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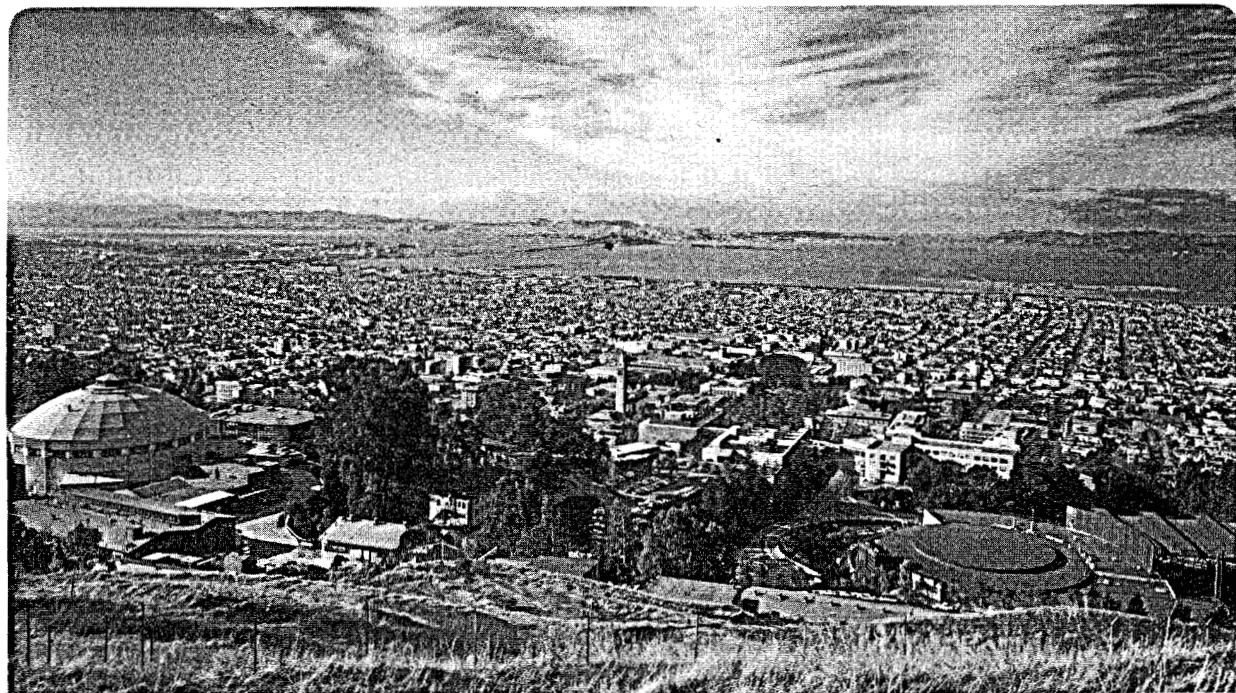
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ANALYSIS OF INTERNAL WELLCORE FLOW

M. Ripperda and G.S. Bodvarsson

ABSTRACT

Most two-phase geothermal wells are located in fractured rocks and intersect a few major feedzones. It is well known that internal wellbore flow between feedzones often occurs during warmup or pressure recovery periods. The internal flow can occur even when the reservoir is initially in pressure equilibrium, because of the different phase composition that develops within the wellbore. Internal flow can cause large apparent pressure drawdowns and significantly affect pressure and temperature surveys as well as pressure buildup tests. This paper presents an analytic method for using static pressure surveys to calculate internal flowrates between two zones when the reservoir characteristics are known. Conversely, the transmissivity of the feedzone with the lowest transmissivity can be calculated from measurements of internal flowrates and wellbore pressures.

INTRODUCTION

Internal wellbore flow occurs in many systems with multiple feedzones. In geothermal wells, relatively small pressure differences may cause substantial flows within a wellbore. Measurements of internal flowrates for wells in the Ngawha and Wairakei fields in New Zealand have ranged from several kg/s to 80 kg/s (Grant et al., 1983). This has significant effects on the interpretation of pressure transient tests and wellbore pressure and temperature profiles. The characteristics of internal flow on static pressure and temperature surveys have been well documented by several authors, including Grant et al. (1983) and Haukwa and O'Sullivan (1982). Bixley and Grant (1980) discussed a method for calculating internal flowrates during injection tests and using the results to estimate pressures and productivities of the individual feedzones.

This paper discusses an alternative method to calculate internal flow rates between the feedzones, using shut in pressure profiles. Under certain conditions, this method may also be used to calculate transmissivities.

CAUSES OF INTERNAL FLOW

A shut-in wellbore will obviously transmit fluids between feedzones that have different pressure poten-

tials. However, internal wellbore flow often occurs even when the reservoir is initially in vertical pressure equilibrium. This happens after either drilling or production, when the density of the fluid in the wellbore does not match the reservoir fluid density at both feedzones. After drilling, the wellbore is filled with cold fluid, which has a much higher pressure gradient than the reservoir fluid. When circulation is stopped, the fluid level will fall so that pressures are in equilibrium at the pivot point (Fig. 1). If the pivot point is located somewhere between the two feedzones, then the reservoir pressure is higher than the wellbore pressure at the top feedzone and lower at the bottom feedzone. This causes the downflow as shown in Figure 1. If the fluids in the top feedzone are cooler and denser than the fluids in the bottom feedzone, then these flow conditions may last for a long period of time.

Upflow will occur when the conditions are similar to those shown in Figure 2. During production, the pressure in the wellbore is lower than the reservoir pressure at both feedzones. After the well is shut in, the pressure gradient in the wellbore will be smaller than the reservoir pressure gradient if the fluids in the bottom layer are hotter and less dense than the fluids in the top layer. A continued influx of hotter fluids from the bottom feedzone causes large apparent pressure drawdowns. Thus, the measured pressure conditions within the wellbore provide little or no information about in-situ pressures when crossflow occurs. However, the rate of crossflow and the relative strengths of the two aquifers can be estimated from the wellbore pressure measurements.

CALCULATION OF INTERNAL FLOWRATES

Figure 4 shows an idealized system with internal upflow. Because there is generally very little heat loss within the wellbore, the fluid entering the top feedzone has a temperature T_2 . The rock and fluid properties are as shown. The radial, transient pressure equations can be written for each layer as

$$\frac{\delta^2 P_1}{\delta r^2} + \frac{1}{r} \frac{\delta P_1}{\delta r} = \left[\frac{\phi_1 \mu_1 c_1}{k_1} \right] \frac{\delta P_1}{\delta t} \quad (1)$$

$$\frac{\delta^2 P_2}{\delta r^2} + \frac{1}{r} \frac{\delta P_2}{\delta r} = \left[\frac{\phi_2 \mu_2 c_1}{k_1} \right] \frac{\delta P_2}{\delta t} \quad (2)$$

The initial conditions and outer boundary conditions for both layers are

$$P_1(r,0) = P_{1i} \quad (3a)$$

$$P_1(\infty,t) = P_{1i} \quad (3b)$$

$$P_2(r,0) = P_{2i} \quad (3c)$$

$$P_2(\infty,t) = P_{2i} \quad (3d)$$

The inner boundary conditions are slightly more complicated because the pressures will be changing with time. But we do know that flow out of one layer must equal flow into the second layer if wellbore storage is negligible. Thus,

$$\frac{k_1 h_1}{\mu_1} \frac{\delta P_1(r_w,t)}{\delta r} = - \frac{k_2 h_2}{\mu_2} \frac{\delta P_2(r_w,t)}{\delta r} \quad (4)$$

Also, the relationship between wellbore pressures for layers one and two, $P_1(r_w)$ and $P_2(r_w)$, can be written as

$$P_2(r_w,t) - P_1(r_w,t) = P^* \quad (5)$$

where $P_2(r_w,t)$ and $P_1(r_w,t)$ are taken directly from the wellbore pressure surveys. Although the wellbore pressures change with time, P^* is usually fairly constant.

The problem may be put in dimensionless form by introducing the following parameters:

$$\zeta = \left[\frac{k_1 \phi_2 \mu_2 c_2}{k_2 \phi_1 \mu_1 c_1} \right]^{\frac{1}{2}} \quad (6a)$$

$$\eta = \frac{k_2 h_2 \mu_1}{k_1 h_1 \mu_2} \quad (6b)$$

$$r_D = \frac{r}{r_w} \quad (6c)$$

$$t_D = \frac{k_1 t}{\phi_1 \mu_1 c_1 r_w^2} \quad (6d)$$

$$P_{D1} = \frac{P_{1i} - P_1}{P_{2i} - P_{1i}} \quad (6e)$$

$$P_{D2} = \frac{P_{2i} - P_2}{P_{2i} - P_{1i}} \quad (6f)$$

$$P_D^* = \frac{(P_{2i} - P_{1i}) - P^*}{P_{2i} - P_{1i}} \quad (6g)$$

Solutions to the above equations in the Laplace domain are

$$\bar{P}_{D1} = - \frac{\left(\frac{1}{s} \right) P_D^* K_0(r_D \sqrt{s})}{\left[\frac{K_1(\sqrt{s}) K_0(\zeta \sqrt{s})}{\zeta \eta K_1(\zeta \sqrt{s})} + K_0(\sqrt{s}) \right]} \quad (7)$$

$$\bar{P}_{D2} = \frac{\left(\frac{1}{s} \right) P_D^* \frac{1}{\zeta \eta} \frac{K_1(\sqrt{s})}{K_1(\zeta \sqrt{s})} K_0(r_D \sqrt{s})}{\left[\frac{K_1(\sqrt{s}) K_0(\zeta \sqrt{s})}{\zeta \eta K_1(\zeta \sqrt{s})} + K_0(\sqrt{s}) \right]} \quad (8)$$

The flowrate is then

$$\bar{q}_D = \frac{\delta \bar{P}_{D1}}{\delta r_D} = \eta \frac{\delta \bar{P}_{D2}}{\delta r_D} \quad (9)$$

The above expressions may easily be inverted using numerical techniques such as the Stehfest algorithm. The actual flowrate is then

$$q = 2\pi \rho \frac{k_1 h_1}{\mu_1} (P_{1i} - P_1(r_w)) q_D \quad (10)$$

where q_D represents the numerical Laplace inversion of equation (9).

RESULTS

The factors that strongly affect the internal well flowrate are the transmissivities and storage properties of the two zones. Increasing the transmissivity of both layers has a direct effect on the flowrate, as expected. When both layers have single-phase liquid, the initial flowrate ranges from approximately 10 to 200 kg/s for transmissivities ranging from 1 to 30 Dm (Fig. 4). After 3 years, the flowrates are still significant and vary between about 2 and 50 kg/s, respectively. The effects of changing the compressibility (phase composition) and transmissivity ratio of the two aquifers are shown in Figures 5 and 6. For the results shown in these figures, the transmissivity of layer 1 was held constant at 1 Dm, while the transmissivity of layer 2 was varied. Both figures show that the internal flowrate is strongly controlled by the feedzone with the lowest transmissivity. In Figure 5, for example, increasing the transmissivity of layer 2 by an order of magnitude (from $(kh)_1/(kh)_2 = 0.1$ to $(kh)_1/(kh)_2 = 0.01$) has almost no effect. However, when the transmissivity of layer 2 is less than layer 1, increasing its value from $(kh)_1/(kh)_2 = 100$ to $(kh)_1/(kh)_2 = 10$ increases the flowrate by a factor of 3. When both layers have high compressibility, two-phase fluids (Fig. 6), the initial flowrate is increased by a factor of 3 compared to single-phase conditions (Fig. 5). But the decline is much steeper for the case with high compressibilities, and after 3 years the flowrates are almost equal.

CONCLUSIONS

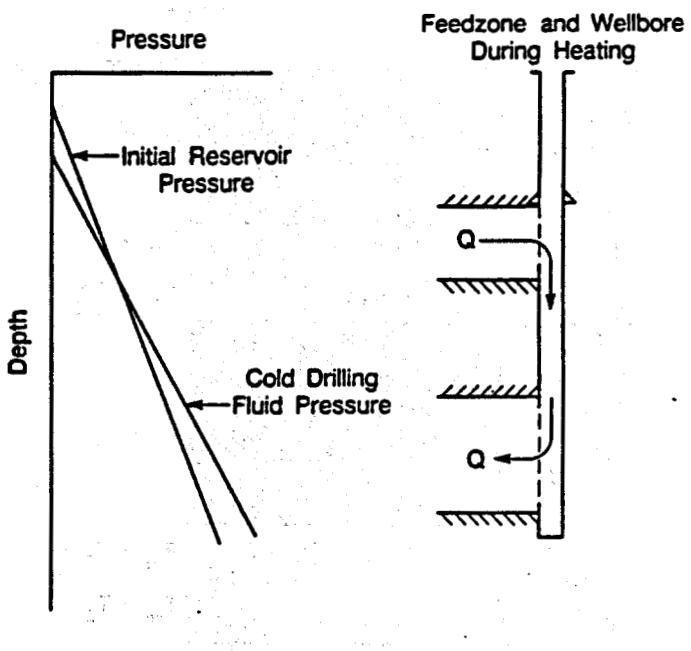
An analytical model of internal flow between two feedzones has been developed. The equations can be used to calculate the pressure distributions in the two aquifers and the internal flowrates. The flowrates will be higher if the reservoir fluids have a high compressibility (two-phase conditions). The properties of the aquifer with the lowest transmissivity controls the internal flowrate. The predicted flowrates range from about 1 to over 100 kg/s for reasonable reservoir characteristics. This range is similar to flowrates measured in several geothermal fields in New Zealand. The flowrates are predicted to decline by a factor of between 2 and 10 after 3 years, depending primarily on the phase compositions.

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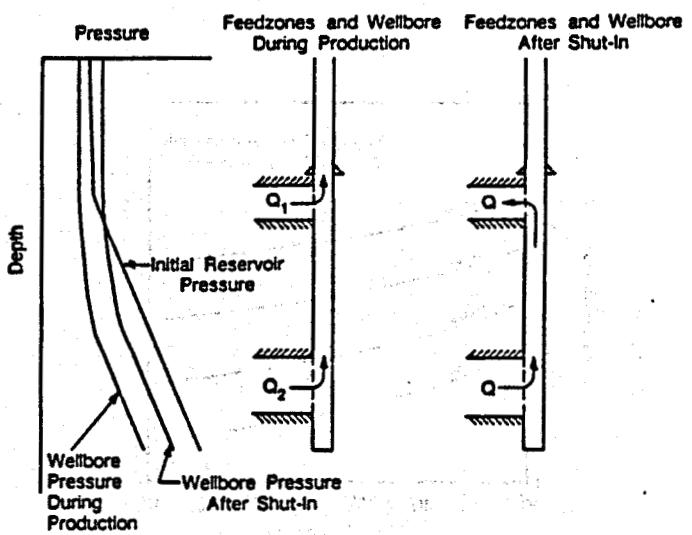
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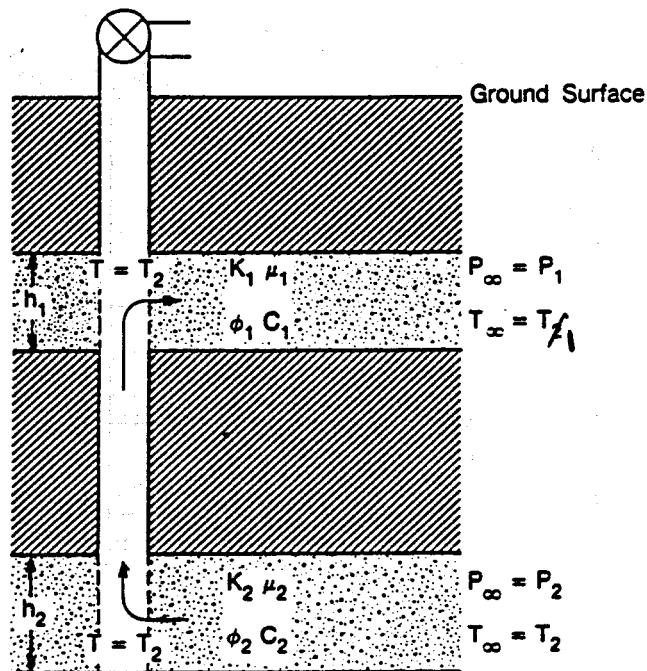
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Figure 1. Wellbore pressure and flow conditions during the warmup period after drilling.



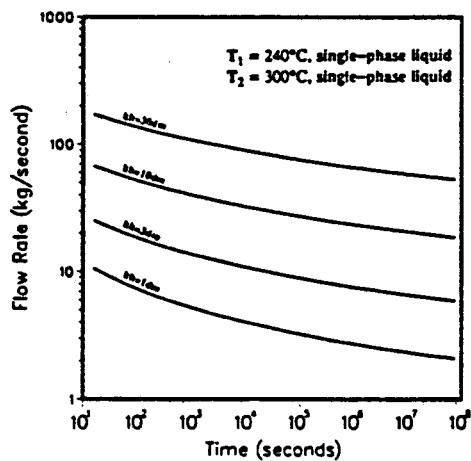
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Figure 2. Wellbore pressure and flow conditions during and after production.



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Figure 3. Idealized reservoir with two feed-zones used in analytic model.



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Figure 4. Flowrate versus time for various reservoir transmissivities. The transmissivity of the two feedzones are equal.

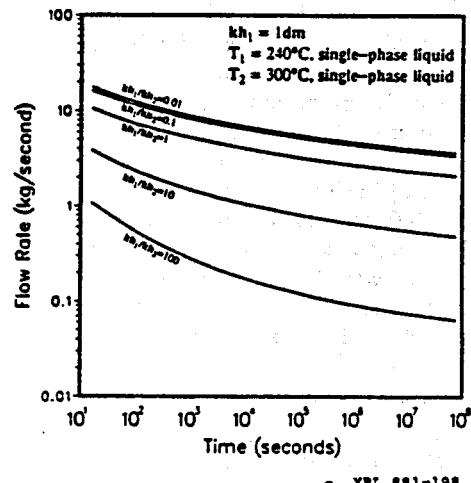


Figure 5. Flowrates versus time for various ratios of the transmissivities between the two feedzones. The reservoir fluid is single phase liquid in both layers.

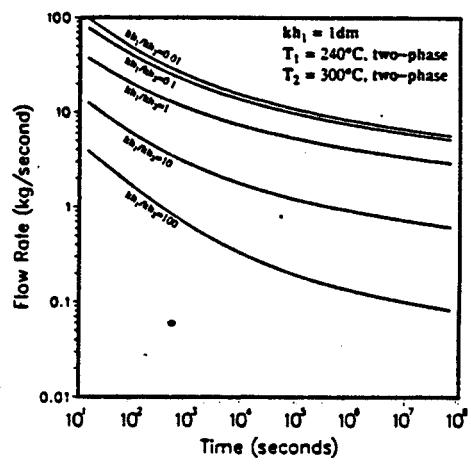


Figure 6. Flowrates versus time for various ratios of the transmissivities between the two feedzones. The reservoir fluid is two-phase in both layers.