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INVESTIGATION OF WELLBORE COOLING BY CIRCULATION AND FLUID PENETRATION INTO THE FORMATION USING A WELLBORE THERMAL SIMULATOR COMPUTER CODE

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ABSTRACT

The high temperatures of geothermal wells present severe problems for drilling, logging, and developing these reservoirs. Cooling the wellbore is perhaps the most common method to solve these problems. However, it is usually not clear what may be the most effective wellbore cooling mechanism for a given well. In this paper, wellbore cooling by the use of circulation or by fluid injection into the surrounding rock is investigated using a wellbore thermal simulator computer code. Short circulation times offer no prolonged cooling of the wellbore, but long circulation times (greater than ten or twenty days) greatly reduce the warming rate after shut-in. The dependence of the warming rate on the penetration distance of cooler temperatures into the rock formation (as by fluid injection) is investigated. Penetration distances of greater than 0.6 m appear to offer a substantial reduction in the warming rate. Several plots are shown which demonstrate these effects.

INTRODUCTION

Geothermal reservoirs are a potentially large energy resource in the U.S. and throughout the world. In order to effectively utilize this resource, many problems must be overcome. One of the principal problems is that created by the high temperatures present in these geothermal wells. These temperatures, which are typically above 200°C but can be in excess of 330°C in hot and deep reservoirs, make wells difficult to drill, log, and complete. For example, Bentonite based drilling muds form a high viscosity gel in the temperature regime of 120 to 230°C making them difficult or impossible to circulate. In addition, downhole logging equipment has a typical maximum temperature limit near 175°C. Finally, cooler wellbore temperatures are desirable for both cementing and stimulation operations.

In previous work (Duda 1984,1985) the effect on downhole wellbore temperatures due to fluid circulation in the wellbore and fluid injection or infiltration into the surrounding rock matrix was investigated. The wellbore temperatures after short fluid circulation times (< 5 days) were found to rapidly rise following shut-in, reaching near the undisturbed geothermal gradient after only 24 hours. This result confirmed the work of earlier investigators (Raymond, 1969; Holmes and Swift, 1970; Keller, et al., 1973; Traeger, et al, 1981) who calculated wellbore temperatures using a variety of analytical and numerical methods. The rapid temperature rise even a few hours after shut-in would preclude the use of fluid circulation for short time periods as an effective wellbore cooling mechanism.

An enhanced cooling effect may be produced in the wellbore by two methods: 1) fluid circulation for long times in the wellbore, and 2) fluid injection or penetration into the rock formation from the wellbore. Fluid circulation in the wellbore with conduction-dominated heat transfer in the rock formation (i.e., no fluid influx from the wellbore) can cool a considerable distance into the formation from the wellbore when long fluid circulation times are used. In fluid injection, the fluid convectively penetrates into the formation around the wellbore to a distance which depends on the formation permeability and porosity and the fluid pressure. The injected fluid then substantially cools the contacted rock. The temperature of the formation near the wellbore may be cooler from fluid injection than from fluid circulation in the wellbore. Geothermal wells that have recently been drilled sometimes exhibit a rather low rate of warming after shut-in or when drilling has been stopped (Kasameyer, 1984) indicating that some process must be occurring which produces an enhanced cooling effect.

In this paper, the effect of the penetration distance of cooler temperatures into the formation surrounding a wellbore is studied. The rate of warming of the fluid inside the wellbores of three different geothermal well models was calculated as a function of the penetration distance of cooler temperatures in the formation. In the next section these well models are described by presenting the casing program and temperature profiles used in the calculations. Next, the calculations are described with special attention given to the assumptions used. The results of these calculations are then presented and discussed. Finally, the conclusions which can be drawn from these results are presented.

GEOTHERMAL WELL MODELS

The three geothermal well models chosen for this study are from geothermal fields in southern California. The casing program for each well is shown in Table 1, and the temperature profile information is shown in Table 2. All the temperature profiles are bilinear consisting of two lines of different slope. The first part of each profile, extending from the surface to some intermediate depth, has a very steep temperature gradient compared to the second part of the profile. The first well, called the Salton Sea Shallow well, has a depth of 1400 m (4600 ft) with a bottom-hole temperature of 332°C (620°F) and is an example of a relatively shallow and hot reservoir. The second well, the Salton Sea Deep well, has a depth of 3050 m (10,000 ft) with a bottom-hole temperature of 360°C (680°F) and illustrates a deep and hot reservoir. Finally, the third well, which is called the East Mesa well, has a depth of 2320 m (7600 ft) with a bottom-hole temperature of 204°C (400°F). This is a relatively cool well of an intermediate depth.

Table 1. Casing program for the three well models used. Both the Shallow well and the Deep well are from the Salton Sea geothermal area. All casings extend from the setting depth to the surface. Fluid was circulated with 2-7/8-inch tubing for all three wells. TD denotes the total well depth. There is no casing extending to the well bottom.

Well	Casing Size (in)	Setting Depth (m)	Cemented Interval (m)
Shallow	20	183	0-183
Well	13-3/8	396	0-396
	9-5/8	914	335-914
	TD	1400	
Deep	20	183	0-183
Well	13-3/8	396	0-396
	9-5/8	914	335-914
	TD	3050	
East Mesa	20	30	0-30
Well	13-3/8	518	0-518
	9-5/8	1680	457-1630
	TD	2320	

CALCULATIONS

Calculations of the downhole wellbore temperatures were made using the GEOTEMP2 Version 2.0 computer code. This code and the fluid flow and heat transfer equations and correlations employed have been treated in detail elsewhere (Mondy and Duda, 1984; Mitchell, 1982; Wooley, 1980a). The ability of this code to accurately predict temperatures down the wellbore has been evaluated previously (Wooley, 1980b). Good agreement was found between the code predictions and field data.

Table 2. Temperature at an intermediate depth and at the bottom of the well for the three well models. Temperatures at the surface were set to 21°C (70°F).

Well	Depth (m)	Temperature (°C)
Shallow Well[a]	747	288
	1400	332
Deep Well[b]	900	300
	3050	360
East Mesa Well[c]	625	152
	2320	204

[a] Riney, Pritchett, and Garg (1978)

[b] Helgeson (1968)

[c] Riney, Pritchett, and Rice (1978)

GEOTEMP2 employs a finite difference scheme to calculate heat transfer within and between the wellbore and the soil formation. A radial geometry is used in the code with the wellbore centerline as the origin of the coordinate system. Vertical grid size is constant and was set at 61 m (200 ft) for these calculations. The size of the grids in the radial direction is not constant but exponentially increases away from the wellbore centerline. Up to 50 grids were used in the radial direction with the last grid set at a distance of 15 m (50 ft) from the wellbore centerline. This last grid defines the boundary conditions for the temperature and is set at the undisturbed temperature gradient of the specific geothermal area. The first three radial grid blocks define the wellbore. The first grid contains the tubing, the second grid consists of the annulus, and the third grid contains the region consisting of all the casing, cemented intervals, and finally, the beginning of the soil formation. The fourth grid defines the penetration distance for the fluid influx or simulated injection calculations.

Two different sets of calculations were made to investigate the two cooling methods of circulation and fluid injection. For fluid circulation, calculations of the wellbore and formation temperatures were made using fluid circulation times of 1 and 50 days with a flow rate of 500 gpm. After the specified circulation time, the flow was stopped and the wellbore and formation temperatures were calculated for a period of 50 days following shut-in. Fluid injection could not be exactly modeled since the computer code does not treat convective transport. However, the consequence of fluid injection, that is, cooler formation temperatures near the wellbore could be simulated by the code in the following manner. The code initially sets all the grid temperatures equal to the undisturbed geothermal gradient temperature. Hence, it is necessary to circulate fluid in the wellbore to obtain cool fluid temperatures. The fluid temperatures were calculated for 1 day of circulation using a flow rate of 500 gpm. This time and flow rate were chosen to correspond to the 1-day circulation calculations. Additionally, the short circulation time would not change fluid in the formation temperatures very far from the wellbore. Following this initial calculation, the effect of injection was modeled by setting the temperatures of the first four radial grids equal to the wellbore fluid temperature at the given depth. For an actual injection process, the fluid in the formation would be warmer than the injected fluid temperature due to frictional heating of the fluid through the porous media (Smith and Steffensen, 1970, 1975). This effect is minor and so was ignored for these calculations.

The effect of this process on the temperatures of the radial grids is illustrated in Fig. 1. Note that the temperature in the fourth grid for the injection simulation was lower than the temperature in the grid after 50 days of water circulation. As in the case of the circulation calculations, the wellbore temperatures were calculated for up to 50 days following the end of fluid influx. The heat transfer to the wellbore was assumed to be conduction dominated so any possible fluid movement, such as fluid injected near the wellbore returning to the wellbore, was ignored. Fluid influx was simulated for distances of 0.49 m, 0.50 m, 0.54 m, 0.68 m, and 0.85 m (1.61 ft, 1.64 ft, 1.77 ft, 2.23, and 2.79 ft) from the wellbore centerline. Finally, the terms injection and fluid influx refer to what is called the penetration distance of the fluid or the cool temperatures into the formation. This is the distance at which the first four radial grids have been set to the same temperature after the initial cooling period.

The thermal conductivity, k, of the surrounding rock was considered to be a constant with a value of 0.0041 cal/cm s °C (1.0 Btu/ft hr °F) (Riney, Pritchett, and Garg, 1978). The dependence of the heat transfer rate on k has been investigated (Duda, 1984). As k increases, heat can be transferred from the wellbore more quickly through the rock. Thus the rock nearest the wellbore is cooled less and the fluid in the wellbore warms more quickly after shut-in. If fluid invades the rock, k may change. These changes and the effect of other formation parameters on k have not been considered in these calculations.

RESULTS AND DISCUSSION

The results of calculations for one day following shut-in or the end of fluid influx for the Salton Sea Shallow well are shown in Fig. 2. The dashed curves show the wellbore warming rate following 1 and 50 days of circulation with the lower warming rate corresponding to temperatures

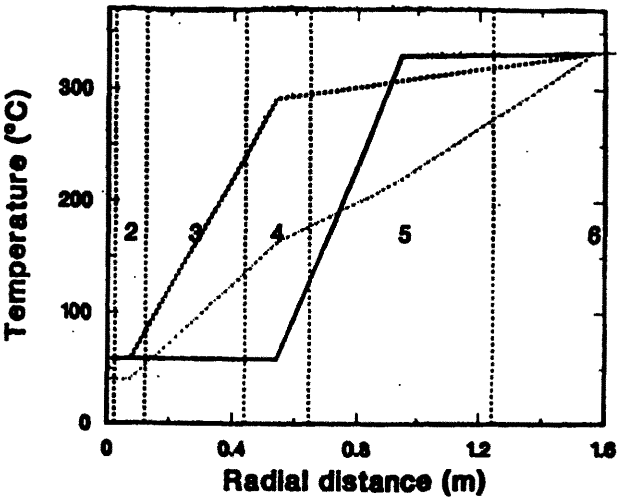

Figure 1. The temperatures of the first six radial grids. The dashed line shows the temperatures following 1 day of water circulation in the wellbore. The dotted line are the temperatures after 50 days of circulation. The solid line illustrates the simulation of the fluid injection process by setting the temperatures of the first four radial grids equal to the fluid temperature inside the tubing. This simulation is for a penetration distance of 0.54 m.

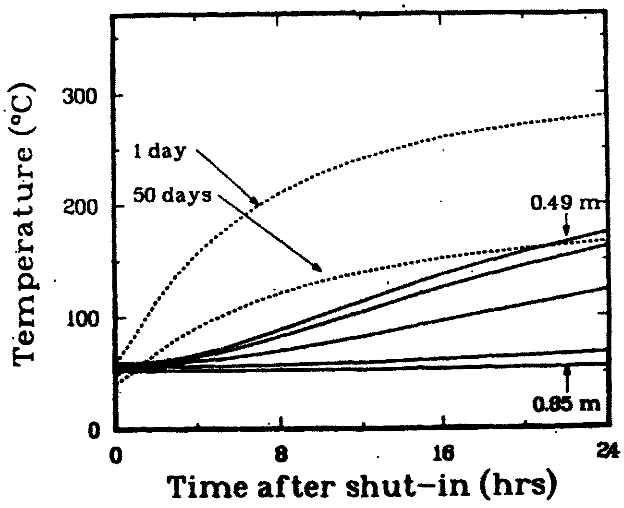

Figure 2. Temperatures inside the tubing at the bottom of the hole calculated for the first 24 hours after shut-in for the Salton Sea Shallow well. The two dashed lines are the circulation calculations while the solid lines are the warming rates for the five penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m.

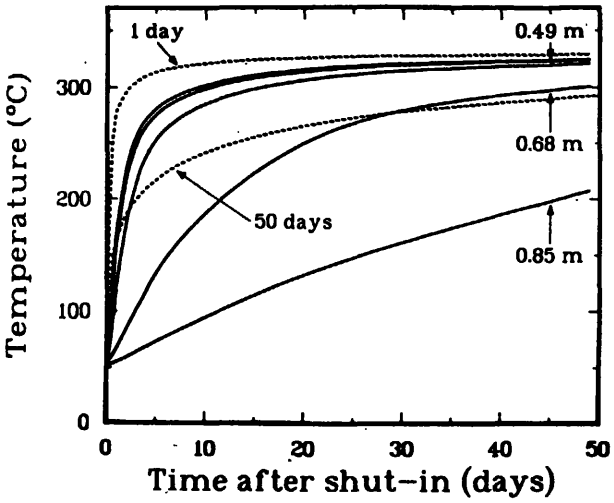

Figure 3. Temperatures inside the tubing at the bottom of the hole calculated for 50 days following shut-in for the Salton Sea Shallow well. The dashed lines are the circulation calculations while the solid lines are the warming rates for the five penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m.

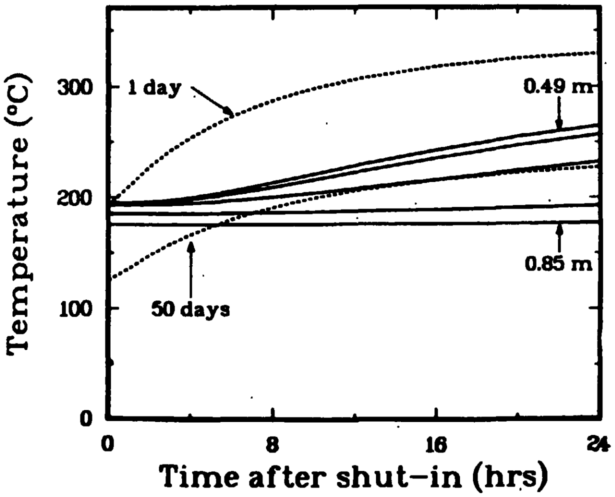

Figure 4. Temperatures inside the tubing at the bottom of the hole calculated for the first 24 hours after shut-in for the Salton Sea Deep well. The two dashed lines are the circulation calculations while the five solid lines are the warming rates for the five penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m.

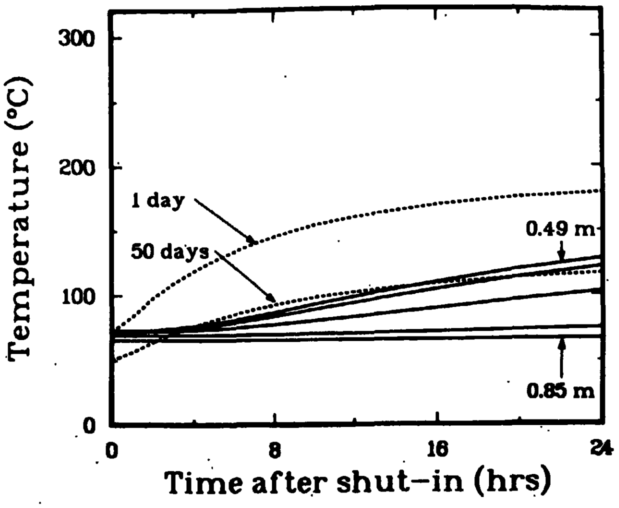

Figure 5. Temperatures inside the tubing at the bottom of the hole calculated for the first 24 hours after shut-in for the East Mesa well. The two dashed lines are the circulation calculations while the five solid lines are the warming rates for the five penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m.

after 50 days of circulation. For the fluid influx calculations, the warming rate increases as the penetration distance into the formation decreases. At a penetration distance of 0.85 m, the warming curve is virtually flat as shown in Fig. 2. In Fig. 3 the calculations are extended to 50 days following shut-in or the end of fluid influx. Note that the warming curve after 50 days of circulation is similar to the curve for a penetration distance of 0.68 m at long times after shut-in. As described in the previous section, in the fluid influx calculations, the formation near the wellbore, defined by the first four radial grids, was set to a low temperature, but the rock in the remaining grids remained at a fairly high temperature. In contrast, the formation temperatures calculated for the 50-day circulation case were much warmer near the wellbore. However, much cooler temperatures were calculated at greater distances from the wellbore than in the fluid influx case. The result was to produce a reduction in the warming rate of fluid in the wellbore similar to the reduction obtained by fluid influx or injection.

The results for one day following shut-in for the Salton Sea Deep well and the East Mesa well are shown in Figs. 4 and 5, respectively. Note that these curves are qualitatively similar to the shallow well results in Fig. 2. The differences are due to the greater depth of the Deep well which gives higher temperatures and the lower formation temperature of the East Mesa well which produces lower wellbore temperatures.

In Fig. 6 the bottom-hole temperatures for the fluid inside the tubing are plotted as a function of the penetration distance of the cooler temperatures. At large penetration distances, the temperature asymptotically approaches a minimum value which depends on the specific well. However, at small penetration distances from the wellbore, the temperatures rapidly increase. The curves clearly show that there is a minimum penetration distance at which the cooling effect becomes important. The curves of Fig. 6 can be collapsed to a single curve by plotting the dimensionless temperature given by:

$$T = \frac{T_2 - T_1}{T_{gp} - T_1}$$

where T_2 is the temperature in the wellbore at a specified time after shut-in, T_1 is the wellbore temperature immediately before shut-in begins, and Tgp is the temperature of the undisturbed geothermal profile at the given depth. This variable was chosen to have the following values:

$T = 0$ when $T_2 = T_1$
$T = 1$ when $T_2 = T_{gp}$

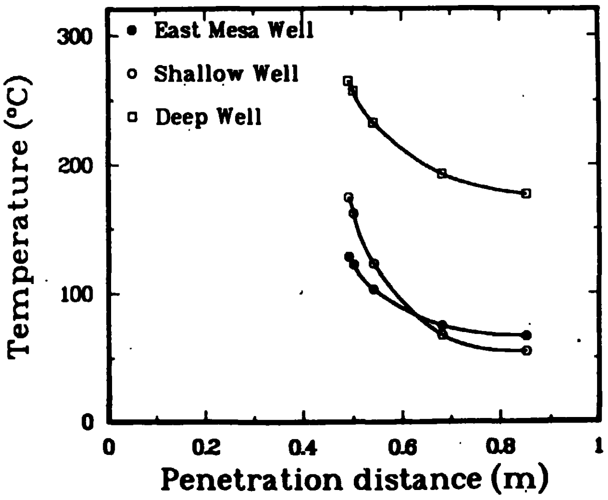

Figure 6. Temperatures at the penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m for the Salton Sea Shallow well, Deep well, and the East Mesa well. Temperatures were calculated for the fluid at the bottom of the well inside the tubing.

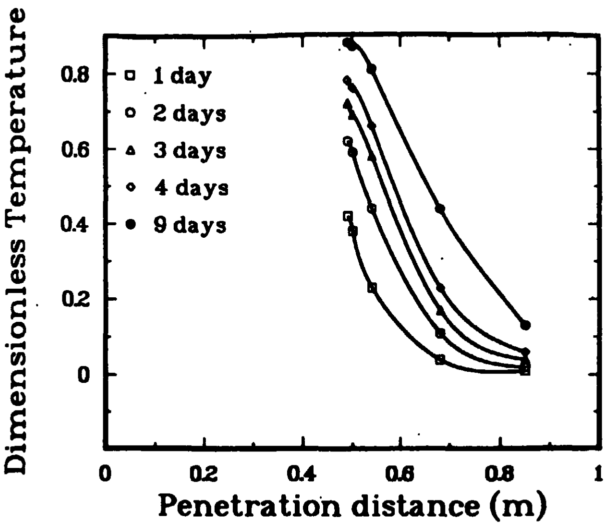

Figure 7. Dimensionless temperatures at the fluid penetration distances of 0.49, 0.50, 0.54, 0.68, and 0.85 m for the Salton Sea Shallow well, Deep well, and the East Mesa well for 1, 2, 3, 4, and 9 days after the end of fluid influx.

Note that T_2 is a function of the penetration distance of cooler formation temperatures. The resulting curves are shown in Fig. 7 at several times after shut-in or the end of fluid influx. As might be expected, the curves move to higher temperatures as time increases. The temperatures at a distance of 0.54 m rapidly increase while those at 0.85 m increase much more slowly. At 9 days following shut-in, the curves are more linear than the curves at the earlier times. It appears from this graph that a minimum distance of at least 0.6 m is required to reduce the rate of warming of the fluid in the wellbore for even a few days.

SUMMARY AND CONCLUSIONS

Wellbore temperatures after shut-in were calculated for fluid circulation times of 1 and 50 days and for several penetration distances of fluid or, alternatively, cool temperatures into the rock surrounding a wellbore. Three well models were used in these calculations. Two were from the Salton Sea geothermal area, called the Shallow and the Deep well, and the third was from the East Mesa goethermal area. The calculations shown here indicate that the fluid in a wellbore may be reduced to a reasonably low temperature either by circulating fluid for long times or by injecting cool fluid into the rock surrounding the wellbore.

The following conclusions can be made from these calculations:

1) The 50-day circulation time at a flow rate of 500 gpm was found to decrease the warming rate of fluid in the wellbore. Increasing the circulation rate above 500 gpm would only be useful for the Deep well and of no benefit for the Shallow well (Duda, 1985).

2) Penetration distances greater than 0.6m were also found to substantially reduce the warming rate after shut-in. Fluid invasion or injection into the formation may require less time than circulation to produce a cooling effect, but the penetration distance cannot be easily controlled. In addition, if the permeability and porosity of the formation varies considerably with depth, the penetration distance will also vary, producing large variations of fluid temperature with depth after shut-in. Substantial fluid invasion into the formation is not desired for most purposes.

3) Circulation for short times (~1 day) and small fluid penetration or injection distances do not greatly decrease the warming rate of wellbore fluid.

4) To keep a geothermal well cool for a significant time following shut-in in a conduction-dominated system either long fluid circulation times are required or fluid must penetrate some minimum distance from the wellbore to cool the surrounding formation.

These calculations could be used to obtain a qualitative picture concerning formation conditions in a well. For instance, if fluid temperatures inside the wellbore increase very slowly when the well is shut-in after a short period of drilling or circulation, there has probably been substantial invasion of the formation by drilling fluids. Alternatively, if the warming rate is low after prolonged drilling or circulation in a well, the degree of fluid invasion cannot be estimated from these results. Finally, note that all these calculations assumed a conduction-dominated system. This is the case for many systems, but where flow in the formation is significant, these calculations are no longer applicable.

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