Numerical Simulation of Instability of Geothermal Production Well

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ABSTRACT
Oscillations in wellhead pressure are sometimes observed in production wells with multiple feedzones. This instability affects stable steam production, and in extreme cases may cause steam production from the well to cease altogether. In this study, we developed a coupled model of transient wellbore and reservoir flows with two well feedzones. Then, numerical simulations were carried out to evaluate the effects of reservoir temperature on the flow characteristics of wells with multiple feedzones. These simulation results show that the cyclic changes in wellhead pressure are caused by temporal changes in the flash point depth within the wellbore.

1. Introduction
Steady, reliable steam production is essential for stable operation of a geothermal power plant. Production wells are drilled to penetrate fractured reservoir zones at different depths to enhance productivity. However, cyclic production characteristics have been observed in wells that intersect multiple permeable production zones where fluids of different temperatures may enter the wellbore (Iwata et al., 2002; Kumagai et al., 2012). These wells ultimately stopped supplying steam to the power plant because the fluctuating wellhead pressure eventually fell below the production header pressure. This unstable production well behavior is highly undesirable from a resource management standpoint.

In order to understand the conditions (either in the wellbore or the reservoir) that lead to this kind of discharge instability, numerical analysis using a coupled flow model of the wellbore and the reservoir is required. Tokita and Itoi (2004) developed a coupled model for multiple-feedzone wellbore simulation under steady state assumptions. But such a steady state model cannot describe wellbores exhibiting cyclic changes in wellhead pressure with time. In this study, we developed a coupled model of wellbore and reservoir transient flows involving two feedzones and used it for simulation studies to examine the effects of reservoir and wellbore conditions on well discharge characteristics.

2. Instability of Production Wells at Sumikawa
The Sumikawa geothermal field is located in Akita Prefecture, northern Japan. A 50 MW steam-turbine geothermal power plant started operating in 1995 with 7 production wells and 10 reinjection wells. All of the separated water and a portion of the condensed water from the cooling tower are injected back into the reservoir. Repeated tracer tests indicated a return of reinjected water to the production wells (Kumagai et al., 2004). A couple of production wells exhibited cyclic changes in wellhead pressure and eventually stopped discharging. This may have been caused by return of low-temperature reinjected water into the production wells. Figure 1 shows a history of wellhead pressure in Well SA-6. This well was completed with two feedzones at different depths, and exhibits unstable behavior. The wellhead pressure starts oscillating soon after discharge is initiated with a cycle period of about 100 minutes and amplitude 0.12 MPa. The well eventually stops discharging after about 10 days. But after a period of recovery, the well can be restarted again and tends to repeat this cycle of discharge followed by flow interruption.

3. Simulation Model
We used the WELLBORE simulation code developed by Miller (1983). WELLBORE is a computer program that simulates...
one dimensional transient non-isothermal flow of single-phase water and two-phase steam-water mixtures in a wellbore. We modified the code to simulate wellbore flow with two feedzones (the original WELLBORE could only treat wellbore flow with one feedzone). Thermodynamic properties of water were calculated using a software package for thermophysical properties of fluids called PROPATH (PROPATH group, 1999).

Figure 2 shows a conceptual model of the fluid flow in the wellbore and the reservoir. The well has two zones through which single-phase liquid water enters. Fluid from the deep reservoir enters the wellbore at the deep feedzone and flows upward. Then, this fluid mixes with the fluid from the shallow reservoir at the shallow feedzone. This mixed fluid rises further up the wellbore and then starts flashing. Thereafter, the steam fraction increases as the wellhead is approached.

![Figure 2. Conceptual model of fluid flow in reservoir and wellbore.](image)

### 3.1 Reservoir Model

A conventional constant-thickness horizontal radial-flow porous-medium reservoir model was used. Reservoir pressure in the radial coordinate system is governed by:

\[
\frac{\partial P}{\partial t} = -k \left( \frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} \right) \tag{1}
\]

where \(c\) is the fluid compressibility (1/Pa), \(k\) is the rock permeability (m²), \(P\) is pressure (Pa), \(r\) is radial distance (m), \(t\) is time (s), \(\phi\) is porosity, and \(\mu\) is the coefficient of viscosity (Pa s).

In this study, the heat conduction equation in radial geometry is also used to calculate the heat transfer between the wellbore and the surrounding rock formation:

\[
\rho_c c_w \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{T}{r} \frac{\partial T}{\partial r} \right) \tag{2}
\]

where \(c_w\) is the specific heat of the rock (J/kg K), \(T\) is the rock temperature (°C), \(\lambda\) is the heat conductivity of rock (W/m K) and \(\rho_c\) is the rock density (kg/m³).

### 3.2 Wellbore Model

Transient two-phase flow in the wellbore is described by the mass, momentum and energy conservation principles (Miller, 1983; Atomic Energy Society of Japan, 1993):

\[
\frac{\partial \rho_m}{\partial t} + \frac{\partial}{\partial z} (G) = 0 \tag{3}
\]

\[
\frac{\partial G}{\partial t} + \frac{\partial}{\partial z} (Gv) = -\frac{\partial P}{\partial z} - \rho_m g \sin \theta - F_w \tag{4}
\]

\[
\frac{\partial}{\partial t} \left[ \rho_m (E_m - P/\rho_m) \right] + \frac{\partial}{\partial z} (GE_m) = q \tag{5}
\]

where,

\[
E_m = e + P/\rho_m \tag{6}
\]

\[
F_w = \frac{f \rho_m v^2}{4 r_w} \tag{7}
\]

\[
G = \rho_m v \tag{8}
\]

\[
q = \frac{H (T_w - T_r)}{2 r_w} \tag{9}
\]

and where \(e\) is the internal energy per unit mass (J/kg), \(E_m\) is the specific enthalpy or total energy per unit mass (J/kg), \(f\) is the coefficient of pipe friction, \(F_w\) is the frictional pressure loss per unit volume (Pa/m), \(g\) is the gravitational acceleration (m/s²), \(G\) is the mass flow rate per unit area (kg/s-m²), \(H\) is the coefficient of heat transfer (W/m² K), \(q\) is the heat transfer per unit volume (W/m³), \(r_w\) is the wellbore radius (m), \(T_w\) is the rock temperature surrounding the well (°C), \(T_r\) is the fluid temperature in the wellbore (°C), \(v\) is the average fluid velocity (m/s), \(\theta\) is the inclination angle of the well (rad), and \(\rho_m\) is the average fluid density (kg/m³). An additional equation of state is required to correlate fluid density, pressure and energy,

\[
\Delta P = \left( \frac{\partial P}{\partial \rho} \right) \Delta \rho + \left( \frac{\partial P}{\partial e} \right) \Delta e \tag{10}
\]

Steam-water mixture density \(\rho_m\) is calculated using a void fraction that is expressed by Smith’s formula (Smith, 1969-1970). The pipe friction factor for single-phase water flow is calculated using Karman’s formula:

\[
\lambda = \frac{1}{(1.14 + 2 \log D/e)^2} \tag{11}
\]

where \(e\) is the surface roughness of the pipe (m) and \(D\) is the pipe diameter (m). The heat transfer coefficient in Eq. (9) is calculated by (Holman, 1976):

\[
H = 0.023 \left( \frac{\rho v (2 r_w)}{\mu} \right)^{0.8} \tag{12}
\]

where \(\mu\) is the fluid viscosity (Pa s).
3.3 Fluid Flow in Wellbore With Two Feedzones

Figure 3 shows fluids mixing at the shallow feedzone. At the shallow feedzone, the mass flow rate of mixed fluid $M_{\text{total}}$ (kg/s) is given by:

$$M_{\text{total}} = M_1 + M_2$$

where $M_1$ is the fluid mass flow rate from the well’s deep feedzone and $M_2$ is the mass flow rate into the wellbore at the shallow feedzone from the shallow reservoir. The specific enthalpy of the mixed fluid $h_{\text{total}}$ (J/kg) is calculated using:

$$h_{\text{total}} = \frac{M_1 \cdot h_1 + M_2 \cdot h_2}{M_{\text{total}}}$$

where $h_1$ and $h_2$ are the specific enthalpy of the shallow reservoir fluid and deep reservoir fluid, respectively. Partial differential equations in both wellbore and reservoir were discretized using implicit finite difference techniques and solved with Thomas’ method.

4. Numerical Simulation

In this study, we assumed that the well is vertical with uniform diameter. In order to evaluate the effects of shallow reservoir temperature on wellbore flow, the temperature of the fluid entering at the shallow feedzone was either 200°C or 220°C while that of the deep feedzone fluid was fixed at 240°C. Numerical simulations were conducted by specifying reservoir and wellbore parameters and boundary conditions as follows. The permeability-thickness product of both reservoirs was taken to be $3.0 \times 10^{-12}$ m$^3$. Deep and shallow reservoir pressures were 122.6 and 92.0 bar, respectively. The well radius was 0.1 m; the well depth was 2000 m with the shallow feedzone and the deep feedzone at depths of 1700 m and 2000 m, respectively. Therefore, there is 300 m of vertical distance between the two feedzones. The boundary condition imposed on wellhead pressure was sinusoidal in time with cycle period 6000 sec (100 min) and amplitude 1.2 bar as shown in Fig.4. This prescription was taken from the measurements of wellhead pressure in Well SA-6 at Sumikawa (Fig.2).

In the simulation, a steady state condition was first created in the wellbore at a constant wellhead pressure (7 bars) by assuming that only the deep reservoir supplies high temperature fluid into the wellbore. After the wellbore flow stabilized, fluid flow into the wellbore from the shallow reservoir was added and the boundary condition at the wellhead shown in Fig.4 was imposed for the unsteady state simulation.

5. Results and Discussion

Figure 5 shows the simulated well production rate history for two cases of shallow reservoir temperature: $T_{r2}=200°C$ and 220°C. In the $T_{r2}=220°C$ case, the discharge rate shows a minor fluctuation in early times, then remains constant as 26.7 kg/s in the rest of the period. The flowrate for $T_{r2}=200°C$ ranges from 15 to 32 kg/s and exhibits oscillations with a cycling period of around 2000 s and its magnitude grows smaller with time.

Figure 6 shows the produced specific fluid enthalpy histories for the two cases. For $T_{r2}=220°C$, the specific discharge enthalpy remains constant at 1024 kJ/kg except in early times. On the other hand, the specific discharge enthalpy fluctuates with time for $T_{r2}=200°C$ over the range from 1005 to 1038 kJ/kg. Lower
shallow reservoir fluid temperature results in a larger range of variation in the produced fluid enthalpy. The enthalpies of the deep 240°C reservoir fluid and the shallow 220°C reservoir fluid are 1037.8 kJ/kg and 943.7 kJ/kg, respectively. Thus, for the \( T_{r2}=220°C \) case, the flowrates from the deep and the shallow reservoirs do not change with time and results in a constant specific enthalpy with time. However, for the \( T_{r2}=200°C \) case, the produced fluid experiences significant enthalpy change due to mixing with lower temperature fluid from the shallow 200°C reservoir of 852.4 kJ/kg and to the fluctuations of the flowrates from both reservoirs.

Saturation pressure increases with increasing fluid enthalpy, so the saturation pressure of the fluid in the wellbore changes as its enthalpy changes with time. This implies that the depth of the flash point also changes with time.

The flowrates from the shallow and deep feedzones for the \( T_{r2}=200°C \) case are illustrated in Fig.7. The flowrate at the shallow feedzone represents the fluid flowing into the wellbore from the shallow reservoir. This flowrate varies between 0 and 5 kg/s whereas that from the deep reservoir varies from 16 to 25 kg/s. These flowrates seem to be synchronized and become stabilized with time. These flowrate variations are responsible for the variation of the specific enthalpy of the produced fluid shown in Fig.6.

Figure 8 shows histories of the flash point depth and the shallow feedzone pressure for the \( T_{r2}=200°C \) case. The flash point is where single phase water flowing upward in the wellbore reaches its saturation pressure; then vapor begins to form and the mixture continues flowing upward to the wellhead with increasing steam fraction. The depth of the flash point ranges from 960 to 1060 m and exhibits changes with time. As shown in the figure, the shallow reservoir feedzone pressure increases as the flash point becomes shallower. As the flash point moves deeper, for example from A to B, the pressure at the shallow feedzone decreases from A to B.

Since the shallow feedzone is located at 1700 m depth, it lies below the flash point depths shown in Fig. 8. Thus, the height of the single phase water flow region decreases as the flash point depth increases from A to B, by about 50 m. This results in a decrease of the shallow feedzone pressure from A to B. Decrease in the pressure at the shallow feedzone leads to an increase in the flowrate of fluid that flows from the shallow reservoir into the wellbore because of an increase in the horizontal reservoir pressure gradient just outside the wellbore surface. These ascents and descents in flash point depth of the fluid in the wellbore are caused by the changes in water saturation pressure due to the enthalpy oscillation.

Based on the above, the mechanism of instability of wellbore flow can be summarized as follows. The cyclic flow from two reservoirs with different temperatures into the wellbore causes the specific enthalpy of the fluid in the wellbore to vary with time. This causes a change in the depth of the flash point, and then the pressures of the shallow feedzone as well as the deep feedzone are strongly affected as the height of the single phase water flow region in the wellbore varies. This results in the change in flowrates of fluid from both reservoirs.

6. Conclusions

1. Instability of wellbore flow in a production well with two feedzones at different depths was simulated with a coupled wellbore/reservoir model.
2. Magnitude of the cyclic discharge can be operationally significant if the fluid temperature difference between the shallow and deep production zones is large.

3. Changes in flash point depth in the wellbore control the periodic changes in wellhead pressure.

References


