two is the best and it is proposed to carry out the production from NW-Sabalan geothermal filed match to this case. The forecasting from simulation suggests that the NW-Sabalan field can easily sustain a power generation level of 20MWe with the initial use of six production wells and four injection wells.

CONCLUSION

The natural state simulations were carried out in the NW-Sabalan geothermal field. The results indicated good agreements in temperature and pressure profile between simulated and measured temperatures in the wells. High temperature fluid at a rate of 90 kg/s with enthalpy 1139 kJ/kg recharged over an area 3 km^2 from 6 grid blocks at the bottom in southeast of the area.

The forecasting from simulation suggests that the NW-Sabalan field can easily sustain a power generation of 20 MWe with the initial use of six production wells and four reinjection wells. Production simulations by assigning reinjection wells in injection area B indicated least decline in pressure and steam production rate compared with other two cases. The results showed that the fluid production rate of 311 kg/s could be maintained for 30 years, which is enough for 20 MWe electricity power generations.

ACKNOWLEDGMENT

Authors thank Renewable Energy Organization of Iran (SUNA) for permission to publish the data. Thanks are also extended to the geothermal Institute of The University of Auckland for permission to use new version of MUGRAPH2 code.

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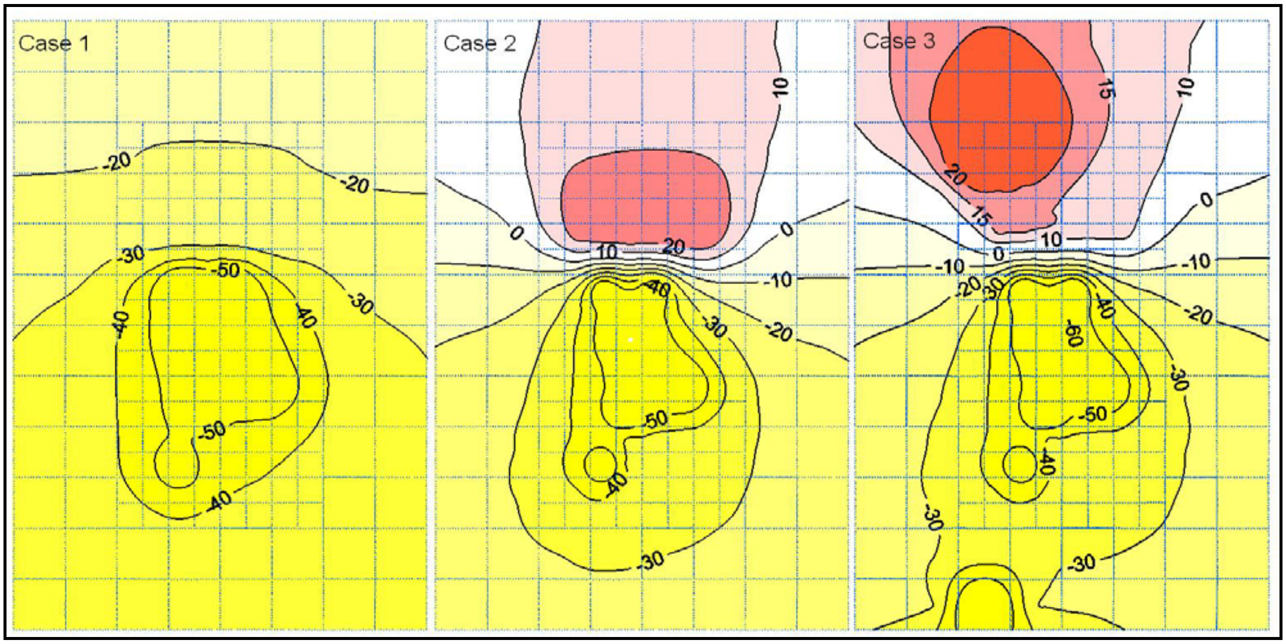

Figure. 6. Pressure changes after 30 years of the production at layer MM for three cases. The pressure drop is denoted with negative and pressure increases with positive value

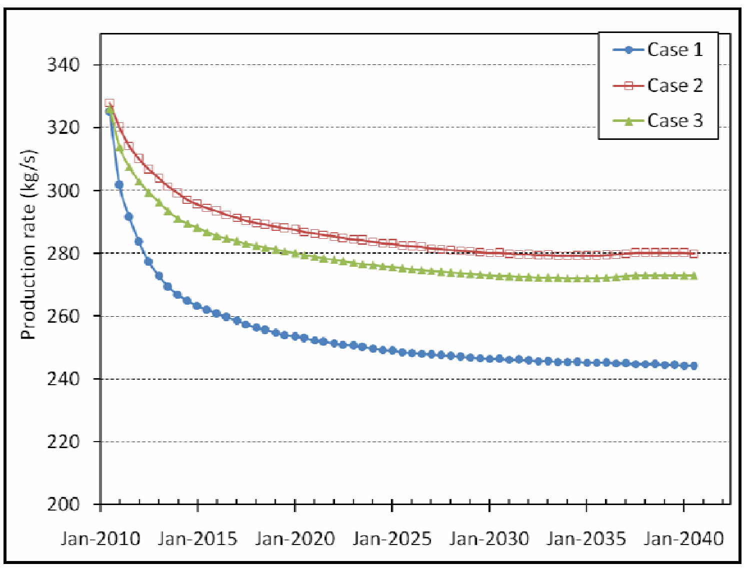

Figure. 7. Total mass flow change over 30 years of production for all cases