Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

A Middle-Term Power Output Prediction at the Hatchobaru Field by Coupling Multifeed Wellbore Simulator and Fluid-Gathering Pipeline Simulator to Reservoir Simulator

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Keywords: Hatchobaru, wellbore simulator, multi-feed, coupled simulator, MULFEWS, TPGS

ABSTRACT

A method has been developed to predict the response of a reservoir to exploitation using a new simulator that is the coupling of a reservoir simulator, a multi-feed wellbore simulator and a two-phase pipeline network simulator. This method was applied to the reservoir management of the Hatchobaru geothermal field in Kyushu, Japan. The operation of the three-coupled simulators was successfully tested. Results of a middle term forecasting of power output at the power plant indicated a constant power decline with the decline rate of about 4% per year due to the return of reinjected water into the production zones. The study on the problem using the newly developed simulation tool indicated that relocating the reinjection zone to the north of the field would mitigate the cooling of the production zones influenced by reinjection while maintaining pressure support to the reservoir. In the case of Hatchobaru the simulation results also indicated the need of drilling a make-up well every year for steadily maintaining the rated power output.

1. INTRODUCTION

Numerical simulation technology is indispensable for estimating the expected power potential of a geothermal field. This knowledge is essential for the management of the reservoir exploitation and of the power plant operation. Coupling a reservoir simulator with a wellbore simulator is required for predicting the discharge rate of each production well at given wellhead pressure and then to estimate its power output. There are two forms to couple a reservoir simulator and a wellbore simulator. The direct coupling of simulators consists in operating one simulator after the other. In this case the reservoir simulator provide reservoir pressure and enthalpy to the wellbore simulator to calculate mass flow rate at given wellhead pressure. The calculated mass flow rate is then used as the mass generation of the subsequent time step and so forth. In the indirect form of coupling tables of the relationship between reservoir pressure and enthalpy and mass flow rate at the specified wellhead pressure of each production well is prepared in advance using a wellbore simulator independently (Lima et al., 1998). The reservoir simulator accesses these tables during its calculations and interpolates for pressure and enthalpy to obtain well mass flow rate.

The above two methods are basically same. The indirect coupling is faster than the direct coupling, because of the use of pre-calculated values. On the other hand, the direct coupling, although it requires more calculation time, is more accurate because wellhead conditions are calculated directly by the wellbore simulator. In addition, if the production wells have multiple feeds zones, the direct coupling method is more amenable, because of the complications to pre-calculate tables for such conditions.

Defenders of the indirect coupling (Murray and Gunn, 1993), reports that table lookups are computationally efficient and quick to perform when applied to large numbers of wells and when modeling reservoirs with high levels of exploitation, that frequently involve simulating in excess of one hundred production wells. In addition, they also report that the use of wellbore tables calculated externally from the reservoir simulator gives the user an opportunity to review and smooth any discontinuities as required, which can reduce numerical convergence difficulties. They introduced an attempt of a coupling simulation, a simple interfacing between the WELLSIM wellbore simulator (Gunn and Freeston, 1991), and the TETRAD reservoir simulator (Faulder and Shook, 1991). Hadgu et al. (1995) introduced sample calculations by coupling simulators TOUGH reservoir simulator (Pruess, 1987) and WFSA wellbore simulator (Hadgu and Freeston, 1990). However, considering that in the Hatchobaru geothermal field there are about twenty production wells with multiple feed zones, the direct coupling simulation method was adopted for the simulation work reported here.

To complete the study on the steam field, TPGS, a two-phase pipeline network simulator was developed to analyze pressure distributions in the pipelines from the wellheads of each production well up to the inlet of turbines (Lima et. al., 2004). When the production wells are connected to an interconnected network of steam supply, the pressure at the plant's main steam separator defines the pressure at each wellhead, and therefore the productivity of the well. Thus in order to precisely predict the plant power output, it is necessary to consider the reservoir, wellbore and pipeline network as a one coupled system.

This paper describes a middle-term power output prediction of the Hatchobaru power plant by coupling the MULFEWS multi-feed wellbore simulator (Tokita and Itoi, 2004), the TOUGH2 multi-purpose reservoir simulator (Pruess, 1991), and the TPGS pipeline network simulator.

2. HATCHOBARU MODEL

The Hatchobaru geothermal filed (Northern part of the Kyushu Island in Japan) is a water-dominated reservoir with temperatures in the range of 240-300 ℃ and where the underground fluid movement is strongly controlled by faults. The fluids supplied to the power facilities are being tapped at depths between 1000 m to 2300 m. These fluids reside in five main productive faults; the Komatsuike Fault, the Komatsuike-sub Fault, the NE3 Fault, the NE4 Fault and the Hatchobaru Fault as shown in Fig.1.

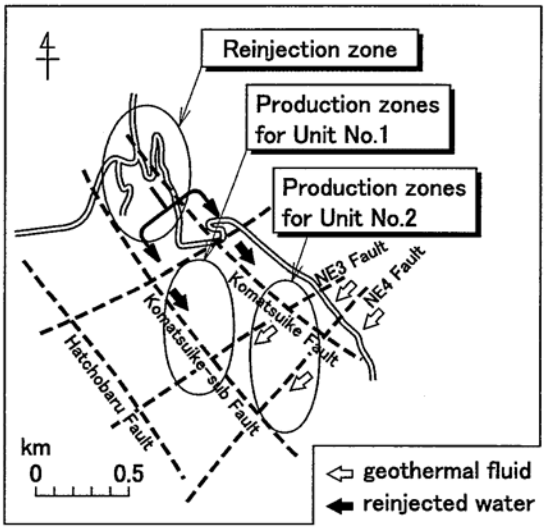

Figure 1: The Hatchobaru geothermal field

Through the years of operation of the power facilities, precise conceptual and numerical models have been constructed and periodically updated. The changes in reservoir temperature are estimated applying geothermometers to the results of chemical analysis of discharged fluids sampled in production wells every six months. The total mass of water after the flashers, around 380 kg/s, is reinjected at about 90℃ and at atmospheric pressure using ten reinjection wells.

The reinjection strategy is to separate the production and reinjection zones although reinjection depths are similar to those of the production zones. Currently, the northern part of the field is used for reinjection and the southern part for production. In the past, there was a cooling of the reservoir due to the inflow of reinjected fluids to the production zones. This was corroborated using tracer and by monitoring Cl (chloride) concentration. This caused a drop of reservoir temperature and a corresponding gradual decline in productivity of some of the production wells (Mimura et al., 1995).

In Hatchobaru, a reservoir management procedure based on reservoir monitoring techniques and on computer simulation has been applied for over the more than 20 years to calibrate the conceptual and numerical models to new conditions and to forecast the tendency of future changes in reservoir and production characteristics. The essence of this procedure is in updating the three-dimensional numerical model as new data from the field is available. Currently, the numerical model is capable of simultaneously reproducing changes in pressure, temperature, gravity and tracers behavior, which have been recorded during the reservoir monitoring and periodical well testing.

The numerical model covers 16.5 km^2 (3.70 km×4.45 km) as shown in Fig. 2. In the vertical direction, the top and bottom of the numerical model correspond to elevations of about 1100m above sea level and 1400 m below sea level respectively. The 2500 m of total model thickness are divided into 10 layers. The layer thickness ranges from 100 to 400 m. The top two layers are defined to consider the topography. The total number of the grid blocks is 3960. The boundary conditions and distribution of rock properties such as density, porosity, permeability etc., were initially selected based on the results of well testing and rock-core analysis. These properties were progressively revised through repeated trial-and-error calibration process until the model could successfully reproduce not only the actual measured temperature and pressure distributions in natural state, but also the actual pressure and temperature changes over time during the plant operation. The fracture modeling technique called Multiple Interacting Continua (MINC) method was partially applied for modeling faults representing the dominant fluid flow pattern.

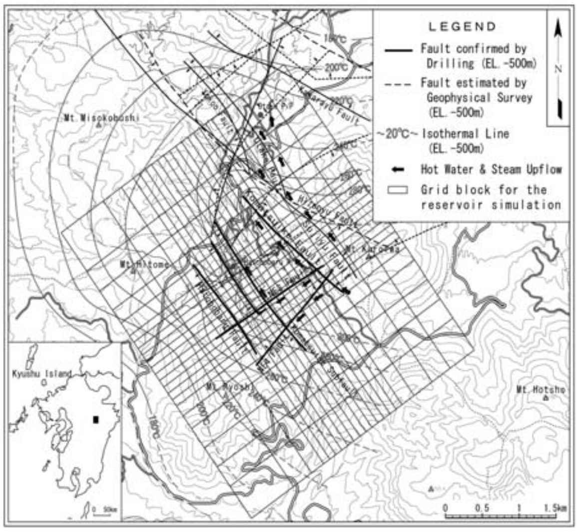

Figure 2: Plain view of the grid design of the Hatchobaru numerical model

3. COUPLING WELLBORE SIMULATORS

3.1 Welbore Simulator WELLFLOW and MULFEWS

In Hatchobaru, since 1993, combined pressure, temperature, and spinner surveys (PTS) have been run during the periodical inspection of the power plants. The results of these surveys have been used to determine the depth and distribution of feed zones of each production well. The PTS surveys indicate that 25 of production wells are supplied of geothermal fluids through several feed zones (Tokita and Itoi, 2004). The vertical position of these feed zones is variable depending on the structure of faults the well taps. When feed zones are located close together, the single-feed zone wellbore simulator, WELLFLOW was used to simplify the model and calculations of the wellbore condition by interpreting that the well has a single-feed zone. When this is not the case, a multi-feed zone wellbore simulator, MULFEWS, was used to calculate production characteristics and by allocating each feed zone a different grid block within the numerical model of the reservoir. WELLFLOW is a wellbore simulator developed in West JEC based upon the basic formulations with a computer code derived by researchers in the Kyushu University (Itoi et al, 1988, Itoi et al., 1983, Sekiguchi K. 1967).

This wellbore simulator has two coupled components. One is to calculate the flow characteristics within the wellbore. The other component is to calculate, assuming a radial model, the flow characteristics in the formations around the well and to define whether the flash point occurs within the formation or within the wellbore. These two components allows the estimation of the relationship between the wellhead pressures and mass flow rates with the pressure and enthalpy of the reservoir.

MULFEWS is the multi-feed zones version of WELLFLOW (Tokita and Itoi, 2004) and which basic concept is graphically presented in Fig. 3. As depicted in this figure, the well is connected to three different horizontal reservoirs, each of which has specific characteristics such as pressure, enthalpy and permeability-thickness product, kh etc. The enthalpy of each feed zone is determined by the pressure and temperature of the feeding reservoir if the fluid is in liquid state, or by the pressure and steam saturation (or quality) if the reservoir fluid is in two-phase.

The properties of the surrounding reservoir are the input data, and are held constant. Assumptions were made to simplify the development of the computer code; steady state conditions in the reservoir fluids surrounding the well, homogeneous porous media used to represent the reservoir around the wells and radial flow obeying the Darcy's law. The geothermal fluid is assumed pure water at either single liquid phase or two-phase conditions, depending on the fluid pressure and temperature. Accordingly, flow rates for the single and the two-phase flows are represented by the following equations, respectively, which are derived from the equations of conservation of mass and momentum (Sekoguchi, 1967, Itoi et al., 1983, 1988).

[Water single region]

$$Q = \frac{2\pi kh}{\left\{ \ln(\frac{R}{r_w}) + S \right\}} \frac{(\mathrm{Pr} - P_{feed})}{\nu_w} \quad (1)$$

[Two phases region of water and vapor]

$$Q = \frac{2\pi kh}{\left\{ \ln(\frac{R}{r_w}) + S \right\}} \left\{ \int_{P_{feed}}^{P_{sat}} \frac{1}{\nu_t} dp \right\} \quad (2)$$

When the water pressure decreases below the saturation pressure with respect to its temperature due to pressure while moving towards the well, the fluid starts flashing in the reservoir. As the flashing point is the boundary between the single liquid phase and the two-phases, the flow rate for the case that a flashing point locates in the reservoir can be rewritten as follows, using the saturation pressure at the flashing point at a radial distance.

$$Q = \frac{2\pi kh}{\left\{ \ln(\frac{R}{r_w}) + S \right\}} \left\{ \frac{P_r - P_{sat}}{\nu_w} \int_{P_{feed}}^{P_{sat}} \frac{1}{\nu_t} dp \right\} \quad (3)$$

Where, Q is the mass flow rate for the fluid (kg/s). kh is the permeability-thickness product (m^3). R is the outer boundary radius of the reservoir surrounding the well (m). r_w is the wellbore radius (m). S is the dimensionless skin factor (-). Pr is the reservoir pressure (Pa). P_{sat} is the saturation pressure (Pa). P_{feed} is the feed zone pressure (Pa). ν_w is the kinematic viscosity of water (m^2/s). ν_t is the kinematic viscosity of the two-phase fluid (m^2/s).

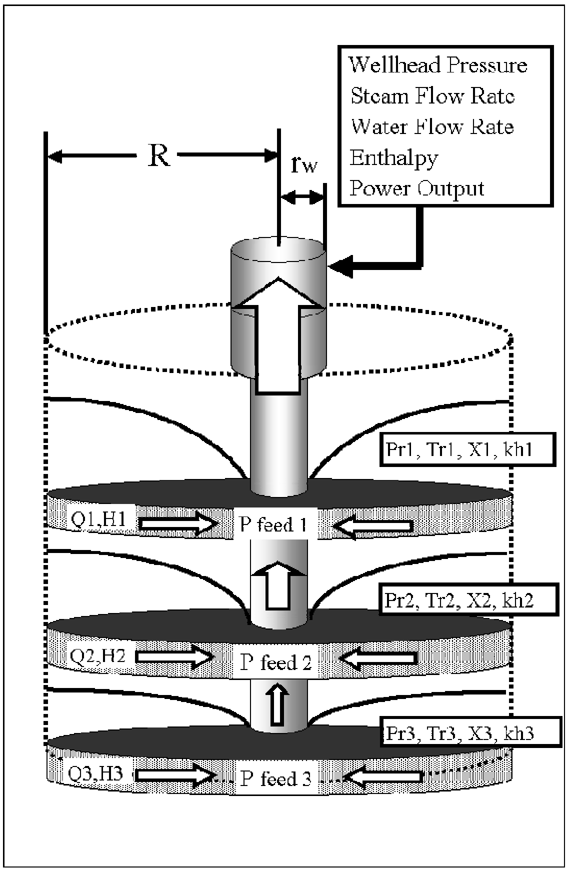

Figure 3: Schematic numerical model of a multi-feed well surrounded by individual reservoirs

3.2 Coupling WELLFLOW, MULFEWS and TOUGH2

The coupling parameters between the reservoir simulator and the wellbore simulator are the pressure and enthalpy values, calculated by TOUGH2 for the grid element of the discrete reservoir model where the well has been assigned. The reservoir pressure and enthalpy to be used as input of the wellbore model are not always those at the grid element of the reservoir model, because the depth of feed zone of a well is not always same as that of the center at grid block. It is, therefore, necessary to correct the reservoir pressure and enthalpy surrounding well by adjusting the difference between the depth of feed zone and the center of the grid element. After adjusting the above difference, the assumption should be made to couple the wellbore simulator and the reservoir simulator that the changes in pressure and enthalpy at the surrounding of the well are the same as those at the center of the grid element. Namely, applying the following equations mathematically does the coupling.

$$p_{rW(n)} = p_{rW(n-1)} + \Delta p_{rR(n)}$$
$$i_{rW(n)} = i_{rW(n-1)} + \Delta i_{rR(n)} \quad (4)$$

Where $P_{rW(n)}, P_{rW(n-1)}$ is the reservoir pressure for the wellbore model at time step (n) and (n-1), respectively; $\Delta P_{rR(n)}$ is the pressure change for reservoir model at time step (n); $i_{rW(n)}, i_{rW(n-1)}$ is the reservoir enthalpy for wellbore model at time step (n) and (n-1), respectively; $\Delta i_{rR(n)}$ is the enthalpy change for reservoir model at time step (n).

In order to simplify the calculations MULFEWS was applied for the only wells that have multiple feed zones where locate at multiple grid blocks. Otherwise, the wells having feed zones at the same grid element of the reservoir model are treated as single-feed wells, for which WELLFLOW was applied, even if the wells actually have multi-feed zones.

4. COUPLING PIPELINE SIMULATOR

4.1 Fluid-gathering Pipeline Simulator TPGS

When there is a pipeline network connecting different production wells to the power plant, the pressure at the main separator of the power plant and that of the head of each well will depend on several factors. The pressure at each wellhead of the wells connected to a two-phase pipeline network has to be that which will produce a single unique value at the nodes joining the branches connecting different wells.

The variation of the pressure at this node will induce a change in the wellhead pressures, which will depend on the pressure drop in the branch joining the node and the wellhead (which in turn will depend on length, diameter, pipe internal conditions and fittings). In addition, it will depend on the difference in elevation between the node and the wellheads and in the production characteristics of the different wells. If the inlet of the main separator at the power plant is considered as the final node of several nodes interconnecting the pipeline network, any variation in the pressure of this final node will propagate back to each wellhead. The resulting wellhead pressure will determine the mass production (depending on the individual production characteristics of the well) and therefore, will determine the power output delivered by the well.

Considering the potential of all the wells in the steam field, the total power output of the plant can be estimated.

Sanchez et al. (1987) introduced a design methodology for the sizing of two-phase pipelines (single branch) using the FLUDOF computer program in Mexico. They applied the FLUDOF for the calculations of pressure drop in pipelines at the Mexican geothermal fields, which agreed with a slight error within 10% with the field data. Andreussi et al. (1994) presented a one-dimensional, steady-state model for the computation of hold-up and pressure losses in horizontal and near-horizontal pipes. The model has been implemented in the two-phase flow simulator, HORF (single branch). The predictions showed good agreement with the field data obtained at the Latera geothermal field, Italy, relative to a flow line of 2.4 km with 18 inches (457 mm) nominal diameter.

In order to have a more realistic estimation (forecasting) of the combined power output of well connected to a network, based upon these works, Lima et al (2004) developed a simulator, TPGS (Two-Phase Gathering System) to calculate pressure drop in two-phase flow in pipeline networks, representing the gathering system connecting the steam field to a geothermal power plant. TPGS can handle several flow patterns and can handle the effects of fittings (valves, and elbows).

Fig.4 indicates the layout of the two-phase gathering system for the Hatchobaru power station. The mass supply to each of the units is transported in two-phase from the wellheads to the power plant separators through an independent network of pipelines. Both networks are interconnected at the plant area to allow part of the fluids from the sector supplying Unit-2 to flow into the pipeline network for Unit-1. The total length of pipelines is 4.7 km and the average difference in elevation between the power plant and the steam field is 167 m, respectively. The total number of the fittings is 440. The turbine inlet pressure of Units No.1 and No.2 is 0.6MPa and 0.7MPa, respectively. The wellhead pressure of production wells is in average 0.8MPa.

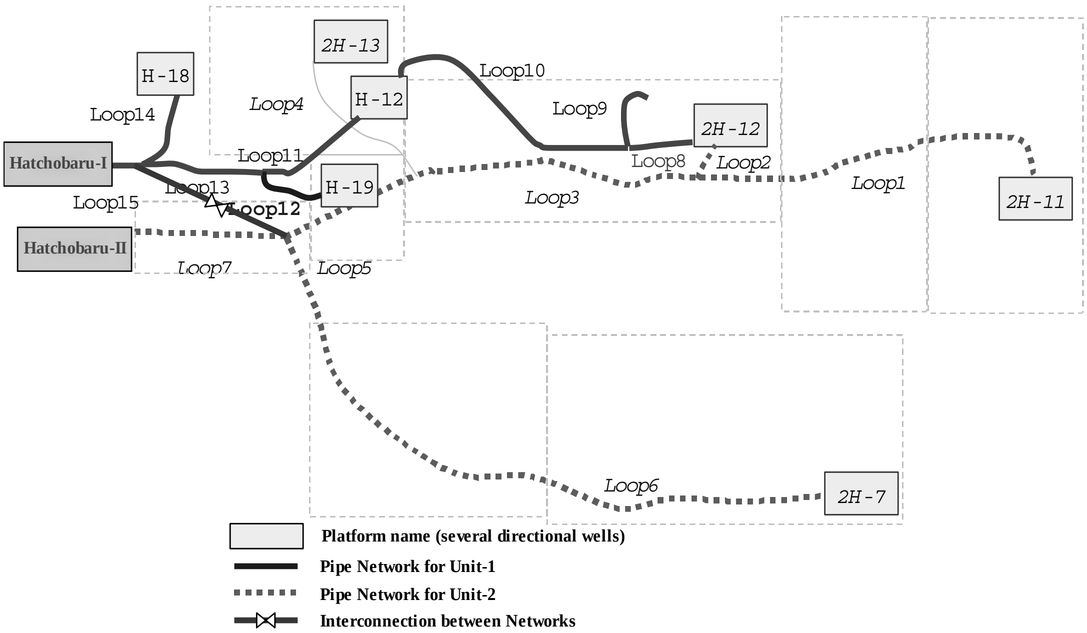

Figure 4: Layout of the two-phase gathering system for the Hatchobaru power station

4.2 Operation of the Coupled Software

The coupling between the wellbore simulator and the two-phase pipeline network simulator is through the well production parameters calculated by WELLFLOW for single feed zone and MULFEWS for multiple feed zones.

Fig. 5 shows the coupled simulation process. For the case of Hatchobaru, the constraining parameter is the separation pressure of either of the power units. For each time step, the coupled TOUGH2 and WELLFLOW or MULFEWS calculates well production characteristics at different wellhead pressures. This information is used by TPGS to progressively transform the different loops in the piping network into simpler loops until it is reduced to an equivalent network representing the whole piping system. TPGS utilizes the equivalent loop representing the whole piping network to calculate pressure and mass production at the wellhead of each production well in and inverse calculation process that starts at the separation pressure. TPGS then calculates the mass flow and enthalpy entering the separators of each unit, which is followed by the calculation of the amount of separated steam and hot water since a double flash scheme is used in Hatchobaru. TPGS calculates steam and the remaining water resulting from a secondary flashing. With the total amount of steam, the power plant output is calculated. Plant efficiency with respect to the atmospheric temperature can be also taken into account for calculating the plant power output.

The total mass production and the total mass of remaining hot water is then used to set the conditions for TOUGH2 as its sink and source terms, respectively to proceed to the subsequent time step calculations and so forth until the total simulation time is completed.

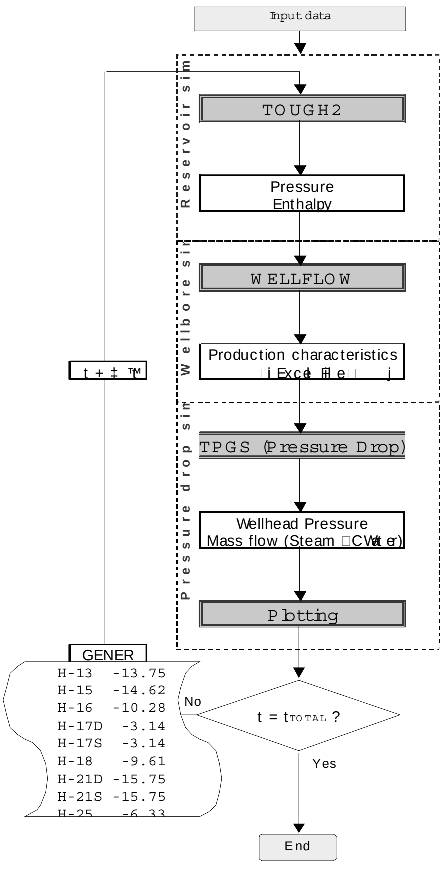

Figure 5: Coupled simulation process

5. MIDDLE-TERM POWER OUTPUT PREDICTION

5.1 Power Output Prediction of the Hatchobaru Power Plant, Japan

The Hatchobaru geothermal power plant (110 MW) is known as the first plant in the world to adopt the double-flash system. Unit No.1 (55 MW) started commercial operation in 1977 and Unit No.2 (55 MW) in 1990. The two double-flash units of the power plant are being supplied of geothermal fluids from two different sectors of the field. Seventeen production wells (nine wells for Unit-1 and eight wells for Unit-2) have produced around 710 kg/s of geothermal fluids.

Fig. 6 and Fig. 7 shows the current and revised reinjection allocations, respectively. The revised allocation partially distributes the current reinjection allocation to the north far away from the production zones to mitigate the phenomenon that the reinjected water returns back to the production zones. Fig.8 shows the predicted declines of the plant power output within 5 years in the future by the coupled simulation, in which the current (case 1) and the revised (case 2) reinjection allocations are examined. The case 2 assumes the condition that 28% of the total amount of reinjection water relocates to the north area block A. The remains are distributed to the area block B (48%) and block C (24%), while the case 1 distributes the reinjected water to block A (19%), block B (57%), and block C (24%), respectively.

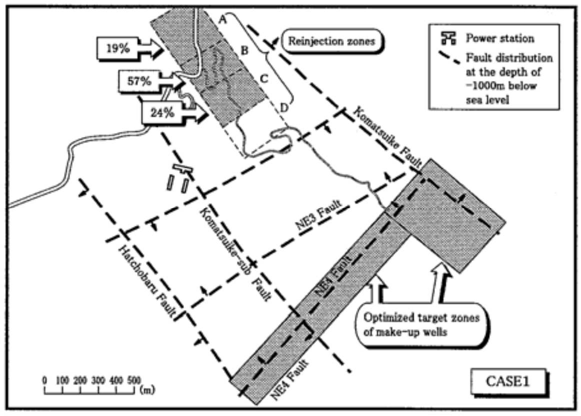

Figure 6: The current reinjection allocation at the Hatchobaru field (case 1)

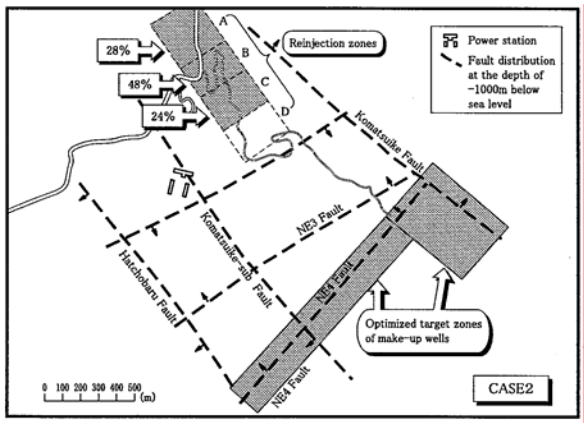

Figure 7: The revised reinjection allocation at the Hatchobaru field (case 2)

Results of the coupled simulation forecasted that the plant power output would decline by about 20 MW within 5 years. It indicates that the power output will decrease by about 4 MW per year, representing the annual power decline rate of about 4%. As the simulated enthalpy was predicted to decrease over time, the main reason of the power output decline is considered the cooling of the production zones. It would cause due to not only return of the reinjected water, but also inflow of the surrounding water with lower temperature to the production zones. Both fluids flow into the lower pressure regions at the production zones along the dominant faults. The simulated result for case 2 suggests that a relocation of reinjection area to the north far away from the production zones would be effective to mitigate the return of the reinjected water to the production zones in comparison with that for case 1. Although it is desirable to completely relocate the reinjection zones out of the production zones, we have constraints for the exploitation boundaries.

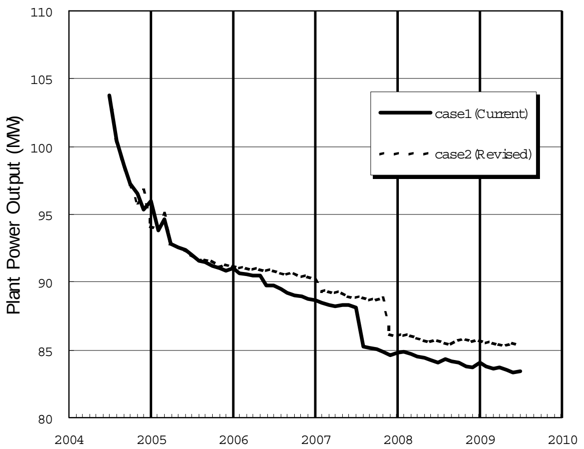

Figure 8: Predicted decline of the plant power output

5.2 Predicted changes in reservoir properties and power output of multi-feed well H-27

The production well H-27, which locates at the southern part of the production area, has four feed zones, 1550 m, 1697 m, 1870 m and 1920 m. The well was, therefore, interpreted as a multi-feed well, and then MULFEWS was applied for the coupled simulations. The reservoir properties of multiple feed zones were given by those of the relevant grid blocks of the reservoir model. Fig.9 shows the simulated changes in reservoir enthalpy and mass flow rates over time. The results of the coupled simulation predicted that the mass flow rates of H-27 would gradually decrease, because the reservoir enthalpy at the deeper feed zones 1870 m and 1920 m would decrease. The decrease of the deeper enthalpy is considered to occur due to the contamination of shallower water to the deeper feed zones, because the chloride concentration has been actually decreasing.

One of the advantages of the coupled simulation is to predict the change of wellhead pressure of production well over time as well as the mass flow rate, which is unique in comparison with the ordinary simulation method that usually fixes the wellhead pressure at the operation pressure as a initial calculation condition. The coupled simulation forecasted the rapid decrease of the wellhead pressure of H-27, reflecting its decrease of the reservoir enthalpy.

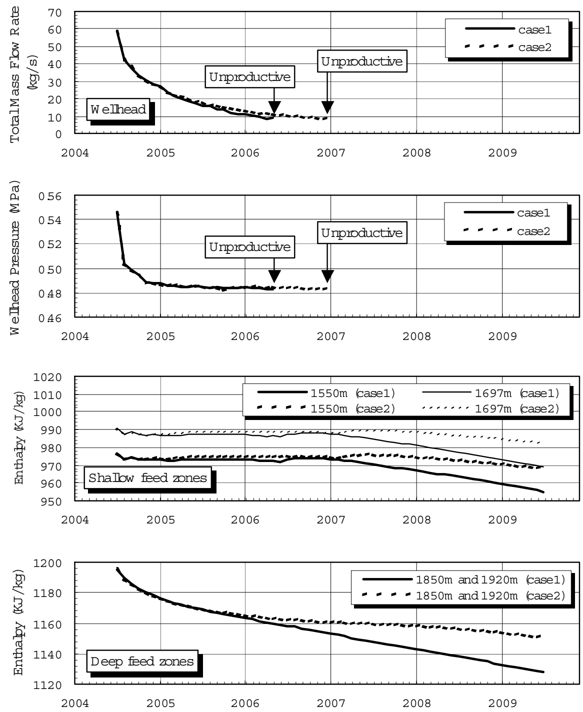

Figure 9: Predicted changes in the reservoir enthalpy and mass flow rate of the well H-27

5.3 Predicted power recovery by drilling make-up wells

Fig. 10 shows the predicted recovery of the power output considering that a make-up well will be drilled every year targeting the NE4 fault, southern part of the production area. The result suggested that the plant power output could be successfully made recovery to 110M. The conclusion based upon the coupled simulations is that we could maintain the power output at the level of 100 MW to 110 MW within 5 years in the future by drilling a make-up well every year, although the power output would continue to decline with the annual power decline rate of around 4% due to the cooling of the production zones.

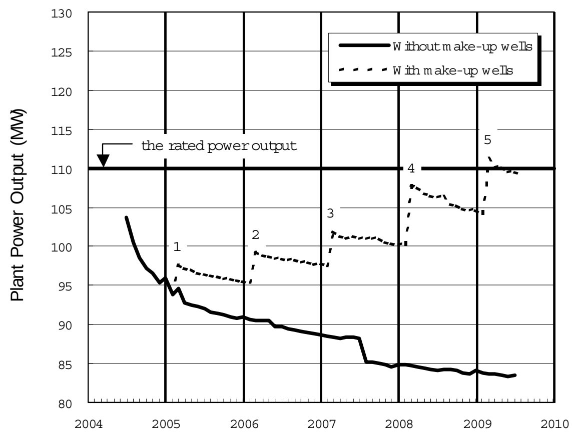

Figure 10: Predicted recovery of the power output by drilling a make-up well every year

6. CONCLUSIONS

1) In order to realistically define the exploitation strategy for an optimum power plant operation and reservoir management, a new simulator was developed to couple a reservoir simulator to a wellbore simulator and a pipeline network simulator. This simulator was applied to forecast middle-term power outputs for the Hatchobaru power plant, Japan. TOUGH2, WELLFLOW for wells with single-feed zone and MULFEWS for wells with multi-feed zones and TPGS were the coupled simulators.

2) The three-dimensional reservoir model consists of 3960 grid blocks covering 16.5 km^2. The reservoir model involves 17 production wells and 8 reinjection wells. The coupled simulation was successfully performed to predict the change of power output of the Hatchobaru power plant within five years in the future.

3) The simulated results predicted that the power output would continue to decline over time with the annual decline rate of 4%. Since the simulated reservoir enthalpies at the production zones were predicted to decrease, the main reason of the power decline is considered the cooling of the production zones. It would occur due to return of the reinjected water and contamination of the lower temperature fluids around wells to the production zones. The future decline of the productivity of the multi-feed wells can be explained by dominant cooling of the deeper feed zones rather than the shallower feed zones where are already cooled by the effects of reinjection.

4) Results of the case studies indicated that the relocation of the reinjection area so that the reinjected water should be partially distributed to the north with keeping far away from the production zones is effective to mitigate the cooling of the production zones. In addition, it would be possible to make recovery to the rated plant power output of 110 MW within five years by drilling a make-up well every year.

5) It was successfully demonstrated that the coupled with the reservoir, wellbore, and piping network simulators allowed changes in reservoir properties that, in turn, induced the changes in well productivities, and thereafter influenced the fluid conduction system operation. The coupling of simulators will also allow studying the inverse process, i.e., the effects on reservoir conditions due to variations in plant operation conditions.

6) Accordingly, it is expected that optimum drilling-target positioning and operation settings of production wells can be analyzed using the coupled simulators more precisely and practically for different exploitation schemes, which will clarify the optimum allocation of production and reinjection wells that prevents overproduction and cooling of production zones.

ACKNOWLEDGEMENTS

We highly appreciate and express our thanks to the staffs of the geothermal section and the Hatchobaru power plant of Kyushu Electric Power Company Inc. for their cooperation in the data provision, selection of observation wells and technical advice and for their permission to publish this data.

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