HEATING AND COOLING OF WATER INJECTED INTO THE WELL

by

Mukhtar G. ALISHAEV[a], Vetlugin D. BEYBALAEV[a,b], Rasul A. ALIEV[a,c], and Abutrab A. ALIVERDIEV[a,b*]

[a] Institute for Geothermal Researches and Renewable Energy – A Branch of the Joint Institute for High Temperatures of Russian Academy of Sciences, Makhachkala, Russia
[b] Dagestan State University, Makhachkala, Russia
[c] Dagestan State Technical University, Makhachkala, Russia

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An analytical solution to the problem of calculating the heating and cooling of water injected into the well is presented. The results of calculations of temperature profiles at various daily flow rates and temperature regimes for White Tigre (Vietnam) and Uzen (Kazakhstan) fields are discussed.

Key words: *water injection, oil reservoir, heat transfer*

Introduction

Water injection into reservoirs is used to maintain reservoir pressure and increase the efficiency of oil displacement. Compensation of oil withdrawals by water injection is widely used in world practice [1-5]. Usually, sea, river, or produced water is injected with its natural temperature, which is significantly lower than the temperature of the oil reservoir. Due to the exchange of heat with rocks along the well string, a slight heating of the water injected into the reservoir occurs. The rise in temperature depends on the depth of the reservoir, the rate of injection, the thermal conductivity of the rocks, and the geothermal gradient. With large injection volumes, the effect of water heating along the wellbore is small. But for deeply located formations, the effect of associated heating of the injected water becomes practically noticeable. At low rates of daily injection, it is advisable to take into account the associated heating [4, 5].

Table 1 shows previously unpublished field data on the heating of water injected into the basement deposit of the White Tigre field (Vietnam). Water carried out from depths of 15-20 m in the South China Sea and pumped to the well on depths of 4000 m and below. On the way down to the well bottom, the water temperature increased from 20 °C to 41-45 °C. The measurements were carried out after heated discussions about the advisability of injecting surfactants into the basement in 2002-2003 due to the sensitivity of surfactants to thermal degradation at high temperatures.

The presented results indicate that the water heating can affect the thermal displacement regime. Having passed 4 km down the column, due to heat exchange with rocks, cold water warms up by about 25 °C with an injectivity of about 1000 m^3 per day. At low

* Corresponding author, e-mail: aliverdi@mail.ru

Table 1. Field measurements of water temperatures at the bottom of injection wells

No.	Flow rate, Q, [m^3 per day]	Depth [m]	T mouth [°C]	T reservoir [°C]	T bottom hole [°C]
914	960	4000	20	146	45.1
911	984	4150	20	150	44.3
424	2004	3930	20	144	43.2
485	902	4100	20	149	52.1

flow rates, the water is in contact with the rock for a longer time and more heating can be expected. When pumping 50 m^3 per day, the same heating could be obtained at a depth of 200 m, if the temperature of the rock layers was not 20-25 °C, as in the White Tiger, but about 70 °C. The rocks temperature rises with depth, and the water heating is provided mainly by the lower hot layers.

Here we present an analytical solution for constant values of the problem parameters together with estimates for a number of specific examples.

Analytical solution

We accept the notation: z is the vertical co-ordinate directed downward from the mouth, $z > 0$, r – the radial co-ordinate, distance from the borehole axis, $r > 0$, R_w – the outer radius of the well, R_T – the conditional radius of the temperature front, L [m] – the well bottom depth, Γ – the geothermal gradient, about 3 °C per 100 meters of depth, λ – the average thermal conductivity of the rocks (usually it is about 2.5-3 W/mK), T_m – the temperature of the water injected at the mouth, T_b – the bottom-hole water temperature, T_r – the reservoir temperature, equal to the temperature of the rock at the bottom-hole, T_n – the temperature of the neutral layer (taken equal to the average annual temperature of the earth's surface), $T_R(z)$ – the temperature of the rock around the well: $0 \le z \le L$, $T_R(0) = T_n$, $T_R(L) = T_r$, $T_R(z) = T_n + \Gamma z$, $\Gamma = (T_r - T_n)/L$, and $T_W(z)$ – the water temperature averaged over the borehole cross-section. The temperature of the metal column and the injected water are considered to be the same functions of z, *i.e.* $T_W(z)$.

On the expiration of weeks or a month after commissioning with a constant flow rate, the thermal regime of the well becomes almost steady. Along the casing the water temperature changes little over time. Since the vertical dimensions are large compared to the horizontal dimensions, the horizontal profiles for the temperature in the rock will be established earlier and become stationary. For the radial distribution of the steady-state temperature, take [4] the logarithmic approximation, with the radius of the temperature front, depending on time according to the square root law:

$$T(r,z) = T_W(z) + \left[T_r(z) - T_W(z)\right]\frac{\ln\dfrac{r}{R_w}}{\ln\dfrac{R_T}{R_w}}, \quad R_T = 1.56\sqrt{at} \tag{1}$$

As shown in [4], for large times (months), in the asymptotic approximation, when calculating the heat inflow into the well, the radius of the temperature front should be taken as $R_T = 1.56\sqrt{at}$, where there a is the thermal diffusivity of rocks around the well. For a unit of column length per unit of time, we have a linear heat flux density according to the generally accepted law for $r = R_\mathrm{w}$.

$$q_\mathrm{T} = -2\pi R_\mathrm{w} \lambda \frac{\partial T}{\partial r} = 2\pi\lambda \frac{T_\mathrm{r}(z) - T_\mathrm{W}(z)}{\ln \dfrac{R_\mathrm{T}}{R_\mathrm{w}}} \tag{2}$$

The increase in water temperature along the column downward by the length dz is determined by the radial exchange of heat with rocks.

$$c_\mathrm{W} Q \mathrm{d}T_\mathrm{W} = q_\mathrm{T} \mathrm{d}z \tag{3}$$

where c_W is the assumed constant specific volumetric heat capacity of water and Q – the volumetric injection flow rate. The effect of the metal column, after reaching the asymptotic regime, can be neglected [4]. For simplicity, we introduce the dimensionless heat transfer parameter:

$$\alpha(t) = \frac{2\pi\lambda L}{c_\mathrm{W} Q \ln \dfrac{R_\mathrm{T}}{R_\mathrm{w}}}, \quad R_\mathrm{T} = 1.56\sqrt{at} \tag{4}$$

It significantly depends on the daily flow rate of the injected water and is directly proportional to the bottom-hole depth. As for the others – heat capacity and thermal conductivity – they are less variable and introduce less significant changes in values. For example, the specific volumetric heat capacity of water for low temperatures is 4.2 MJ/m^{3}K, while for hot water it is 4.5 MJ/m^{3}K. The measured parameters of rocks required for calculations can be found in [6]. The variation limits and PT-behavior of rocks thermal conductivity were discussed in [7, 8].

Substituting (2) in (3) and making some simplifications, for the average water temperature in the well we have an equation with the given initial condition at the wellhead, *i.e.*:

$$T_\mathrm{W}^{/}(z) = \frac{\alpha}{L} T_\mathrm{W}(z) = \frac{\alpha}{L} T_\mathrm{r}(z), \quad T_\mathrm{r}(z) = T_\mathrm{n} + \mathit{\Gamma} z, \quad T_\mathrm{W}(0) = T_\mathrm{m} \tag{5}$$

The solution to eq. (5) is elementary and can be represented:

$$T_\mathrm{W}(z) = \left(T_\mathrm{n} - \frac{\mathit{\Gamma} L}{\alpha} + \mathit{\Gamma} z\right) + \left(T_\mathrm{m} - T_\mathrm{n} + \frac{\mathit{\Gamma} L}{\alpha}\right) \mathrm{e}^{-\frac{\alpha}{L} z} \tag{6}$$

which gives the water temperature profile along the injection well bore. Replacing the geothermal gradient with its mean value: $\mathit{\Gamma} = (T_\mathrm{r} - T_\mathrm{n})/L,$ we get:

$$T_\mathrm{W}(z) = \left[T_\mathrm{n} - \frac{T_\mathrm{r} - T_\mathrm{n}}{\alpha} + (T_\mathrm{r} - T_\mathrm{n})\frac{z}{L}\right] + \left(T_\mathrm{m} - T_\mathrm{n} + \frac{T_\mathrm{r} - T_\mathrm{n}}{\alpha}\right) \mathrm{e}^{-\frac{\alpha}{L} z} \tag{7}$$

The main interest is the temperature at the bottom-hole, where $z = L$:

$$T_\mathrm{b} = T_\mathrm{W}(L) = T_\mathrm{r} - \frac{T_\mathrm{r} - T_\mathrm{n}}{\alpha}(1 - \mathrm{e}^{-\alpha}) + (T_\mathrm{m} - T_\mathrm{n})\mathrm{e}^{-\alpha} \tag{8}$$

The bottom-hole temperature depends on the parameter determined by (4). When cold water is injected, the last term with an exponent in eq. (8) disappears. The ratio of the difference between the temperatures of the reservoir and the water at the bottom-hole to the temperature difference between the reservoir and the neutral layer, δ, shows how much, in relative terms, the injected water simultaneously *does not pick up the temperature* from the rock:

$$\delta = \frac{T_\mathrm{r} - T_\mathrm{b}}{T_\mathrm{r} - T_\mathrm{n}} = \frac{1 - \mathrm{e}^{-\alpha(t)}}{\alpha(t)}, \quad T_\mathrm{b} = T_\mathrm{r} - \delta(T_\mathrm{r} - T_\mathrm{n}) \tag{9}$$

Results and discussion

Figure 1 shows the graphs of the temperature variation of the injected water along the metal column for the times of 0.25 and 1 year at different values of the volumes of daily flow rates of the injected water in the White Tigre field. For times of a quarter of a year and 1 year at the White Tiger field with a daily consumption of 1000 m^3 per day, the values of α are 0.393 and 0.329. The share of heat not caught along the way by water is δ = 0.827 and δ = 0.852, respectively.

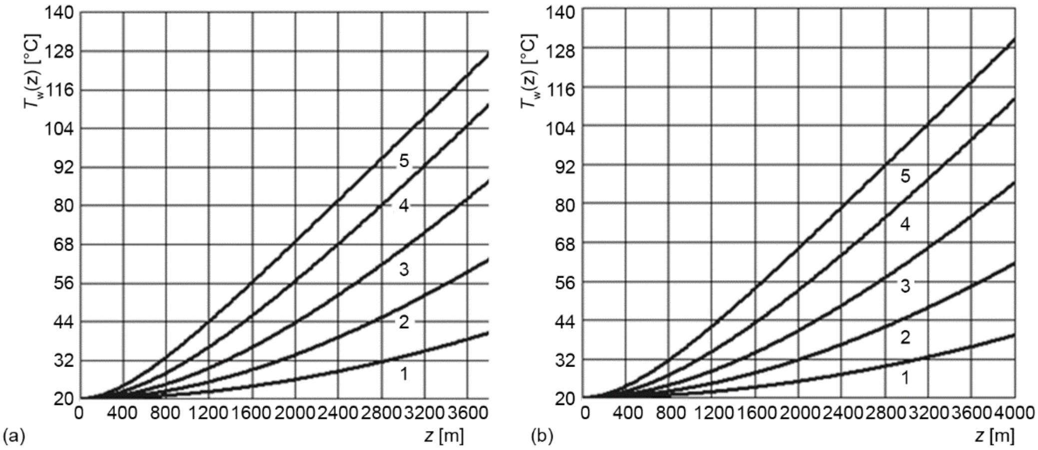

Figure 1. Graphs of temperatures of cold water (White Tiger field) injected by the well for a quarter of a year (a) and 1 year (b); curves 1-5 correspond to daily flow rates of 1000, 400, 200, 100, and 50 m^3 per day, respectively

Down-hole temperatures were close to tab. 1 values of 43.3 and 39.8 °C. With small weft injection, for example, 100 m^3 per day, the parameter values α would be much higher: 3.93 and 3.288. The share would be 0.249 and 0.293. Bottom-hole temperatures would be much higher: 117.8 ° C in a quarter of a year and 112 ° C in 1 year.

At the Uzen field (Kazakhstan, 2000 m), the amount of associated heating is significant, about 4 °C at a flow rate of 1000 m^3 per day. For times of a quarter of a year and 1 year at the field with a daily flow rate of 1000 m^3 per day, the values are 0.182 and 0.152. The fraction of heat not captured along the way is δ = 0.914 and δ = 0.928, accordingly, it is closed to 1. At the bottom hole, the temperatures would be T_b = 19.3 °C and T_b = 18.6 °C. At low injections, for example, for 100 m^3 per day, the parameter values would be significantly higher α = 1.819 and 1.522, and the non-entrained heat fraction δ would be 0.461 and 0.514.

In this field, the process of heating cold water to 90 °C and subsequent injection into the reservoir was established. The injected water had a higher temperature than the rocks, and this temperature decreased along the column until it arrived at the bottom-hole, z = 2000 m. If we take the same previously mentioned parameters, then in the case of hot water injection (T_m = 90 °C, T_n = 15 °C, T_r = 65 °C) then according to eq. (8), in a quarter of a year, and 81.8 °C in a year. Temperature losses from the wellhead to the bottom-hole will be about 7-8 °C. Water will enter the oil reservoir with a temperature that ensures the solubility of wax crystals in oil and a decrease in viscosity.

Figure 2 shows the graphs of changes in the temperature of the injected water along the well for times of 0.25 years and 1 year at various values of the volumes of daily flow rates of injected water.

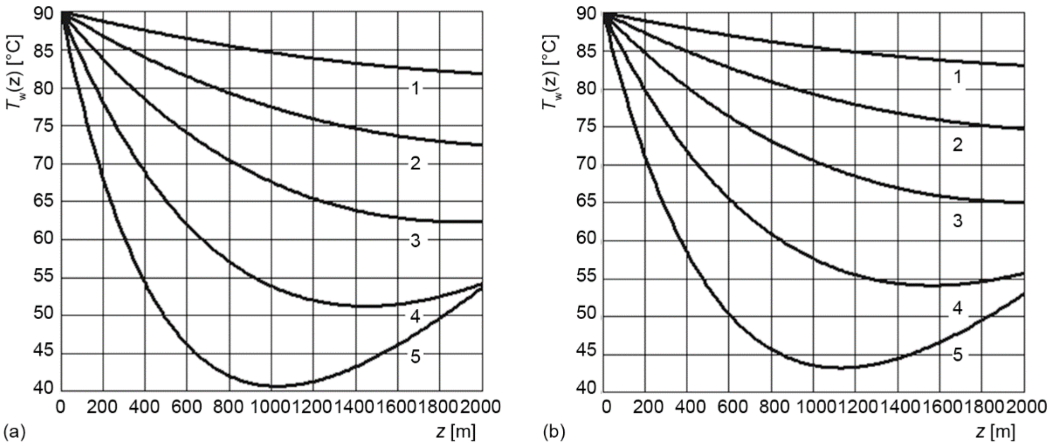

Figure 2. Graphs of temperatures of hot water (Uzen field) injected by the well for a quarter of a year (a) and 1 year (b) at different volumes of daily flow; curves 1-5 correspond to costs: 1000, 400, 200, 100, and 50 m^3 per day, respectively

Equation (8) shows that at low flow rates, it is possible to achieve significant heat exchange of the injected water due to its natural heating from the ground. This circumstance finds application in rare cases of oil displacement by cold water. If the injection is carried out into a layered formation with different layer permeabilities, and there are fears of paraffin crystallization and a decrease in permeability in bad layers, then at the initial stages it is recommended to pump water at a slow rate so that it warms up to the bottom of the well. For all α > 0.5, heating is more than 10% of the temperature difference between the formation and the neutral layer. But in practice, however, low download rates are often unacceptable.

Conclusions

The use of the obtained analytical solution to describe the temperature distribution of injected water (both cold and heated) of a number of other fields for which there are experimental measurements, also gave good agreement with the experiment and will be published in the near future.

Calculations of the oil temperature profile in a production well, taking into account the release of dissolved gas into the free phase and its expansion, can be carried out similarly, using asymptotics. In the case of constancy of thermophysical properties, it is possible to write out analytical formulas for the temperature along the wellbore in the asymptotic approximation for large times.

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Nomenclature

- a – thermal diffusivity, we also used [m^2 per year] with the indication, [m^{2}s^{-1}]
- c_W – specific volumetric heat capacity of water, [Jm^{-3}K^{-1}]
- L – well bottom depth, [m]
- Q – volumetric injection flow rate, we also used [m^3 per day] with the indication, [m^{3}s^{-1}]
- q_T – linear heat flux density [Wm^{-1}]
- R_T – conditional radius of the temperature front, [m]
- R_w – outer radius of the well, [m]
- r – radial coordinate, distance from the borehole axis, $r > 0$ [m]
- T_b – bottom-hole water temperature, for all temperatures we also used [°C], [K]
- T_m – temperature of the water injected at the mouth, [K]
- T_n – temperature of the neutral layer, [K]
- T_r – reservoir temperature, equal to the temperature of the rock at the bottom-hole, [K]
- $T_r(z)$ – temperature of the rock around the well, [K]
- $T_W(z)$ – water temperature averaged over the borehole cross-section, [K]
- z – vertical coordinate directed downward from the mouth, $z > 0$, [m]

Greek symbols

- α – dimensionless heat transfer parameter, [–]
- Γ – geothermal gradient (about 3 K per 100 meters of depth), [m^{-1}K]
- δ – dimensionless ratio of the difference between the temperatures of the reservoir and the water at the bottom-hole to the temperature difference between the reservoir and the neutral layer, [–]
- λ – thermal conductivity, [Wm^{-1}K^{-1}]

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