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Tracking Fluid Flow Between IDDP-2 and the Current Production Reservoir in the Reykjanes Geothermal System in SW-Iceland, Using Drilling Fluid as Tracer

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ABSTRACT

The IDDP-2 well is a 4.6 km deep well in southwestern Iceland, that was drilled into supercritical conditions in the roots of the Reykjanes geothermal system as part of the Icelandic IDDP-project. It was partly supported by the DEEPEGS Horizon 2020 project, which aims at demonstrating the feasibility of deep enhanced geothermal systems (EGS) as a competitive energy alternative for commercial use. Evaluating the connection between the IDDP-2 well and the currently producing 280-300°C reservoir in the Reykjanes geothermal system would conventionally be done via a tracer test. This is however challenging because the temperature of the deep reservoir that the IDDP-2 well is drilled into, is predicted to be close to 500°C, exceeding the temperature tolerance of most tracer molecules. However, during a routine geochemical production monitoring of the Reykjanes production wells, an abrupt change in the chemical composition in a nearby production well, RN-12, was observed during drilling of the IDDP-2 well; with decreasing concentrations of elements such as Na, Cl, and Ca and an increase in the atmospheric gases N_2 and Ar. This change in concentrations is probably due to injection of an air-saturated low-salinity fluid into the saline Reykjanes reservoir during drilling. We propose to use this change in concentration as a substitute for conventional tracers. Using an extended version of an 1D analytical tracer analysis we deduce the fluid flow between the two wells. Also, we predict the temperature evolution in RN-12 due to injection into the IDDP-2 well, assuming an injection rate of 100 kg/s with 50°C water. Two predictions were made: a pessimistic prediction for a wide flow channel that resulted in a 26°C cooling over 40 years and an optimistic prediction with a narrow flow channel that resulted in a less than 1°C cooling over 40 years.

1. INTRODUCTION

For understanding flow paths and connections between wells in geothermal systems, tracer tests are an invaluable method. A tracer test consists of injecting a specific material into one well and measuring its concentration in nearby production wells over a period of several months. From the data of measured tracer concentration, the connection between the well where the tracer was injected, and the wells were the tracer is measured, can be quantified. For the tracer test to be successful the injected concentration of the tracer material must be in stark contrast with its background concentration. Also, it is vital that the tracer material is stable at the conditions found within the geothermal reservoir.

The IDDP-2 well is a 4.6 km deep well in the Reykjanes geothermal area in southwestern Iceland utilized for a 100 MW_e power-plant operated by HS-Orka, which was drilled as part of the Icelandic IDDP-project. The drilling and associate research was partly supported by the DEEPEGS Horizon 2020 project (Deployment of deep enhanced geothermal systems for sustainable energy business), which aims at demonstrating the feasibility of deep enhanced geothermal systems (EGS) as a competitive energy alternative for commercial use. Well IDDP-2 is drilled into environment where the temperature, close to 500°C, exceeds the expected tolerance of most tracer materials. This makes a tracer test a challenging operation to perform through the IDDP-2 well. However, while drilling, a large amount of drilling fluid was lost to circulation into the reservoir, mainly to a large aquifer at 3.4 km depth. This drilling fluid, air-saturated low-salinity water, has strikingly different chemical composition to the saline fluid found in the Reykjanes geothermal reservoir. Shortly after the start of drilling a noticeable increase in N_2 and Ar and decrease in Na, Cl and Ca in addition to changes in stable isotope values (δ^2H, δ^{18}O) of the produced fluid were observed in well RN-12 (Galeczka and Óskarsson, 2019). These changes in the chemistry of the produced fluid indicate possible mixing of the drilling fluid from the IDDP-2 well with the reservoir fluid.

In this paper we discuss the potential of using the dissolved Cl concentration found in the drilling fluid and in the reservoir fluid to track the fluid flow within the reservoir, especially between the deep roots of the system and the shallower production reservoir. The conservative behavior of Cl and large difference between its concentration in the drilling fluid and in the deep aquifer makes it a good candidate for tracer material. In this tracer analysis we build on the method described by Axelsson et al. (2005). There, the assumption is that all the tracer material is injected instantaneously. This is, however, not applicable in this study as the drilling lasted nearly 5 months. Therefore, we will start in Section 2 by generalizing the theory of Axelsson et al. (2005) to encompass a prolonged injection of tracer material. In Section 3 we will calibrate the generalized flow model developed in Section 2 with measured Cl concentration in well RN-12. With the calibrated flow model we construct a model that describes the temperature evolution in well RN-12 as a function of injection rate into the IDDP-2 well and use it to make predictions for temperature of the production fluid in well RN-12. This is covered in Section 4. Finally, we summarize our work with conclusions in Section 5.

2. THEORY

In this study we will use the shortage of Cl in the fluid flowing from the IDDP-2 well to well RN-12, compared to its background level in the reservoir fluid, as our tracer material. This means that we define a shortage concentration as

$$C = C_r - C_f, \tag{1}$$

where $C_r = 18300$ mg/kg represents the geothermal reservoir background Cl concentration and C_f is the Cl concentration of the fluid, measured or calculated. According to Weisenberger et al. (2019), the IDDP-2 well has its largest feed zone at around 3350 m depth. The largest feed zone in well RN-12 is at 2200 m, according to Gudmundsdóttir (2019). To simplify our analysis we assume that only one channel connects IDDP-2 to well RN-12, via the beforementioned feed zones. By assuming that this channel is a straight line the length of it can be calculated as L=1200 m. We assume the flow through this single channel follows the 1D dispersion-convection equation

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x} \tag{2}$$

where D is the dispersion coefficient (m^2/s), C is the shortage in the tracer concentration in the flow-channel (kg/m^3) as defined in Equation (1), x is the distance along the flow channel (m) and u represents the average fluid velocity in the channel (m/s) given by

$$u = \frac{q}{\rho A \phi} \tag{3}$$

with q=27 kg/s being the injection rate, $\rho = 1000$ kg/m^3 the water density, A the average cross-sectional area of the flow-cannel (m^2), and ϕ=0.1 the porosity of the flow-channel. Molecular diffusion is neglected in this simple model. Therefore, we can write $D = \alpha_L u$ with α_L being the longitudinal dispersivity of the channel (m). In what follows the mass M (kg) is the shortage mass of injected Cl, i.e. the difference between the mass of Cl in the injected fluid and the mass of Cl in an equivalent amount of fluid with the background Cl concentration of the reservoir. Assuming an instantaneous injection of tracer mass M, at time $t = 0$ the solution to Equation (2) at well RN-12 (at the end of the flow channel) is given by:

$$c(t) = \frac{uM}{Q}\frac{1}{2\sqrt{\pi D t}}\exp\left(-\frac{(L-ut)^2}{4Dt}\right) \tag{4}$$

Here $c(t)$ is the shortage tracer concentration in the production well fluid, Q=53 kg/s is the average production rate in well RN-12 from August 2016 to March 2018, and L the length of the flow channel between the wells. Note that conservation of the tracer material according to $cQ = Cq$, has been applied.

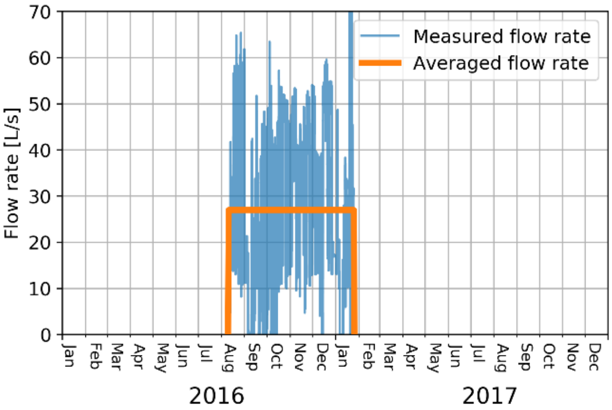

Figure 1. Measured injection flow rate of drilling fluid during the drilling of the IDDP-2 well. The constant average flow rate over the drilling period is also plotted.

In this study, the injection cannot be assumed to be instantaneous as the drilling lasted nearly six months, see Figure 1. If we want to model injection over more and longer (non-instantaneous) time periods we will have to integrate the instantaneous contribution shown in Equation (3). The contribution from an instantaneous time period $d\tau$ at time $\tau \in [0, T]$ is

$$dc(t;\tau) = \frac{u\frac{dm(\tau)}{d\tau}}{Q}\frac{1}{2\sqrt{\pi D(t-\tau)}}\exp\left(-\frac{\left(L-u(t-\tau)\right)^2}{4D(t-\tau)}\right) \tag{5}$$

Here T is the time over which the tracer is being injected and $dm(\tau)/d\tau$ is the mass injection rate of the tracer which should sum upp to the total mass of

$$M = \int_0^T \frac{dm(\tau)}{d\tau}d\tau\,. \tag{6}$$

To simplify, we assume that the mass injection rate $dm(\tau)/d\tau$ is constant over the time period $[0, T]$, i.e. we use the average flow rate shown in Figure 1. Also, we assume that the velocity u is constant, i.e. there is the same flow through the channel even when we are not injecting (the flow into the channel then comes from other sources within the reservoir). This should be correct if the production rate in well RN-12 is stable. The total contribution from all the instantaneous contributions is then

$$c(t) = \int_0^T dc(t;\tau)d\tau = \frac{u}{2Q\sqrt{\pi D}}\frac{dm}{d\tau}\int_0^T \frac{1}{\sqrt{t-\tau}}\exp\left(-\frac{\left(L-u(t-\tau)\right)^2}{4D(t-\tau)}\right)d\tau \qquad (7)$$

Let us now make the following change of variables: $\xi = t - \tau$ and $d\xi = -d\tau$. This gives us (after reversing the integral)

$$c(t) = \frac{u}{2Q\sqrt{\pi D}}\frac{dm}{d\tau}\int_{t-T}^{t} \frac{1}{\sqrt{\xi}}\exp\left(-\frac{(L-u\xi)^2}{4D\xi}\right)d\xi\,. \qquad (8)$$

The integral in Equation (8) can be evaluated with the following code in the open source software wxMaxima 17.10 (obtainable from https://wxmaxima-developers.github.io/wxmaxima/)

```
>>assume(L>0, u>0, D>0, t0>0, t1>0, t1-t0>0);
>>ratsimp(integrate(1/sqrt(x)*exp(-(L-u*x)^2/(4*D*x)) ,x, t0, t1));
```

Giving the following result for the integral in Equation (8)

$$\int_{t-T}^{t} \frac{1}{\sqrt{\xi}}\exp\left(-\frac{(L-u\xi)^2}{4D\xi}\right)d\xi = \frac{\sqrt{\pi D}}{u}\left[\exp\left(\frac{u}{D}L\right)\operatorname{erfc}\left(\frac{u(t-T)+L}{2\sqrt{D(t-T)}}\right) + \operatorname{erfc}\left(\frac{u(t-T)-L}{2\sqrt{D(t-T)}}\right) - \exp\left(\frac{u}{D}L\right)\operatorname{erfc}\left(\frac{ut+L}{2\sqrt{Dt}}\right) - \operatorname{erfc}\left(\frac{ut-L}{2\sqrt{Dt}}\right)\right]. \qquad (9)$$

Here erfc is the complimentary error function. Combining Equation (9) into Equation (8) gives the following solution for the measured tracer concentration in well RN-12 for non-instantaneous tracer injection

$$c(t) = \frac{1}{2Q}\frac{dm}{d\tau}\left[\exp\left(\frac{u}{D}L\right)\operatorname{erfc}\left(\frac{u(t-T)+L}{2\sqrt{D(t-T)}}\right) + \operatorname{erfc}\left(\frac{u(t-T)-L}{2\sqrt{D(t-T)}}\right) - \exp\left(\frac{u}{D}L\right)\operatorname{erfc}\left(\frac{ut+L}{2\sqrt{Dt}}\right) - \operatorname{erfc}\left(\frac{ut-L}{2\sqrt{Dt}}\right)\right]. \qquad (10)$$

3. CALIBRATION OF THE FLOW MODEL

In Equation (10) we have three unknown parameters: the average flow rate u, the dispersion coefficient D, and the shortage in Cl mass injection rate $dm/d\tau$ into the flow channel. We cannot calculate directly the shortage in Cl mass injection rate because we do not know how much of the injected drilling fluid goes into the channel. We therefore must calibrate it along with u and D when we fit our model to measured Cl concentration in the production well (from Galeczka and Óskarsson, 2019). Comparison of the measured Cl concentration values in well RN-12 to values calculated by the calibrated model via Equation 10 can be seen in Figure 2. Note that we have used Equation 1 to asses real concentration values from the model, instead of shortage values and the calibration was done with the purple colored points. The model shows a good correspondence to measured values.

The calibrated values for u, D, and $dm/d\tau$ can be seen in Table 1. The cumulative shortage mass m of Cl at well RN-12, according to the model, can be calculated via the integral $\mathrm{m} = \int \mathrm{Qc(t)\,dt}$ and the injected cumulative shortage mass of Cl at the IDDP-2 well is estimated as $\mathrm{M} = \mathrm{q}\left(\mathrm{C_r} - \mathrm{C_{inj}}\right)\Delta\mathrm{t}$, where $\mathrm{C_{inj}}$=150 mg/kg is the Cl concentration of the drilling fluid and $\Delta\mathrm{t} = 1.45 \times 10^7$ s is the duration of injection of the drilling fluid. The ratio m/M =0.468 tells us that nearly half of the drilling fluid made its way into the flow channel. From Equation 3 we can calculate that the effective flow cross section of the channel is $A\phi$=116 m^2. The values of m/M and $A\phi$ are also listed in Table 1.

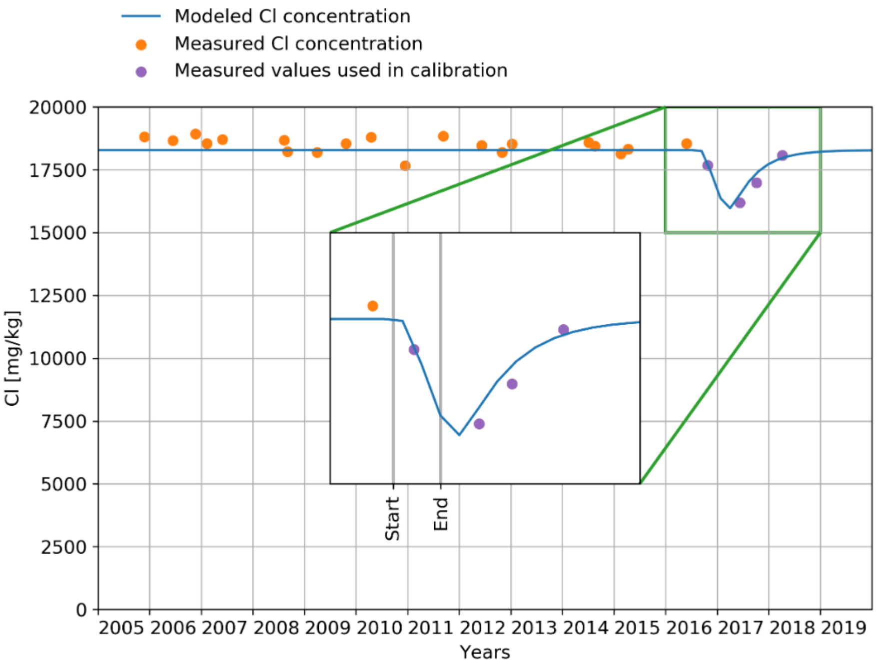

Figure 2. The Cl concentration calculated by the calibrated flow model compared to measured values. The inset focuses on the period of the decrease in Cl background concentration. Also, in the inset the start and end of drilling is indicated.

Table 1. Calibrated values of the flow model.

Parameters	**u [m/s]**	**D [m^2]**	$dm/d\tau$ **[g/s]**	m/M **[%]**	$A\phi$ **[m^2]**
Values	9.88×10^{-5}	3.96×10^{-3}	280	46.8	116

4. TEMPERATURE MODEL AND PREDICTIONS

With the calibrated parameters found in Table 1 we can construct a model of the temperature evolution in well RN-12 in response to the injection into the IDDP-2 well. We use the same model as presented in Axelsson et al. (2005). Water flowing from the IDDP-2 well to well RN-12 heats up due to thermal conduction from the geothermal reservoir rock. Here we assume a fixed rectangular cross section along the flow channel. If T_0 of 300 °C is the initial aquifer temperature before for well RN-12, and T_i is the temperature of the reinjected water the fluid temperature in the production well is as follows

$$T(t) = T_0 - \frac{q}{Q}(T_0 - T_i)\left[1 - \mathrm{erf}\left(\frac{kLh}{c_w q\sqrt{\kappa(t - L/\beta)}}\right)\right], \tag{11}$$

if reinjection rates and production rates are constant. Here erf is the error function, $q_{ch}=q{\cdot}m/M$ is the flow rate in the channel, and $\beta=qc_w/\langle\rho c\rangle_f$ where $\langle\rho c\rangle_f=\rho_w c_w\phi+\rho_r c_r(1-\phi)$. Also, $c_w = 4200$ J/(kg°C), c_r=1000 J/(kg°C), $\rho_w = 1000$ kg/m^3 and ρ_r=2700 kg/m^3 are the heat capacity and density of water and the reservoir rock, k=2 $W/(m°C)$ is the thermal conductivity of the reservoir rock, and $\kappa=k/(c_r\rho_r)$ is the thermal diffusivity of the reservoir rock.

Although we can obtain the values of most of the unknown variables in Equation (11) from the nonlinear regression analysis discussed in Section 3, the width b and the height h of the channel, and the porosity of the reservoir rock ϕ are undefined. From the regression analysis we obtain the value of the multiplication $A\phi=bh\phi$. If we assume commonly measured porosity of ϕ = 10%, the only significant uncertainty is the ratio between b and h.

Two scenarios for the temperature evolution of the fluid produced from well RN-12 when a constant injection rate of q=100 kg/s and hot water at T_i= 50 °C is injected into the IDDP-2 well are assessed: A pessimistic prediction with a width-height ratio of b/h = 0.01 and an optimistic prediction where the ratio is b/h = 0.001, respectively. The values for the channel's width and height corresponding to these ratios can be seen in Table 1. These predictions can be seen in Figure 2 where the calculated temperature evolution for well RN-12 is plotted over a 40-year period. We get a rapid cooling for the pessimistic width height ratio after 5 years, cooling by 25°C after 40 years. For the optimistic prediction there is only a slight cooling of 1 °C after a 40-year period.

Table 2. The width and height of the flow channel for the pessimistic case (*b/h*=0.01) and the optimistic case (*b/h*=0.001).

Width-height ratio	***b* [m]**	***h* [m]**
***b/h*=0.01**	3.6	358

***b/h*=0.001**	1.1	1130

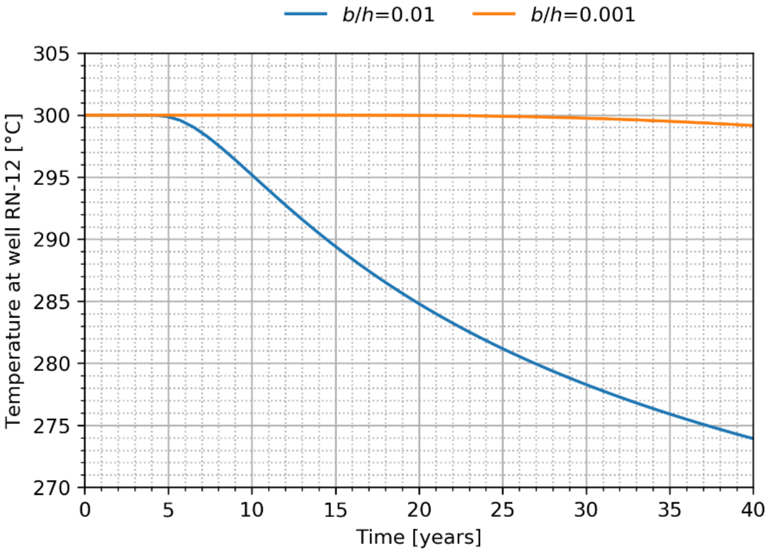

Figure 3. Predicted temperature evolution of the production fluid in well RN-12 in response to injection into the IDDP-2 well for two different width height-ratios of the flow channel.

5. CONCLUSIONS

We have developed a flow model, using the 1D advection – dispersion equation for instantaneous tracer injection, to simulate constant injection of tracers (in contrast to instantaneous injection). This model was then successfully calibrated with the measured decrease in Cl concentration in well RN-12 due to nearly 6 months injection of low-salinity drilling fluid during the drilling of the IDDP-2 well. Here the tracer material was defined as the difference between measured Cl concentration in the fluid within the flow channel and the background Cl concentration of the saline reservoir fluid. The time evolution of N_2, Ar, $\delta^{18}O$ and δD in RN-12 confirms that the Cl concentration difference was caused by the low-salinity drilling fluid. In the analysis it was assumed that the IDDP-2 well and the RN-12 well are effectively connected with one straight 1200 m long flow channel. From the calibrated model it was deduced that the effective cross section of the flow through the channel was 116 m^2 and that nearly half of the drilling fluid found its way through the channel.

Using the calibrated flow model that resulted from the tracer analysis, a model for the temperature changes in well RN-12 as a function of injection rate into the IDDP-2 well was constructed. Two predictions were made with this model assuming an injection rate of 100 kg/s of 50°C water into the IDDP-2: a pessimistic prediction for a wide flow channel that resulted in a 26°C cooling over 40 years and an optimistic prediction with a narrow flow channel that resulted in a less than 1°C cooling over 40 years.

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