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Numerical Simulation of Periodic Wellbore Flow Due to the Inflow of Low-Enthalpy Fluid

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ABSTRACT

Periodic wellbore flow, that degrades the efficiency of geothermal power generation, is occasionally observed, in production wells. Revealing the conditions and underlying mechanisms for generating the periodic flow is essential for sustainably operating geothermal power plants. We simulated transient wellbore flow with shallow and deep feed zones to study the mechanism of periodic flow due to the inflow of low-enthalpy fluid at the shallow feed zone depth. The conditions for generating periodic wellbore flow depending on the pressures and specific enthalpies of the shallow and deep reservoirs were revealed through exhaustive numerical experiments, which will significantly reduce the computational loads for simulating several operational scenarios of geothermal power plants. The responses of the periodic flow to the wellhead and reservoir pressure variations were also investigated, which implied that the same operations of a wellhead valve could potentially stabilize or destabilize, depending on the abundance of natural recharge to the reservoir. Future studies should validate and extend these findings from diverse perspectives.

1. INTRODUCTION

In production wells, periodic changes in wellhead pressure and flow rate are occasionally observed, complicating the connection of these wells to geothermal power plant facilities (Grant et al., 1979; Iwata et al., 2002; Grant and Bixley, 2011; Yanto et al., 2019; Matus et al., 2020). Thus, revealing the conditions and underlying mechanisms for generating a periodic flow is essential for the sustainable operation of geothermal power plants, which will enable to develop effective mitigation measures to stabilize wellbore flow. As per preceding studies, diverse mechanisms generate periodic wellbore flow, involving flows in a wellbore and reservoirs that intersect at multiple feed zone depths. Thus, comprehensive models, including wells and reservoirs constrained by adequate observational data, are crucial for understanding the mechanism of periodic wellbore flow observed in actual fields.

We have studied a mechanism generating periodic wellbore flow, the inflow of low-enthalpy fluid at the shallow feed zone depth, for a dozen years by simulating a production well that intersects and produces from shallow and deep reservoirs (Katayama et al., 2011, 2013; Itoi et al., 2013, 2014; Inagaki et al., 2014; Yamamura et al., 2016, 2017; Matsumoto et al., 2021). By successfully simulating transient wellbore flow, we revealed a condition for generating periodic wellbore flow through exhaustive numerical experiments (Matsumoto et al., 2021). The condition is described using the mean specific enthalpy of the reservoirs weighted by their productivity indices. Determining the generation of periodic wellbore flow without directly simulating transient wellbore flow, which significantly reduces the computational load, enables us to dynamically evaluate the stability of production wells while simulating several production and reinjection scenarios to determine the optimum operational conditions of geothermal power plants.

This paper summarizes the findings of our recent studies, as well as the prospects for future studies. Recent findings include extending the condition for generating periodic wellbore flow to reveal dependence on reservoir pressures, in addition to dependence on reservoir-specific enthalpies studied previously (Matsumoto et al., 2021). The responses of periodic wellbore flow to wellhead and reservoir pressure variations were also simulated, which implied that the same operations of a wellhead valve potentially stabilized or destabilized the wellbore flow depending on the abundance of natural recharge to the reservoir. Future studies will validate and extend the current findings from diverse perspectives by investigating periodic wellbore flow under further general and practical conditions, which will employ an extended code applying the discrete fracture network model intersected by multiple directional wells.

2. CONDITION FOR GENERATING PERIODIC FLOW

Using the homogeneous flow model in a wellbore intersecting shallow and deep reservoirs, Matsumoto et al. (2021) derived an empirical equation that depicted the boundary between the conditions generating constant and periodic flows through exhaustive numerical experiments. The empirical equation describes the mean specific enthalpy of the reservoirs weighted by their productivity indices as follows:

$$h_{\mathrm{L}} = \frac{\kappa \mathrm{PI_D} h_{\mathrm{reD}} + \mathrm{PI_S} h_{\mathrm{reS}}}{\kappa \mathrm{PI_D} + \mathrm{PI_S}}, \tag{1}$$

where PI and h_{re} scripted by D or S denote the productivity index and specific enthalpy of the deep or shallow reservoirs, respectively; h_{L} represents the lower limit of the specific enthalpy to sustain production solely from the deep reservoir; and κ represents an empirical factor. A periodic flow is generated when the right-hand side of Equation 1 is less than h_{L}. The lower limit of the specific enthalpy h_{L}, depending on the well specifications and deep reservoir conditions, was empirically determined using numerical experiments, assuming steady-state production from the deep reservoir. The factor κ, which tends to be greater than unity, modifies the weight empirically, implying that the deep reservoir has an excess impact beyond the significance of the productivity indices. This excess impact is potentially generated because of the asymmetrical condition ascribed to the fluids produced from the deep and shallow reservoirs: the fluid originating in the deep feed zone depth z_{D} partially shares the wellbore interval above the shallow feed zone depth z_{S}, whereas that in the shallow feed zone depth z_{S} fully shares the wellbore interval (Figure 1). Sharing of the wellbore interval degrades the productivity of each reservoir.

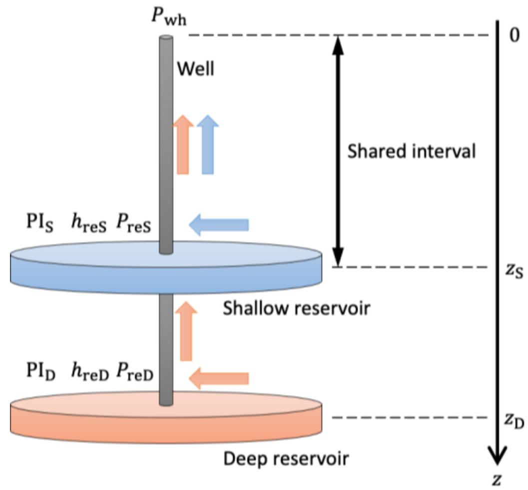

Figure 1: Schematic of the wellbore model intersecting shallow and deep reservoirs. The fluids originating in the shallow and deep reservoirs share the wellbore interval above the shallow feed zone depth z_{S}, which potentially yields the factor κ tending to be greater than unity.

We attempted to extend Equation 1 to one by considering the dependence on deep and shallow reservoir pressures. The extended equation will enable evaluation of the stability of production wells without directly simulating the transient wellbore flow, which will significantly reduce the computational loads. Such an extension is essential for simulating the operational scenarios of geothermal power plants for several decades within a practically acceptable execution time. Equation 1 can be rewritten in terms of the relationship between the ratios of the specific enthalpy and productivity index as follows:

$$1-\frac{h_{\mathrm{reS}}}{h_{\mathrm{reD}}}=\kappa(\bar{P}_{\mathrm{reD}},\bar{P}_{\mathrm{reS}})\left(1-\frac{h_{\mathrm{L}}}{h_{\mathrm{reD}}}\right)\left(\frac{\mathrm{PI_S}}{\mathrm{PI_D}}\right)^{-1}+1-\frac{h_{\mathrm{L}}}{h_{\mathrm{reD}}}, \tag{2}$$

$$\bar{P}_{\mathrm{reD}}=\frac{P_{\mathrm{reD}}-P_{\mathrm{wh}}}{\rho g z_{\mathrm{D}}}, \tag{3}$$

$$\bar{P}_{\mathrm{reS}}=\frac{P_{\mathrm{reS}}-P_{\mathrm{wh}}}{P_{\mathrm{reD}}-P_{\mathrm{wh}}}, \tag{4}$$

where $\bar{P}_{\mathrm{re}}$ and P_{re} scripted by D or S denote the scaled and unscaled pressures of the deep or shallow reservoirs, respectively; P_{wh} is wellhead pressure; ρ is the bulk density of the liquid and gas phases; and g is gravitational acceleration. Currently, we assume that the bulk density ρ depends on the wellhead pressure and deep reservoir specific enthalpy, considering the significance of expansion due to flash. Assuming the conditions summarized in Table 1, the variation in factor κ, depending on the scaled reservoir pressures, yields an extended condition for generating periodic flow (Figure 2).

Table 1: Conditions of the problem in Figure 2.

Well conditions	Wellhead pressure [MPa]	Inclination	Depth interval [m]	Inner diameter [m]	Roughness [m]
	0.7	Vertical well	0–2000	0.2	4.78×10^{-5}
Reservoir conditions	Depth [m]	Pressure [MPa]	Specific enthalpy [kJ kg^{-1}]	Permeability–thickness product [$\times 10^{-12}$ m^3]	Radius [m]
	1400	4.059–5.925	677.8–1085.8 (160–250°C)	1.0–8.0	1000
	2000	9.5–12.0	1134.8 (260°C)	1.0	1000

The surface in Figure 2a depicts the dependence of factor κ on the scaled reservoir pressures $\bar{P}_{\mathrm{reD}}$ and $\bar{P}_{\mathrm{reS}}$, based on the results of numerical experiments denoted by solid circles. Each solid circle corresponds to the value of κ empirically determined by 50 simulation runs to successfully depict the boundary between the constant and periodic flow regions under given shallow and deep reservoir pressures as described by Matsumoto et al. (2021). Using the numerical optimization method implemented in Mathematica version 12.2 (WOLFRAM), an empirical equation for κ as a function of $\bar{P}_{\mathrm{reD}}$ and $\bar{P}_{\mathrm{reS}}$ was introduced as follows:

$$\kappa = 1 + a\exp(-b\bar{P}_{\mathrm{reD}} - c\bar{P}_{\mathrm{reS}}), \tag{5}$$

where $a = 2.37 \times 10^5$, $b = 1.74 \times 10^{-1}$, and $c = 1.74 \times 10^1$. The average and standard deviation of the absolute error are 0.133 and 0.106, respectively. As Equation 5 implies, factor κ converges to unity with increase in reservoir pressures, which indicates the absence of excess impact of the deep reservoir. Finally, the extended condition for generating a periodic flow was determined by combining Equations 2 and 5 (Figure 2b). The surfaces depicted in Figure 2b separate the regions for constant and periodic flows, below and above, respectively. The extended condition quantitatively describes the dependence on the reservoir pressure: an increase in the deep reservoir pressure stabilizes the wellbore flow by moving the surface upward, while the increase in the shallow reservoir pressure destabilizes because of the downslope of the surface in the $\bar{P}_{\mathrm{reS}}$-direction. Thus, the stability of wellbore flow can be dynamically evaluated via identification of the current reservoir conditions, as shown in Figure 2b.

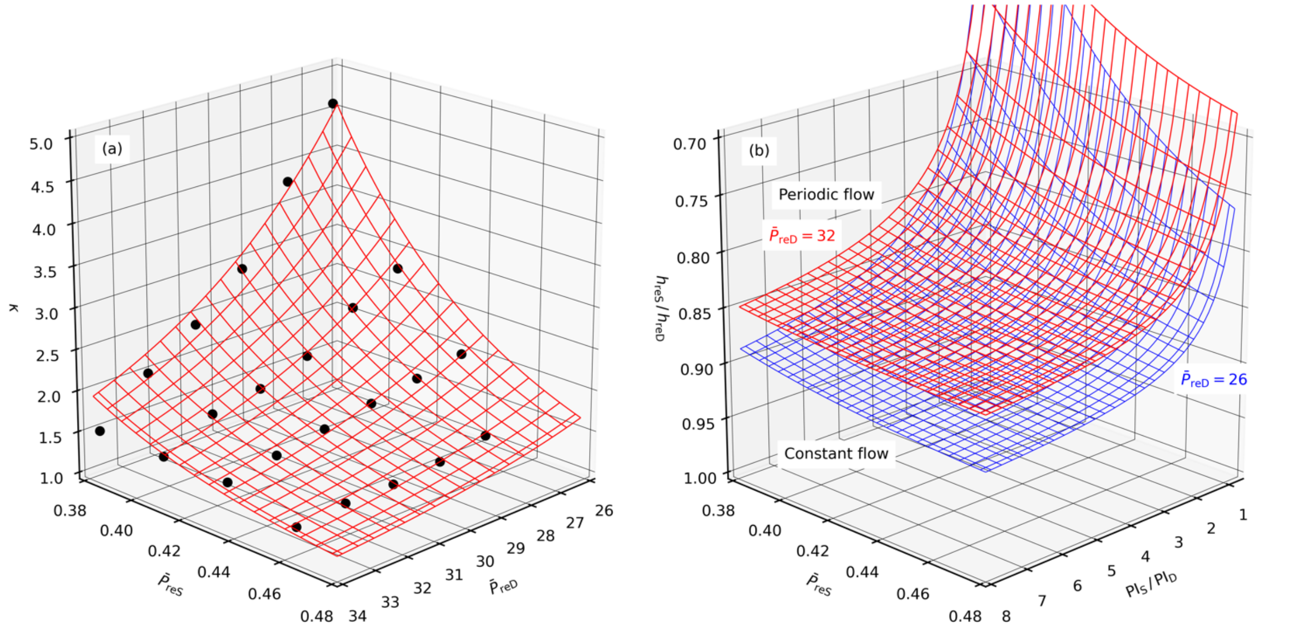

Figure 2: Extended condition for generating periodic flow. (a) Dependence of factor κ on the scaled reservoir pressures computed using Equation 5. Solid circles denote the results of numerical experiments. (b) Surfaces separating the regions for constant and periodic flows below and above, respectively, computed using Equations 2 and 5. The blue and red surfaces assume scaled deep reservoir pressure values of 26 and 32, respectively.

3. RESPONSES TO WELLHEAD AND RESERVOIR PRESSURE VARIATIONS

3.1 Wellhead pressure

Matsumoto et al. (2021) assumed that wellhead pressure was held constant for simplicity. We investigated the responses of periodic wellbore flow to wellhead pressure variations, mimicking the stepwise adjustment of a wellhead valve. The temporal variation in the wellhead pressure, assumed in advance, was not dynamically modified based on the simulation results. Stepwise pressure reduction and recovery were smoothed using cubic curves to avoid degrading the numerical stability so that the wellhead pressure changed smoothly in intervals of 0.6 h. The problem conditions are listed in Table 2.

Table 2: Conditions of the problem in Figure 3.

	Wellhead pressure	Inclination	Depth interval [m]	Casing pipe size [inch]	Roughness [m]
Well conditions	Variable (Figure 3)	Vertical well	0–695	13-3/8	4.78×10^{-5}
			695–1256	9-5/8	4.78×10^{-5}
			1256–2000	7	4.78×10^{-5}
Reservoir conditions	Depth [m]	Pressure [MPa]	Specific enthalpy [kJ kg^{-1}]	Permeability–thickness product [$\times 10^{-12}$ m^3]	Radius [m]
	1400	4.5	853.6 (200°C)	6.0	1000
	2000	10.0	1134.8 (260°C)	1.0	1000

The responses of the periodic wellbore flow to several patterns of wellhead pressure variation are shown in Figure 3. The reference case (Figure 3a), assuming a constant wellhead pressure value of 0.7 MPa, generated periodic flow. The other cases (Figure 3b–e) were intended to investigate the difference from the reference case by modifying a mode of stepwise change in wellhead pressure. Wellbore flow was stabilized and destabilized by the reduction and recovery of the wellhead pressure, respectively, regardless of the modification time. The amplitude and frequency appeared after modifying the wellhead pressure (Figure 3c, e), which differed from those of the reference case (Figure 3a), implying hysteresis. Future studies will investigate this hysteresis and its significance.

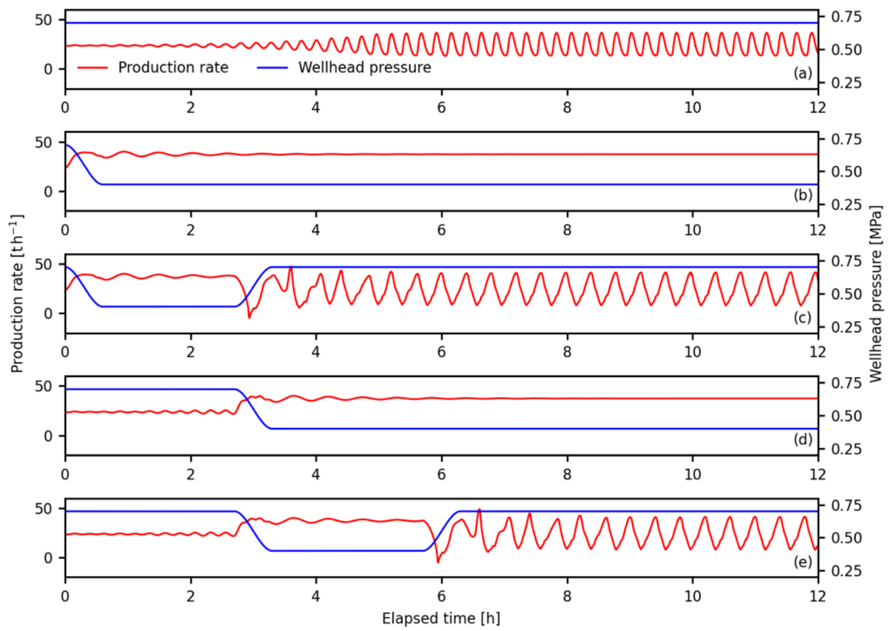

Figure 3: Responses of the periodic wellbore flow to several patterns of wellhead pressure variations.

3.2 Reservoir pressure

The model described in Section 3.1 assumed abundant natural recharge to the shallow and deep reservoirs, which was implemented by assuming a steady-state radial pressure distribution in each reservoir. In this model, the reservoir pressure at the external boundary was maintained. We investigated the response of periodic wellbore flow to variations in the deep reservoir pressure at the external boundary. For an extremely severe situation, we assumed that the external boundary pressure in the deep reservoir declined linearly from 10.0 MPa at a rate of 1.0 MPa per 1.5 d because of the shortage of natural recharge. The shallow reservoir had abundant natural recharge, assuming that the external boundary pressure was constant. The problem conditions are listed in Table 3.

Table 3: Conditions of the problem in Figure 4.

Well conditions	Wellhead pressure [MPa]	Inclination	Depth interval [m]	Casing pipe size [inch]	Roughness [m]
	0.7	Vertical well	0–695	13-3/8	4.78×10^{-5}
			695–1256	9-5/8	4.78×10^{-5}
			1256–2000	7	4.78×10^{-5}
Reservoir conditions	Depth [m]	Pressure [MPa]	Specific enthalpy [kJ kg^{-1}]	Permeability–thickness product [$\times 10^{-12}$ m^3]	Radius [m]
	1400	4.5	853.6 (200°C)	4.0	1000
	2000	Variable (Figure 4)	1134.8 (260°C)	1.0	1000

The response of the periodic wellbore flow to pressure decline in the deep reservoir is shown in Figure 4. Initially, a slightly wavy flow was observed, followed by amplitude expansion with multiple frequencies from approximately 9.0 h. The wellbore flow finally halted after exhibiting a spike-shaped peak with the maximum flow rate. The decline in the deep reservoir pressure destabilized the wellbore flow, as implied in Section 2. In contrast, under abundant natural recharge, the flow was stabilized by an increase in the flow rate due to wellhead pressure reduction, as simulated in Section 3.1. Hence, the same operations of a wellhead valve potentially stabilized or destabilized wellbore flow. An increase in the openness of the wellhead valve (i.e., a decrease in wellhead pressure) stabilizes the wellbore flow by increasing the flow rate under abundant natural recharge. Otherwise, an increase in the flow rate accelerates the reservoir pressure decline and destabilizes wellbore flow. Based on these results, we conclude that a comprehensive understanding of the conditions of wells and reservoirs is crucial for planning effective mitigation measures to stabilize wellbore flow, which will contribute to optimizing the operation of geothermal power plants.

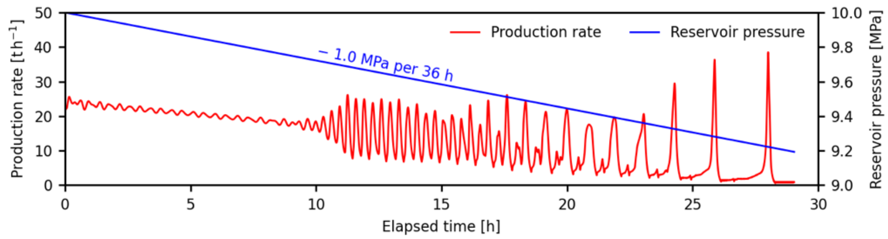

Figure 4: Response of the periodic wellbore flow to pressure decline at the deep reservoir.

4. FUTURE STUDIES

Future studies will validate and extend the current findings to improve our understanding and their applicability. Conditions for generating the periodic wellbore flow described in Section 2 was revealed by employing a homogeneous flow model for simplicity. Condition validation using further sophisticated models, such as the slip and drift-flux models (Tonkin et al., 2021), will be useful for assessing the universality of the condition as well as its applicability to actual fields. Extending the condition to those considering three or more reservoirs will also be useful for improving applicability. The condition described by Equation 1 may or may not be extended by simply considering the mean specific enthalpy of three or more reservoirs weighted by their productivity indices. Comparison between simulations using several wellbore simulation codes (e.g., Pan and Oldenburg, 2014) will enable reliability assessment of several findings and discussions.

The current code can be extended to general and practical reservoir conditions by employing the discrete fracture network model intersected by multiple directional wells with multiple feed zones (Figure 5). The extended code will be capable of two outcomes: directly simulating the transient wellbore flow or applying empirical conditions to evaluate the flow stability. When the former option is selected, flows within wells and reservoirs are fully coupled and numerically solved by converting them into a unified nonlinear system with respect to the primary variables defined at each grid point. Considering the trade-off between precision and computational loads, users can select one of these options. The consistency of simulations when selecting different options is essential, and will be the key point of validation. Matsumoto et al. (2021) demonstrated that the key mechanism for generating a stable periodic flow is the cycle of inflow and outflow periodically switching in a shallow feed zone. A locally refined grid is applied in the vicinity of the wellbore to accurately simulate mass and energy flows in both the wellbore and reservoir associated with periodic inflow and outflow. The extended code will also be useful for investigating the generation of periodic wellbore flow obeying diverse mechanisms, such as those produced from the deep water- and shallow steam-dominated zones of a reservoir (e.g., Iwata et al., 2002).

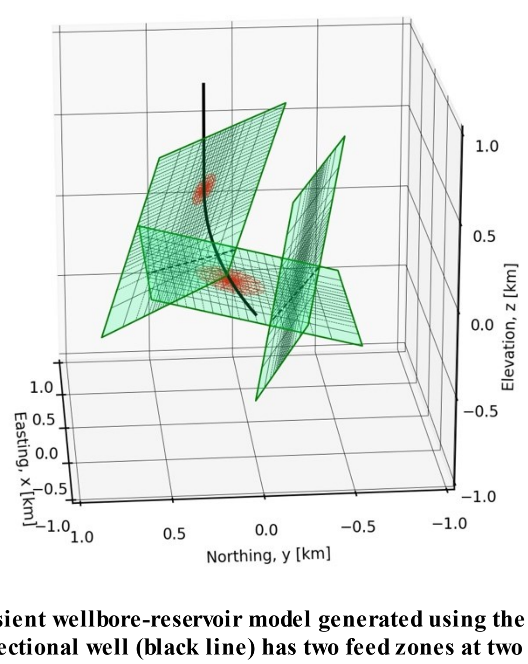

Figure 5: Prototype of the coupled transient wellbore-reservoir model generated using the extended code based on the discrete fracture network model. The directional well (black line) has two feed zones at two intersections. A locally refined grid (red lines) is applied at each intersection to accurately simulate temporal and spatial variations in the vicinity of the wellbore.

5. CONCLUSION

Here, we summarize the findings of our recent studies on periodic wellbore flow due to the inflow of a low-enthalpy fluid. An extended empirical condition for generating periodic flow additionally depending on reservoir pressures was derived, which will enable a significant reduction in computational loads by evaluating the stability of production wells without directly simulating the transient wellbore flow. The periodic wellbore flow responses to variations in wellhead and reservoir pressures imply that the same operations of a wellhead valve potentially stabilize or destabilize the wellbore flow, which depends on the abundance of natural recharge to the reservoir. Effective mitigation measures to stabilize wellbore flow require a comprehensive understanding of the well and reservoir conditions based on adequate observational data. Future studies should validate and extend the current findings from diverse perspectives, including developing an extended code capable of further general and practical reservoir conditions. The extended code employs a discrete fracture network model intersected by multiple directional wells with multiple feed zones, as illustrated.

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