PROCEEDINGS, Twenty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 26-28, 2004
SGP-TR-175

DEVELOPMENT OF THE MULFEWS MULTI-FEED WELLBORE SIMULATOR

Hiroyuki Tokita[1] and Ryuichi Itoi[2]

1. West Japan Engineering Consultants, Inc., 2-1-82 Watanabe-dori, Chuo-ku, Fukuoka, 810-0004, Japan, e-mail: tokita@wjec.co.jp

2. Department of Earth Resources Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan, email: itoi@mine.kyushu-u.ac.jp

ABSTRACT

MULFEWS (a multi-feed wellbore simulator) has been developed to interpret the discharge mechanisms of a geothermal production well with multiple feed points or zones, which is seen ordinarily among wells at the Hatchobaru geothermal field in Japan. MULFEWS, the numerical model of which describes a well surrounded by porous reservoirs, was designed so that it can be used not only stand alone, but also coupled with a reservoir simulator. The main input data for MULFEWS are the depths of the feed zones together with the reservoir properties of each feed zone such as pressure, temperature or steam quality and permeability-thickness product, in addition to the casing design of the well. The main output are the mass deliverability curves as well as the pressure, temperature, flow-rate, and velocity profiles in the well while flowing. When MULFEWS was used for PTS (Pressure, Temperature, and Spinner) well logging data analysis at the Hatchobaru geothermal field, changes with time in the surrounding reservoir properties of each feed zone were quantitatively explained.

1. INTRODUCTION

In order to identify the depths of feed zones of geothermal production wells and the characteristics of those feed points, PTS (Pressure, Temperature, and Spinner) well logging has been conducted at the Hatchobaru geothermal field since 1993 during the periodical inspection of the power plants. Results of PTS well loggings, conducted for 25 production wells to date, indicate that the wells commonly have several feed zones as shown in Fig.1. The average number of feed zones is approximately four. Many of the feed zones show the conditions of both steam and water phases, suggesting that a steam-water two phase is distributed extensively in the vicinity of the well, or that the liquid water begins flashing in the vicinity of the well in the reservoir, due to pressure decline during the flow, although the reservoirs are basically of water-dominated type.

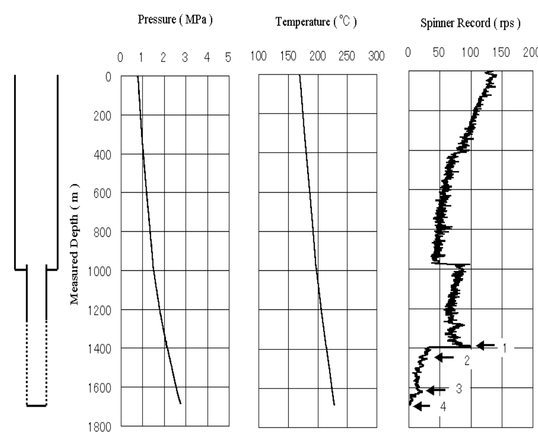

Figure 1 Typical PTS well-logging records for the production well with multiple feed zones at the Hatchobaru geothermal filed

A wellbore simulator has been used to distinguish the depths of feed zones and quantitatively evaluate the mass flow rate and its enthalpy for each feed zone. These data are then clarified through comparison between the measured and the calculated distributions of pressure, temperature and the spinner records for the well. The existing wellbore simulators, such as WELLSIM (Gunn and Freeston, 1991), GWELL (Aunzo et al., 1991) and WELLCARD (Takahashi, 1988, Takahashi et al., 1998), are available for geothermal well logging data analyses. These wellbore simulators have unique features, for example, functions to treat the effects of high concentrations of non-condensable gases included in the geothermal fluids such as CO_2 , as well as flow patterns. These functions have been developed to improve the precision of the well-logging data analysis. The application of these wellbore simulators is, however, mostly limited to the interpretation of the flow within the well, because they were basically developed as a tool of well-logging data analysis. Accordingly, they have some difficulty, unless they are coupled with a reservoir simulator or otherwise modified, in directly interpreting the reservoir properties of each feed zone surrounding the well, such as the static pressure, temperature and permeability.

Itoi et al. (1983) developed a wellbore simulator that treats the fluid flows in both the reservoir and the well for a single feed zone, by taking into account the fact that the feed point is an interface between the reservoir and the inside of the well. The main input data for this simulator are the wellhead conditions and the main output data are the reservoir properties. Thus, this wellbore simulator has been very useful, in particular during the development of the second unit (55MW) at the Hatchobaru geothermal field, for evaluating the distributions of the reservoir properties surrounding the existing production wells to decide the drilling targets for additional wells. Once the commercial operation of the second unit started in 1990, forecasting the mass flow rates of steam and water at the wellhead of the existing production wells became more important in terms of the reservoir management. For this purpose, Tokita et al. (2002) modified the above wellbore simulator such that it can forecast the wellhead conditions of the existing wells based on the reservoir properties. This modified simulator was named WELLFLOW, and is available for a production well surrounded by a single-phase or a two-phase reservoir, but it can handle only a single feed zone.

Regarding a wellbore model including the effects of multiple feed zones, Freeston and Hudgu (1987) presented a preliminary study, in which a model including two feed zones was developed. They illustrated that a wellbore simulator allowing fluid to enter a well at more than one feed zone can explain the characteristics of the output and enthalpy curves and give information on the contribution each makes to the total. Considering that the production wells at the Hatchobaru geothermal field commonly have multiple feed zones, a multi-feed wellbore simulator named MULFEWS has been developed by modifying WELLFLOW. In this paper, the basic program design and some examples of field data analysis using MULFEWS are presented.

2. DEVELOPMENT OF MULFEWS

2.1 Basic Equations

2.1.1 Fluid Flow in the Reservoir Surrounding the Wellbore

Assumptions to simplify the development of computer code are made such as the flow in a reservoir surrounding the well is under steady state and the reservoir of a homogeneous porous type. The flow is described as a radial flow, which obeys Darcy's law. The geothermal fluid is treated as pure water, and the fluid shows either a water single phase or vapor and water two-phase, 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 phase]

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

[Two phases of water and vapor phases]

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

When the water pressure decreases below the saturation pressure with respect to its temperature due to pressure loss during flowing, the fluid begins flashing in the reservoir. As the flashing point is a location of the boundary between the water single 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 P_{sat} at the flashing point of radial distance r_{sat}.

[Water-phase region]

$$Q = \frac{2\pi kh}{\left\{ \ln(\frac{R}{r_{sat}}) + S \right\}} \frac{(\mathrm{Pr} - P_{sat})}{\nu_w} \quad \dots\dots\dots (3)$$

[Two-phase region]

$$Q = \frac{2\pi kh}{\left\{ \ln(\frac{r_{sat}}{r_w}) + S \right\}} \left\{ \int_{P_{feed}}^{P_{sat}} \frac{1}{\nu_t} dp \right\} \dots\dots (4)$$

By substituting Eq. (3) for (4), the flow rate with flashing in the reservoir can be represented as follows:

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

…….. (5)

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); $\boldsymbol{r}_{sat}$ is the radius where the fluid start flashing in the reservoir(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).

2.1.2 Fluid Flow in the Well

The fluid at the depth of the feed zone changes its flow direction from horizontal to vertical in the well. Assuming that the well is vertical and the specific enthalpy of the fluid is constant while flowing, ignoring the heat transfer between the fluids in a well and the surrounding formation, the basic flow equation in the well can be represented by the conservation equations of mass and momentum and expressed as follows (Sekoguchi, 1967, Itoi et al., 1983, 1988).

$$\left.\begin{array}{l} \dfrac{dp}{j(j\upsilon+\dfrac{g}{j\upsilon})}+\dfrac{2jD}{\lambda}\dfrac{d\upsilon}{j\upsilon+\dfrac{g}{j\upsilon}}+dH=0 \\ \quad where \\ j=\dfrac{Q}{F}\sqrt{\dfrac{\lambda}{2D}} \end{array}\right\} \ldots\ (6)$$

When the single phase water reaches its saturation pressure while flowing upward in the well, Eq.(6) can be rewritten as (7) for the single phase flow region, because the change in specific volume of liquid water due to the pressure change can be ignored.

$$\frac{\upsilon}{j^2\upsilon^2+g}(Psat-Pw)+Hw=0 \ \ldots\ldots\ldots\ldots..\ (7)$$

The fluid flow between the flashing point and the wellhead, which is in a two-phase condition, is described by the following equation of integral form.

$$\frac{1}{j}\int_{Psat}^{Phead}\frac{dp}{j\upsilon+\dfrac{g}{j\upsilon}}+\frac{D}{\lambda}\ln\frac{j^2\upsilon^2{}_{head}+g}{j^2\upsilon_{sat}+g}+H-Hw=0 \quad \ldots\ldots\ (8)$$

When the feed zone shows two-phase conditions, the above equation can be rearranged as follows, using P_{feed} and υ_{feed} instead of P_{sat} and υ_{sat}, respectively.

$$\frac{1}{j}\int_{Pfeed}^{Phead}\frac{dp}{j\upsilon+\dfrac{g}{j\upsilon}}+\frac{D}{\lambda}\ln\frac{j^2\upsilon^2{}_{head}+g}{j^2\upsilon_{feed}+g}+H=0 \quad ..\ldots\ldots\ (9)$$

Where υ is the specific volume of the two-phase fluid (m^3/kg); υ_{head}, υ_{sat} and υ_{feed} are the specific volume under the wellhead pressure, saturation pressure and feed zone pressure (m^3/kg); g is the gravitational acceleration (m/s^2); D is the wellbore diameter (m); λ is the friction factor of the wellbore(-); H and Hw are the lengths of the two-phase flow and water-phase flow regions (m); F is the cross-sectional area inside the wellbore (m^2); P_{head}, $P_{sat,}$ and P_{feed} are the wellhead pressure, the saturation pressure and the feed zone pressure (Pa)

2.2 MULFEWS Program Design

2.2.1 Representation of Multiple Feeds

The simplified representation of a coupled wellbore and reservoir model with multiple feeds adopted for MULFEWS is shown in Fig.2. It is not clear yet whether the fluid flows into the wellbore from multiple feeds occurs simultaneously or gradually after discharge at the wellhead begins, because of the lack of this kind of monitoring data. In order to simplify a numerical model with multiple feeds, the assumption is made that the inflow from the deepest feed zone occurs first, and then subsequent inflows occur at the shallower depths, due to the newly formed pressure gradients between the pressures inside the well and the surrounding reservoirs. Namely, the first inflow from the deepest feed zone induces the shallower feed zones to begin to inflow, which is an assumption that is unique to the design of MULFEWS.

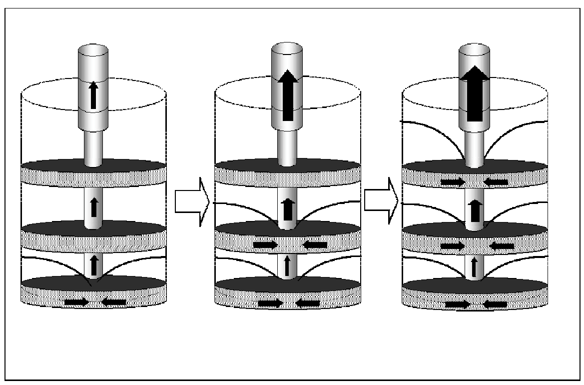

Figure 2 Representation of the multi-feed phenomena

Figure 3 shows a representation of the numerical model of a well having multiple feed zones for

MULFEWS. In this model, the well is connected to three different horizontal reservoirs, each of which has specific characteristics such as pressure, fluid temperature and permeability-thickness product, kh. The pair of local pressure and temperature for the water phase, or the local pressure and steam mass ratio, quality, for the two-phase fluid gives the specific enthalpy, respectively. The surrounding reservoir properties are individually defined as the input data, and also held constant.

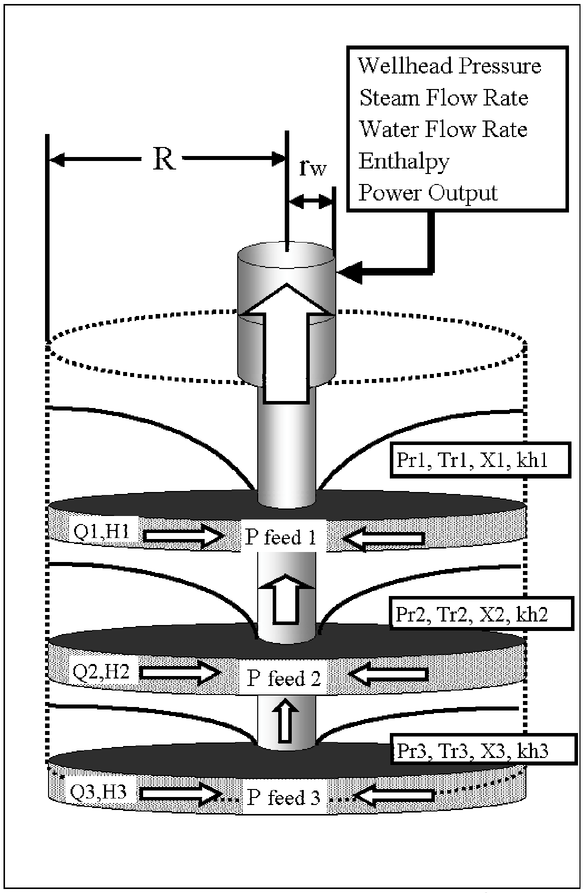

Figure 3 Schematic numerical model of a well surrounded by individual reservoirs

2.2.2 Flow Chart of the Program

The flow chart of MULFEWS is shown in Fig.4. Main use of MULFEWS is to locate the depths of each feed point or zone as well as to predict well deliverability by specifying properties of respective reservoir related to each feed zone. The input data are the depths of the feed zones together with the properties of respective reservoir in addition to the casing design of the well. A mass flow rate from the deepest feed point into the wellbore should be given in a specific range as one of the control parameter.

During the analysis, the deepest feed zone pressure is first obtained with MULFEWS, by calculating the horizontal fluid flow in the reservoir based on the reservoir properties with the defined mass flow rate for the depth. Next, it obtains the upper feed zone pressure by calculating the vertical flow between the feed zones. Once the upper feed zone pressure is obtained, the mass inflow rate from the depth can be calculated on the basis of the pressure gradient, which is formed at the surroundings of the feed zone. The mixing of the fluids therefore occurs at the depth, where both the mass and enthalpy of the mixed fluid should be recalculated. Similarly, the calculations of the feed zone pressure and the subsequent mixing of fluids from each feed zone proceeds up the well until the wellhead is reached.

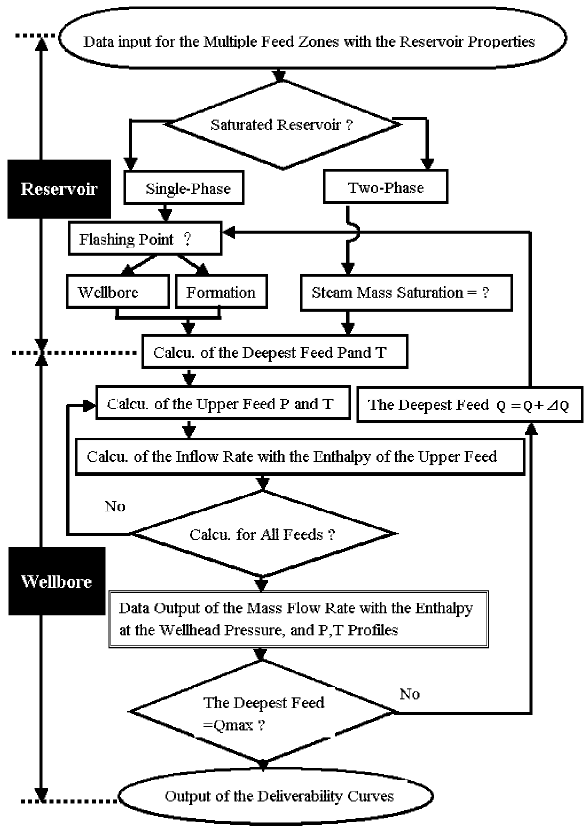

Figure 4 Program flow chart of MULFEWS

Strictly speaking, the feed zone pressure should be recalculated taking the influence of the mixing into account. This adjustment was, however, ignored for convenience to avoid tedious computation. Otherwise, it will require an enormous amount of time to calculate every feed zone, because repeated calculations are necessary until the solutions satisfy a given convergence criteria. MULFEWS is tentatively programmed so that it can deal with up to four feed zones, which is the average number of feed zones for Hatchobaru wells. The procedure of the calculation starts by giving the minimum value of the mass flow rate of the deepest feed zone, and proceeds to the maximum value by increasing it step wise, which are defined as control factors. The fluid flow in the reservoir with a given mass flow rate of the deepest feed zone can be calculated using Eqs.(1) to (5), followed by the calculations in the well that proceeds from the bottom to the wellhead, using Eqs.(6) to (9), taking the variations in well casing diameter into account. Thus, the main results are the mass deliverability curves as well as the profiles of the pressure, temperature, and average velocity in the well.

2.2.3 Model Calculations

Model calculations using MULFEWS were carried out using reservoir properties shown in Table 1, which are based on those at the Hatchobaru geothermal field. The results are shown in Figs.5, 6 and 7. Figure 5 shows the simulated deliverability curves, representing the relationship between the wellhead pressure and the steam, water, and total mass flow rates together with the enthalpy. Figure 6 focuses on the individual mass flow rate from each feed zone with the enthalpy. On the other hand, Fig.7 shows the simulated pressure, temperature, and average velocity profiles at the wellhead pressure of 0.8 MPa, which is the average operating wellhead pressure at Hatchobaru.

Table 1 Input data for the model calculations

Feed Zone	Reservoir properties			
	Depth (m)	Press. (MPa)	Quality (-)	kh (darcy m)
Feed1	1,200	3	0.5	2.0
Feed2	1,400	5	0.4	1.5
Feed3	1,600	7	0.3	1.0
Feed4	1,800	9	0.2	0.5

The simulated deliverability curves indicate that the inflow rates from the shallower feed zones increase, as the wellhead pressure decreases, reflecting the increase of the pressure gradients between the feed zone pressures and the surrounding reservoir pressures. In other words, the inflow from the shallower feed zones is likely to be limited at higher wellhead pressures. This means that the number of feed zones possibly changes in accordance with the wellhead pressure. With lower wellhead pressures, the enthalpy at the wellhead is higher in this case due to the increased inflow of higher enthalpy fluid from the shallower feed zones, which are surrounded by the two-phase reservoirs. Such a well characteristic has actually been observed in Hatchobaru. We should notice, however, that the enthalpy at the wellhead does not always increase, but sometimes decreases depending on the inflow enthalpies from the shallower feed zones. When the shallower feed zones have lower enthalpy fluid, the specific enthalpy at the wellhead is expected to decrease at lower wellhead pressures.

Not only the pressure and temperature profiles, but also the mass flow rate and the average velocity profiles in the well help us to analyze the feed zones with the inflow of mass and energy. We should notice that it is very difficult, particularly for the case of a two-phase flow, to distinguish the feed zones only from the pressure and temperature profiles without the mass flow rate and/or the velocity profiles. That is why we need spinner records in addition to the well logging pressure and temperature profiles.

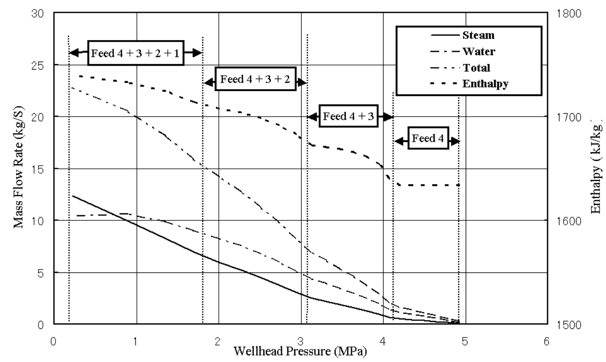

Figure 5 Simulated mass deliverability curve of a well with four feed zones

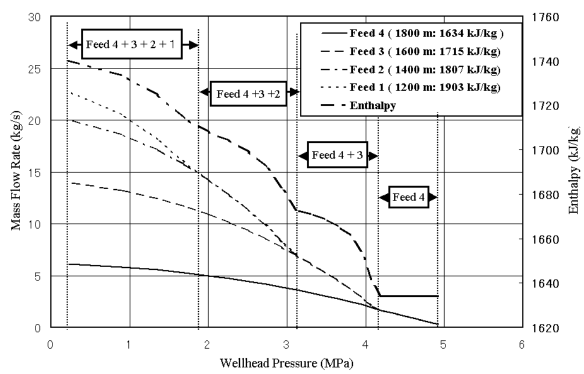

Figure 6 Simulated individual mass flow rates from each feed zone and the wellhead enthalpy

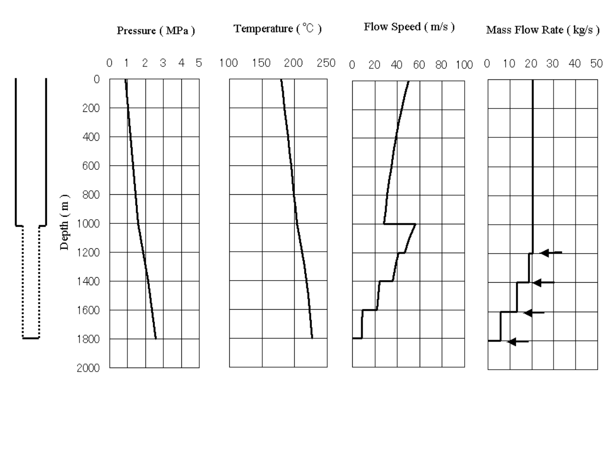

Figure 7 Simulated pressure, temperature, flow rate and velocity profiles in a well with four feed zones.

3. APPLICATION OF MULFEWS FOR FIELD DATA ANALYSIS

3.1 Multi-Feeds of Two-Phase Condition

3.1.1 Matching on the PTS Well Logging Records

In order to verify its validity, MULFEWS was used to analyse the PTS well logging data and the mass deliverability data of Wells 2H-16 and 2H-18 at Hatchobaru . The former has two-phase multiple feed zones, and the latter has single (water)-phase multiple feed zones. During the data analysis the reservoir properties with respect to each feed zone of these wells should be repeatedly revised through matching until simulated pressure, temperature, velocity profiles and mass deliverability curves fit well with the measured data.

Figures 8 and 9 show the comparisons of the measured and simulated pressure and temperature profiles, and of the velocity profile during flow in Well 2H-16, respectively. The results of the PTS well logging carried out for Well 2H-16 during the flow in 1993 indicated that the well had four main feed zones, at depths of 1,392 m, 1,433 m, 1,634 m and 1,678 m, where appreciable changes in spinner rotations were recorded. The data analysis using MULFEWS suggested that the mass flow rates and the inflow fluid enthalpies supplied from the feed 1 to feed 4 are 5.7 kg/s of 1,411 kJ/kg, 4.1 kg/s of 1,377 kJ/kg, 7.7 kg/s of 1,323 kJ/kg and 7.8 kg/s of 1,302 kJ/kg, respectively. Figure 9 should be used only as a reference to discuss the validity of the inflow rates of each feed zone because of the difference between the simulated velocity (m/s) and the spinner rotation speed (rps). Both figures show that the simulated profiles successfully match the PTS well-logging records of 2H-16.

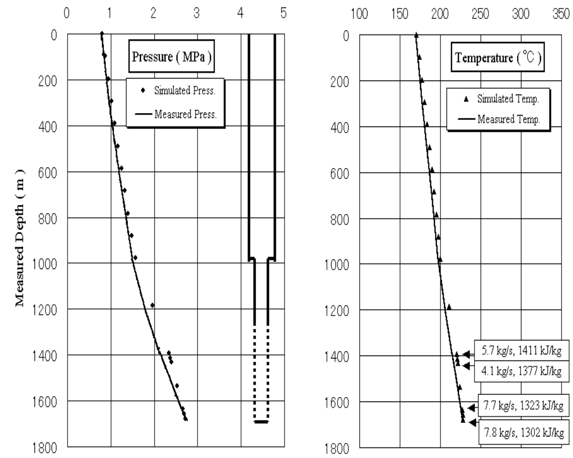

Figure 8 Matching on the PTS well-logging profiles of Well 2H-16

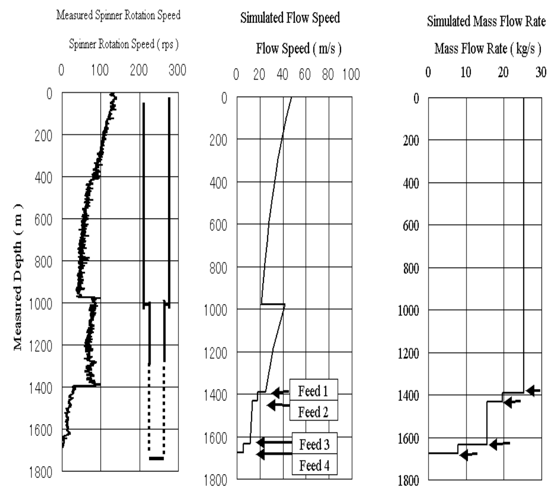

Figure 9 Comparisons between the simulated velocity and the spinner rotation record of Well 2H-16

3.1.2 Matching on the Mass Deliverability Curves

Figure 10 shows the matching on the mass deliverability curves and Table 2 summarizes the reservoir properties obtained through the matching. The well deliverability has usually been measured against three kinds of wellhead pressures at the operating pressure and the operating pressure ± 0.2 MPa. The steam and water mass flow rates were measured by use of an orifice and a weir after separating produced fluids with a separator installed at each production wellhead. As shown in Figs.8, 9 and 10, the reservoir properties of each feed zone satisfactorily explain not only the PTS well logging profiles, but also the mass deliverability curves, confirming that the estimated reservoir properties are appropriate.

Feed Zone	Reservoir properties			
	Depth (m)	Press. (MPa)	Quality (-)	kh (darcy m)
Feed1	1,392	5.20	0.15	1.5
Feed2	1,433	5.49	0.12	1.0
Feed3	1,634	5.69	0.08	1.0
Feed4	1,678	6.18	0.05	2.0

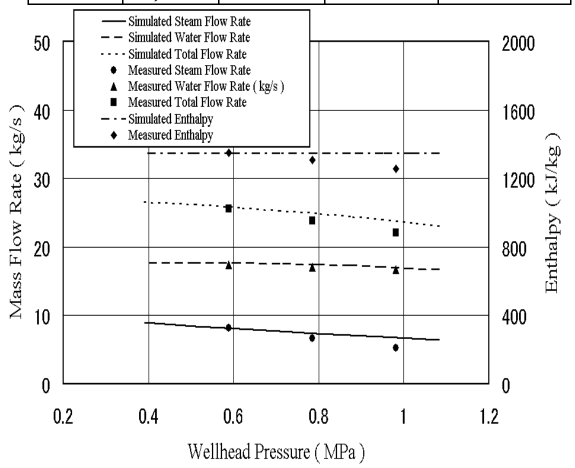

Figure 10 Matching on the deliverability curves of Well 2H-16

Table 2 Simulated reservoir properties of each feed zone of Well 2H-16 in 1993

3.1.3 Simulated Change with Time in the Reservoir Properties

The change with time in the reservoir properties can be interpreted by conducting similar matching analyses for the existing PTS well-logging records with the mass deliverability data. It was suggested that all the reservoir pressures of each feed zone of Well 2H-16 had decreased by 0.8 to 1.3 MPa within 6 years after 1993 due to the effects of the production, as shown in Fig.11. The qualities, representing the steam mass fractions in two-phase regions surrounding the feed zones, have increased gradually in accordance with the reservoir pressure declines. The discharge fluid enthalpy at the wellhead, therefore, increased. It is forecasted that the two-phase regions have expanded in reservoir around Well 2H-16.

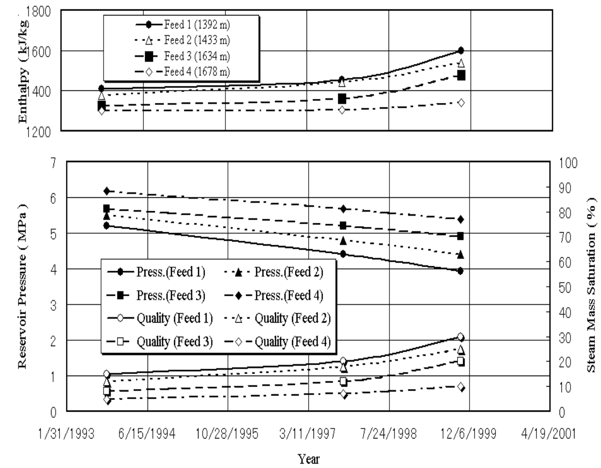

Figure 11 Simulated changes with time in the reservoir properties of Well 2H-16

3.2 Multi Feeds of Single-Phase Condition

The same approach was attempted with the single feed well, 2H-18, which has two water-phase feed zones, at 1,243 m and 1,251 m. The PTS well loggings conducted to date indicate that the majority of the existing production wells at Hatchobaru are of multi-feed type with feed zones of two-phase, reflecting that the reservoir temperatures of the field are generally close to the saturation temperature with respect to the reservoir pressure. We can therefore hardly find a well with water single-phase feed zones, except in the area where the reservoir temperature has remarkably decreased due to the inflow of relatively low temperature reinjected water, such as Well 2H-18. The PTS well logging, conducted for 2H-18 during the flow in 1993, clarified that the flashing point was reached at 744 m in the well at a wellhead pressure of 0.7 MPa. The measured steam and water flow rates and the enthalpy at the wellhead are 5.1 kg/s, 36.4 kg/s and 953 kJ/kg, while the simulated values are 3.8 kg/s, 27.0 kg/s and 932 kJ/kg, respectively. The simulated mass flow rates are slightly smaller than the measured ones. The reservoir properties obtained using MULFEWS and confirmed by matching are shown in Table 3. Figures 12 and 13 show the matching on the pressure and temperature profiles, and the velocity profile in Well 2H-18, respectively. It is estimated from the analyses that the mass flow rates and the enthalpies supplied from the two feed zones at the depths of 1,243 m and 1,251 m into the well should be 26.6 kg/s of 932 kJ/kg and 4.2 kg/s of 932 kJ/kg, respectively. As shown in the spinner records, the upper feed zone is considered to be dominant as compared with the deeper feed zone, reflecting the difference of the kh values. The simulated flashing depth of 703 m almost coincides with the measured flashing depth of 744 m.

Table 3 Analyzed reservoir properties of Well 2H-18 in 1993

Feed zone	Reservoir properties			
	Depth (m)	Press. (MPa)	Temp. (℃)	kh (darcy m)
Feed1	1,243	7.9	217	4.0
Feed2	1,251	8.0	217	1.0

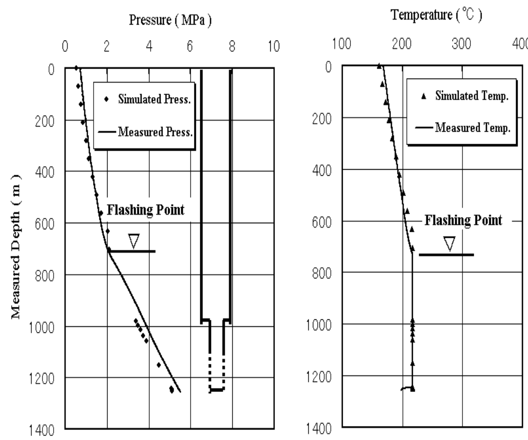

Figure 12 Matching on the pressure and temperature profiles of Well 2H-18

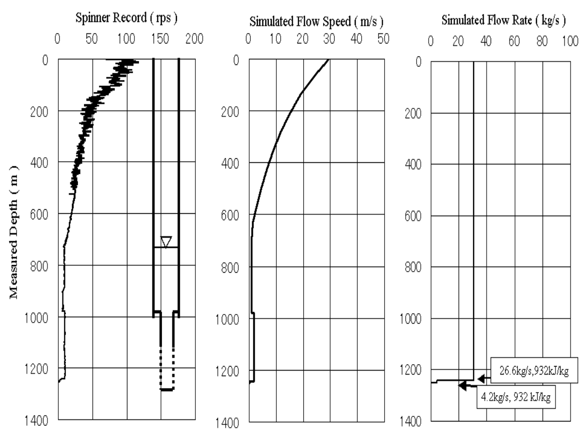

Figure 13 Matching on the velocity profile in Well 2H-18

4. CONCLUSIONS

In some geothermal fields, we often face difficulty in explaining the complicated well characteristics that is probably caused by the presence of multiple feed zones in a well. In this paper, a conceptual model of the multi-feed phenomena in the well and the numerical design of a multi-feed wellbore simulator named MULFEWS are introduced. The field data from the Hatchobaru wells were analyzed with MULFEWS, and the mass flows and energy inflow rates from the multiple feed zones together with the respective reservoir properties were quantitatively explained. The changes with time in the reservoir properties of each feed zone were also described. Good matchings between the simulated and the measured data were obtained for the wells with feed zones where either two-phase or single-phase fluids flows into the wellbore. Accordingly, we confirm that MULFEWS is useful as an analytical tool for understanding the well characteristics of multiple feed zones together with their reservoir properties. It can also be applied to predict deliverability of a well before discharge by assuming the reservoir properties. In addition, a long-term power output prediction for the power plant can be made because it is designed to easily couple with an existing reservoir simulator, and this should be examined as a next step.

REFERENCES

Aunzo, Z. P., Bjornsson, G. and Bodvarsson, G. S. (1991) “Wellbore Models GWELL, GWNACL, and HOLA User’s Guide” *Lawrence Berkeley laboratory Report LBL-31428, DE92 009494, October 1991*

Freeston D. H. and Hadgu Teklu (1987) “Modeling of Geothermal Wells with Multiple Feed Points: A Preliminary Study” *Proceedings of the 9th New Zealand Geothermal Workshop 1987*, 59-64

Gunn C. and Freeston D. (1991), “An Integrated Steady-State Wellbore Simulation and Analysis Package.” *Proceedings,13th New Zealand Geothermal Workshop 1991*, 161-166

Itoi R., Fukuda M., Sekoguchi K. and Iwaki T. (1983) “Theoretical Study on Steam and Water Flow Rates from Geothermal Production Wells.” *Journal of the Geothermal Research Society of Japan, Vol. 5. No.4 (1983)* 235-248 (in Japanese with English abstract)

Itoi, R., Kakihara, Y., Fukuda, M. and Koga, A. (1988) “Numerical Simulation of Well Characteristics Coupled With Steady Radial Flow in a Geothermal Reservoir.” *International Symposium on Geothermal Energy, Exploration and development of Geothermal Resources, Kumamoto and Beppu, Japan*, 201-204

Sekoguchi K. (1967) “Flow Characteristics of Flashing Mixture of Steam and Water through Well.” *Memories of the Faculty of Engineering. Kyushu*

University, 27, 1, 46-49 (in Japanese with English abstract)

Takahashi, M. (1988) "A Wellbore Flow Model in the presence of CO_2 Gas." *Proceedings,13th Workshop on Geothermal Reservoir Engineering. Stanford University*, 151-157

Takahashi M., Kikuchi K. and Akibayashi S. (1998) "Development of Wellbore Flow Simulator (WELLCARD-II) Applicable up to Annular-Mist Flow in Geothermal Wells –Investigation about Friction Factor –." *Journal of the Geothermal research Society of Japan, Vol.20, No.4 (1998),* 243-261 (in Japanese with English abstract)

Tokita H., Momita M., Matsuda K., Takagi H., Tosha T., and Koide K. (2002) "A Rough estimation of Deep Geothermal Potentials of the Hohi and Ogiri Areas, Japan with Simplified Numerical Model" *Proceedings of 23rd Annual PNOC-EDC Geothermal Conference, 2002*, 193-198