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Estimating Individual Injectivity Indices for Two or More Feed-Zones in Geothermal Wells

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ABSTRACT

Spinner logs are widely used for feed zone analysis in geothermal wells, both for location and permeability purposes. Traditionally, temperature logs have been used as a major basis for feed zone location and co-interpreted with circulation loss information during the drilling process, qualitative feed zone size has been estimated. In 2012 spinner logs were added to ÍSOR´s logging toolbox for supporting and improving feed zone analysis of geothermal wells. The feed zone analysis scheme introduced is based on a well-known fluid velocity determination with spinner logs and it assumes the same well diameter above and below each feed zone recognized from a change in fluid velocity. Up and down spinner-logs combined with corresponding pressure log at two different flow rates form the basis for a quantitative feed zone analysis to determine the injectivity index of individual feed zones. With a good quality spinner log, added feed zone indices accurately fit the total injectivity index obtained in a conventional injectivity test.

INTRODUCTION

Spinner logs are extensively used for feed zone recognition in a geothermal well by fluid velocity estimates. Multi rate flow tests are used to obtain permeability estimates for the well and with simple modelling well and reservoir parameters are calculated. An important property obtained in such flow test is the well's flow index, for either injectivity or productivity. However, multi rate flow tests are taken at specific depth inside the well so the obtained flow index represents total flow index of the well. For extensive modelling of a geothermal field, some estimate of permeability of different feed zones are needed. To obtain permeability information on individual feed zones flow through each of them is needed together with corresponding pressure difference governing the flow. It turns out that fluid velocity profiles for two different flow rates together with corresponding well pressures can be used to eliminate individual flow indices and outside-well pressures. Besides, spinner logs for two or more different flow rates are regarded necessary to avoid misses of feed zones due to no flow through them in case of same pressure inside the well and outside it.

In the following work an overview of the generalized method introduced by Grant and Bixley (1995) is given, expressing the output parameters fluid velocity and tool constant which depends on the tool design, impeller design, bearing status and fluid properties such as viscosity which depends on temperature. For determining feed zone parameters, expressions for injectivity index, outside-well pressure and effective section area at each feed zone are derived. The data used for demonstrating the processing scheme are from an injectivity test of well ÞG-17 in Þeistareykir, North-Iceland.

BACKGROUND

Malcolm A. Grant and Paul F. Bixley have introduced a generalized method for interpreting spinner data into fluid velocity profile inside the well (Grant, M.A. and Bixley, P.F., 1995). This method makes use of the complete well profile data set of depth, tool speed and spinner rate are fitted to a model of profile data set of depth, fluid velocity and spinner tool performance. This approach is considered to avoid biases that follow the general cross-plot method (Grant and Bixley, 2011). Besides, an open hole caliper log is preferred.

The simplest conditions introduce the spinner rate as a linear combination of the actual fluid velocity inside the well and the applied tool velocity as

$$\alpha \cdot f = U - V$$

where f is the measured spinner rate, U is the fluid velocity, V is the tool velocity and α is a calibration coefficient for the spinner. The sign convention used is that displacements down the well are positive and positive spinner rate corresponds to downward movement of the tool in static fluid. To use the conventional cross-plot method (Grant and Bixley, 2011) several observations at different tool velocities are required. The generalized method makes use of two profiles of different tool velocities, usually down and up run at current injection/production rate. The well is then divided into separate stations where each station corresponds to fixed depth and the data points used to define the corresponding fluid velocities are taken from some depth interval around that station. If m denotes the station number and n is the data index, the error

$$\varepsilon_{mn} = \alpha_m \cdot f_{mn} + V_{mn} - U_m$$

introduces the difference between the modelled and actual fluid velocity. The processing scheme for modelling the fluid velocity is to minimize the sum

$$I_m = \sum_{n=1}^{N} \varepsilon_{mn}^2 = \sum_{n=1}^{N} (\alpha_m \cdot f_{mn} + V_{mn} - U_m)^2$$

by the choice of calibration constant α_m and fluid velocity U_m, each corresponding to certain station m where N is the number of data points used for individual station. The process for this is a conventional least squares linear regression with the criteria

$$\left(\frac{\partial I}{\partial \alpha}\right)_m = \sum_{n=1}^{N} 2 \cdot (\alpha_m \cdot f_{mn} + V_{mn} - U_m) \quad \cdot f_{mn} = 0$$
$$\left(\frac{\partial I}{\partial U}\right)_m = \sum_{n=1}^{N} 2 \cdot (\alpha_m \cdot f_{mn} + V_{mn} - U_m) \quad \cdot (-1) = 0$$

leading to the 2x2 matrix system

$$\begin{bmatrix} \sum_{n=1}^{N} f_{mn}^2 & \sum_{n=1}^{N} f_{mn} \\ \sum_{n=1}^{N} f_{mn} & N \end{bmatrix} \begin{bmatrix} \alpha_m \\ U_m \end{bmatrix} = \begin{bmatrix} -\sum_{n=1}^{N} V_{mn} \cdot f_{mn} \\ \sum_{n=1}^{N} V_{mn} \end{bmatrix}$$

with the solution

$$\begin{bmatrix} \alpha_m \\ U_m \end{bmatrix} = \frac{1}{N \sum_{n=1}^{N} f_{mn}^2 + (\sum_{n=1}^{N} f_{mn})^2} \begin{bmatrix} \sum_{n=1}^{N} f_{mn} \cdot \sum_{n=1}^{N} V_{mn} - N \sum_{n=1}^{N} V_{mn} \cdot f_{mn} \\ \sum_{n=1}^{N} f_{mn}^2 \cdot \sum_{n=1}^{N} V_{mn} - \sum_{n=1}^{N} f_{mn} \cdot \sum_{n=1}^{N} V_{mn} \cdot f_{mn} \end{bmatrix}$$

which are the outcome parameters tool calibration constant α_m and fluid velocity U_m at each station which determines the depth. Corresponding uncertainty estimates in forms of standard division and regression coefficient are also calculated, see literature (Montgomery and Runger, 2014) for detailed derivation. As spinner data is generally of noisy manner (Grant and Bixley, 2011), smoothing of the data is most often necessary. One way of smoothing is to choose the data points of each station over an appropriate interval depending on both noise level and spatial frequency. For determining individual feed zone injectivity index, at least two flow rates are necessary, and the above fluid velocity analysis is required for each of them.

THEORY

When two spinner logs of known distinctive flow rates are conducted, relationship between effective cross-sectional area, individual flow indices, reservoir pressure, the logged fluid velocities and logged well pressure can be derived. In the following calculations negligible caliper changes are considered across any feed zone recognized from the velocity profiles. Also, the calculations will be based on one primary injection rate since the two of them are connected through the velocity ratio at any certain location inside the well.

At the *k*-th feed zone following relations are evaluated were the indices 1 and 2 refer to the flow rates Q_1 and Q_2 at well head, the index *k* refers to a feed zone identification and the indices *a* and *u* refer to conditions above and below (under) individual feed zones. The initial and flow conservation conditions require that the flow above the 1st feed zone equals the injection rate, i.e. $Q_{j,1,a} = Q_j$, and $Q_{j,k,a} = Q_{j,k-1,u}$ where the *j*-index refers to the well head flow rates 1 and 2. Similarly, I_k refers to the flow index, $P_{0,k}$ refers to the out-side (reservoir?) pressure and $P_{j,k}$ refers to well pressure. β_k refers to the cross-sectional area at the *k*-th feed zone. Otherwise, the applied abbreviation is explained in Figure 1.

The following relationship are derived based on an assumption of same well diameter on each side of a recognized feed zone.

The two flow rates are related by:

$$\frac{Q_{2,k,a}}{Q_{1,k,a}} = \frac{v_{2,k,a}}{v_{1,k,a}};\ Q_{1,k,a} = \frac{v_{1,k,a}}{v_{2,k,a}} \cdot Q_{2,k,a}$$

The flow through each feed zone depends on the difference between the out-side well pressure and the well pressure and it equals the flow difference inside the well across the feed zone.

For flow rate 1:

$$\Delta Q_{1,k} = \beta_k \cdot (v_{1,k,a} - v_{1,k,u}) = (P_{1,k} - P_{0,k}) \cdot I_k$$
$$= Q_{1,k,a} - Q_{1,k,u} = \left(1 - \frac{v_{1,k,u}}{v_{1.k,a}}\right) \cdot Q_{1,k,a}$$
$$= \left(1 - \frac{v_{1,k,u}}{v_{1,k,a}}\right) \cdot \frac{v_{1,k,a}}{v_{2,k,u}} \cdot Q_{2,k,a} = (v_{1,k,a} - v_{1,k,u}) \cdot \frac{Q_{2,k,a}}{v_{2,k,a}}$$

For flow rate 2:

$$\Delta Q_{2,k} = \beta_k \cdot (v_{2,k,a} - v_{2,k,u}) = (P_{2,k} - P_{0,k}) \cdot I_k$$
$$= Q_{2,k,a} - Q_{2,k,u} = \left(1 - \frac{v_{2,k,u}}{v_{2,k,a}}\right) \cdot Q_{2,k,a}$$

$$\frac{Q_{2,k,u}}{Q_{1,k,u}} = \frac{v_{2,k,u}}{v_{1,k,u}}; \quad Q_{1,k,u} = \frac{v_{1,k,u}}{v_{2,k,u}} \cdot Q_{2,k,u} = \frac{v_{1,k,u}}{v_{2,k,u}} \cdot \frac{v_{2,k,u}}{v_{2,k,a}} \cdot Q_{2,k,a} = \frac{v_{1,k,u}}{v_{2,k,a}} \cdot Q_{2,k,a}$$

$$Q_{2,k,u} = \frac{v_{2,k,u}}{v_{2,k,a}} \cdot Q_{2,k,a}$$

Evaluation of the feed zone flow index, I_k:

$$\Delta(\Delta Q_k) = \Delta Q_{2,k} - \Delta Q_{1,k} = \{(v_{2,k,a} - v_{1,k,a}) - (v_{2,k,u} - v_{1,k,u})\} \cdot \frac{Q_{2,k,a}}{v_{2,k,u}} = (P_{2,k} - P_{1,k}) \cdot I_k$$

$$\therefore I_k = \frac{Q_{2,k,a}}{P_{2,k} - P_{1,k}} \cdot \frac{(v_{2,k,a} - v_{2,k,u}) - (v_{1,k,a} - v_{1,k,u})}{v_{2,k,a}}$$

Evaluation of the out-side well pressure, $P_{0,k}$:

$$\frac{\Delta Q_{1,k}}{\Delta Q_{2,k}} = \frac{(P_{1,k} - P_{0,k}) \cdot I_k}{(P_{2,k} - P_{0,k}) \cdot I_k} = \frac{(P_{1,k} - P_{0,k})}{(P_{2,k} - P_{0,k})} = \frac{(v_{1,k,a} - v_{1,k,u}) \cdot \frac{Q_{2,k,a}}{v_{2,k,a}}}{(v_{2,k,a} - v_{2,k,u}) \cdot \frac{Q_{2,k,a0}}{v_{2,k,a}}} = \frac{(v_{1,k,a} - v_{1,k,u})}{(v_{2,k,a} - v_{2,k,u})}$$

$$\therefore P_{0,k} = \frac{(v_{1,k,a} - v_{1,k,u}) \cdot P_{2,k} - (v_{2,k,a} - v_{2,k,u}) \cdot P_{1,k}}{(v_{1,k,a} - v_{1,k,u}) - (v_{2,k,a} - v_{2,k,u})}$$

Evaluation of the effective cross-sectional area, β_k:

$$\Delta Q_{1,k} = \beta_k \cdot (v_{1,k,a} - v_{1,k,u})$$
$$= Q_{1,k,a} - Q_{1,k,u} = \left(1 - \frac{v_{1,k,u}}{v_{1.k,a}}\right) \cdot Q_{1,k,a}$$
$$\therefore \beta_k = \frac{Q_{1,k,a}}{v_{1,k,a}}$$

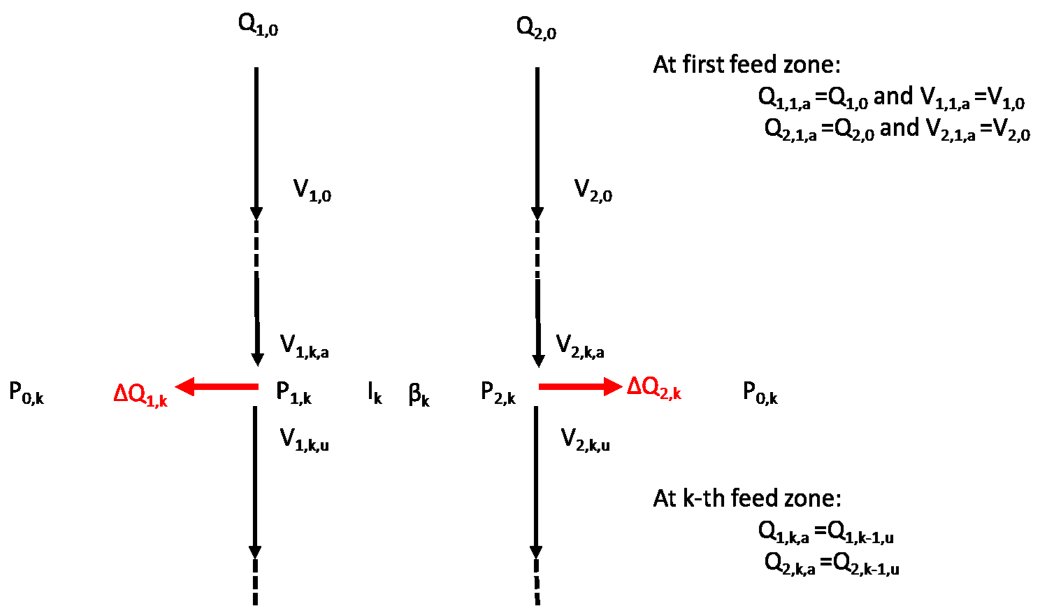

Figure 1. A scheme explaining the abbreviation used in the formulas derived above. I_k is the injectivity index of the k^{th} feed zone, $P_{0,k}$ is the out-side well pressure at the k^{th} feed zone. $Q_{\{1,2\},0}$ are the well head injection rates, $v_{\{1,2\},k,\{a,u\}}$ are the fluid velocities above or below the k^{th} feed zone, corresponding to flow rate 1 or 2.

DATA AND RESULTS

To demonstrate the method introduced above, spinner data from well ÞG-17, Þeistareykir, North-Iceland, are used. Well ÞG-17 is a 2500 m deep well, drilled in three casing stages and a production stage that finished with a 7" perforated liner (Asgeirsdottir et.al., 2017). The data and corresponding processing are presented in figures and the result of individual injectivity indices is presented with a table containing the flow progress down the well for two different flow rates. For primary smoothing of the spinner data a conventional Gauss filter (Gonzalez and Woods, 1992) of length 13 m was applied. Additional smoothing was included in the choice of station interval and sampling rate for each station. The velocity profiles were made with 1 m interval and the applied sampling length for each station was 2 m. The figures that describe the data set are as follows.

Figure 2 shows the raw spinner data sampled in 14.9 l/s and 45.0 l/s injection rates with appropriate tool velocities to secure impeller turning, i.e. avoid logging speed to be similar to fluid speed.

Figure 3 shows the effect of smoothing the data set prior to processing the fluid velocity profile.

Figure 4 shows the outcome of the fluid flow analysis of the filtered data in both 14.9 l/s and 45.0 l/s injection rates. The profiles are drawn with +/- one standard division to demonstrate how well both parameters, fluid velocity and tool constant, are determined. Not only the fluid velocity shows fluctuations in its profile, also the tool constant is dynamic which expresses the importance of using the generalized method (Grant, M.A. and Bixley, P.F., 1995) to avoid biases that follow the when the fluid velocity profile is generated from a single cross-plot (Grant and Bixley, 2011).

Figure 5 shows the comparison between the regression coefficient profiles in both 14.9 l/s and 45.0 l/s injection rates for both raw data and filtered data. Generally, the regression coefficient is very high (close to 1.000) but the effect of smoothing moves the data points at each station close to the straight line defining the fluid velocity and the tool constant.

Figure 6 shows the manually picked feed zones from the fluid velocity profiles. Each black line is drawn over corresponding feed zone and shows the estimate of the fluid velocity above and below it. Where feed zones are considered over some depth interval, the black line is drawn over the center of that depth zone.

Figure 7 shows the measured pressure profiles in 15 l/s and 45 l/s injection rates together with the out-side-well pressure output parameter of the feed zone analysis.

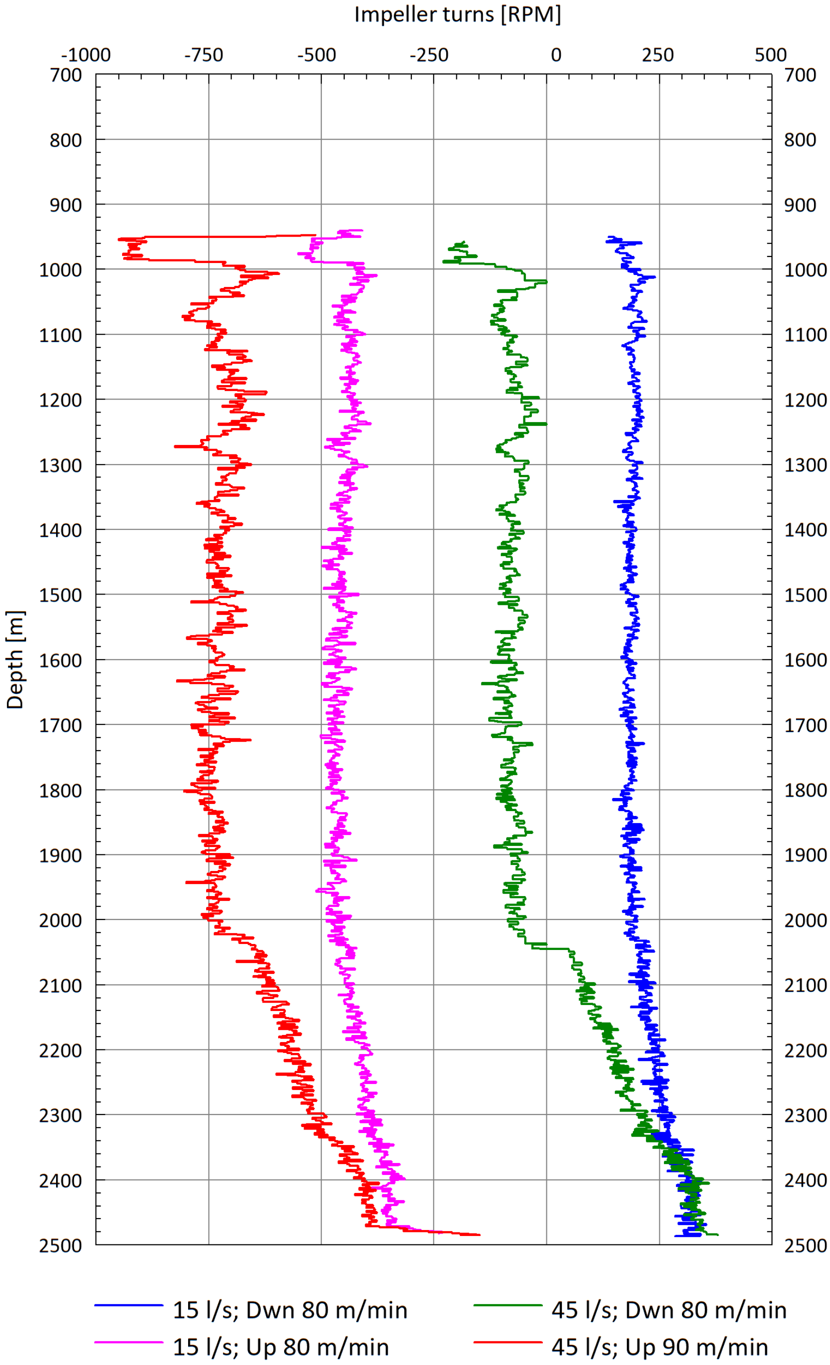

Figure 2. The sampled spinner data with 15 l/s and 45 l/s injection rates.

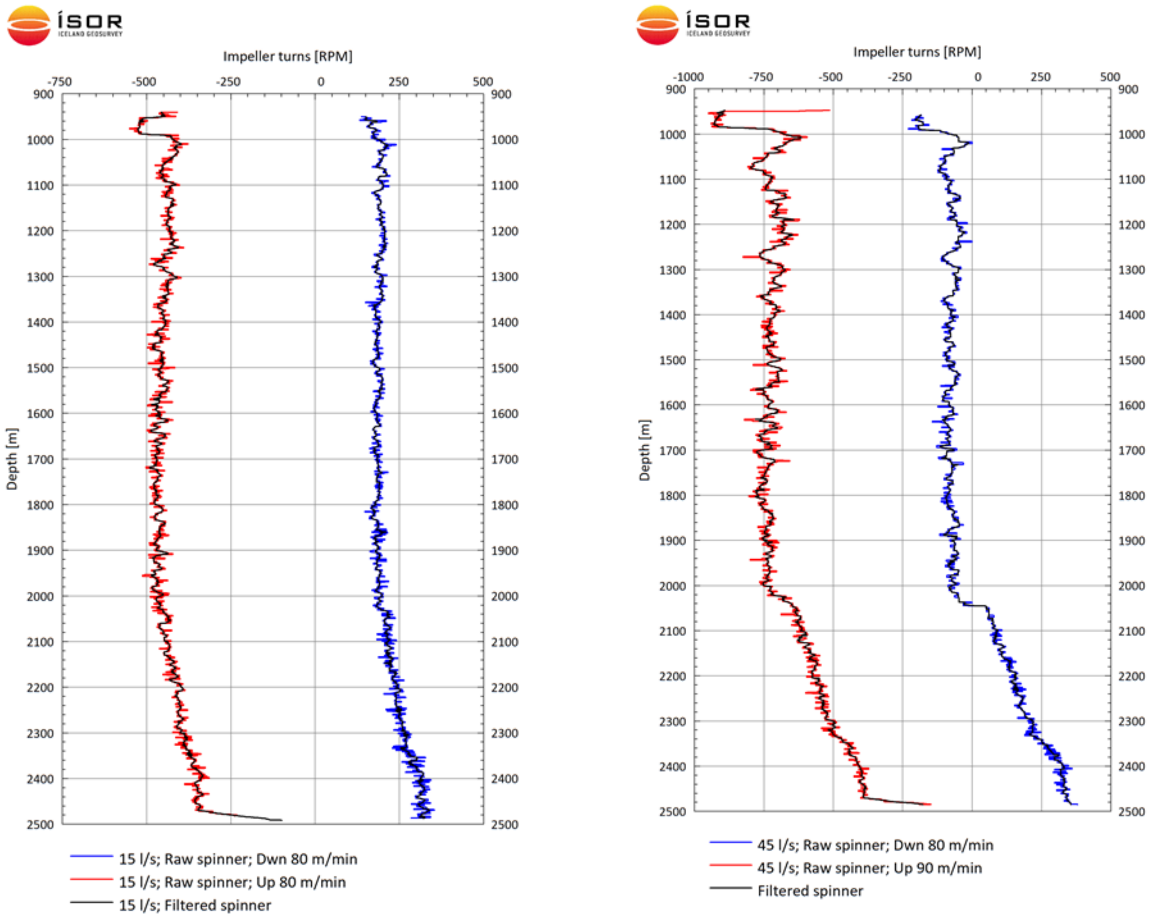

Figure 3. The sampled spinner data with 15 l/s and 45 l/s sampling rate and the corresponding filtered data set used for processing the fluid velocity profile.

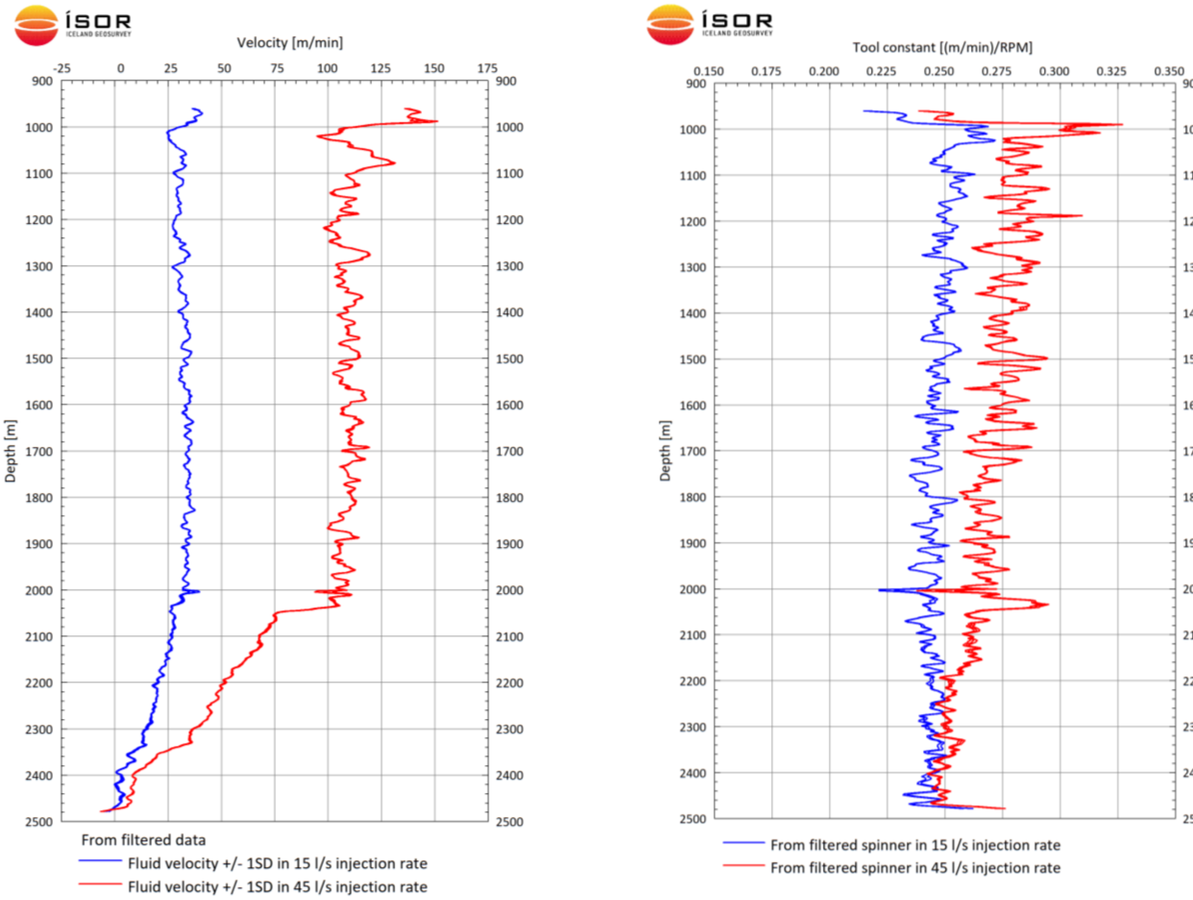

Figure 4. The resulting fluid velocity profiles and tool constant profiles from filtered data in both 15 l/s and 45 l/s with +/- one standard division uncertainty.

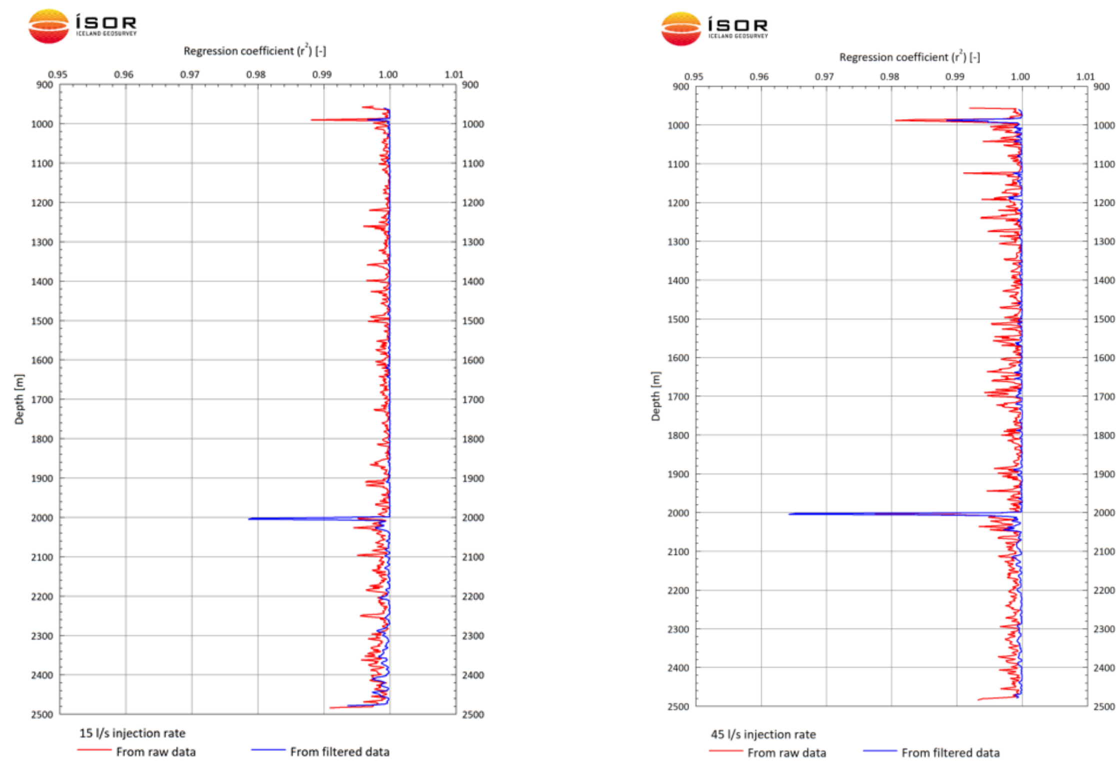

Figure 5. Fitting quality comparison between raw and filtered data through the regression coefficient for the fluid velocity and tool constant determination with both 15 l/s and 45 l/s injection rate.

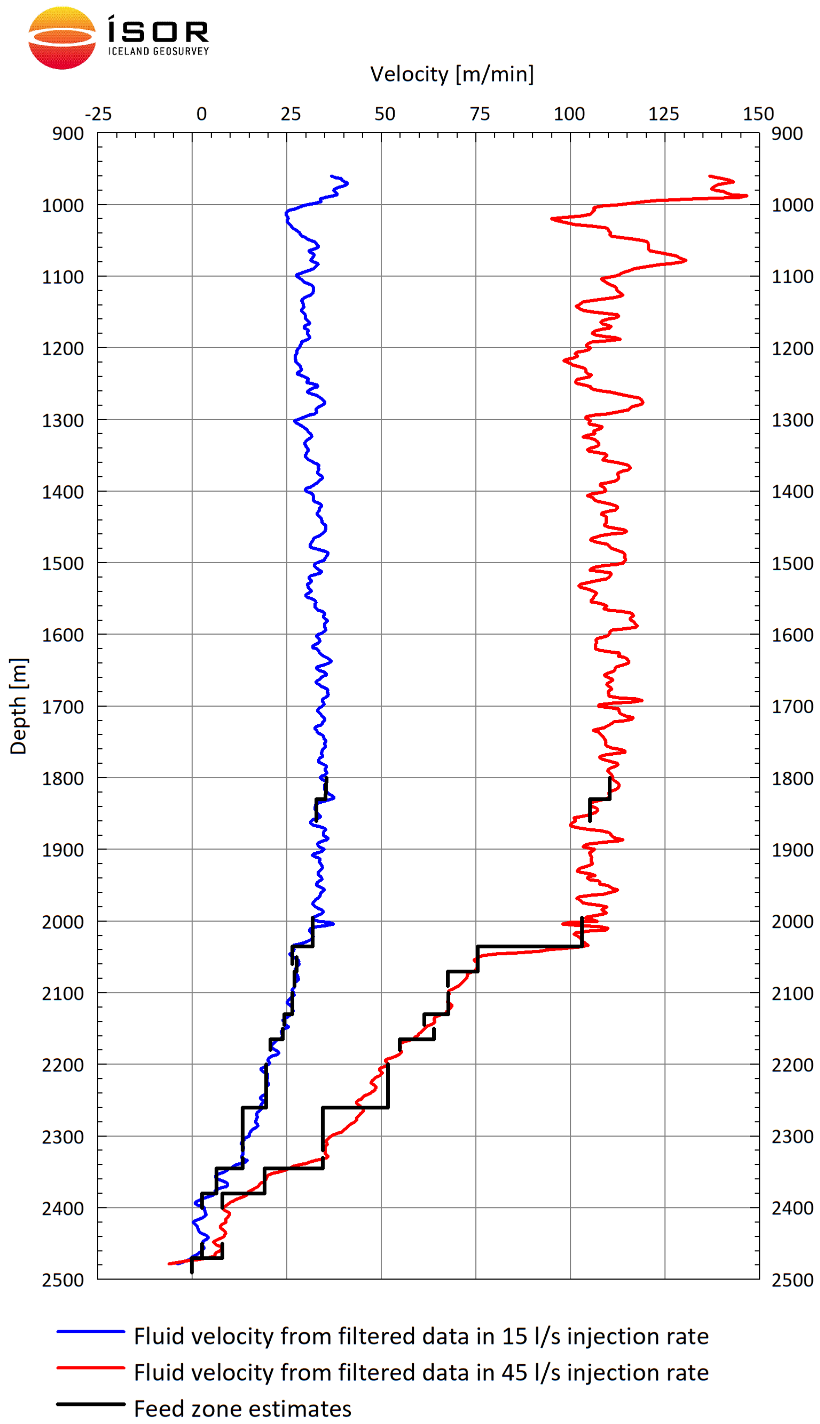

Figure 6. Feed zones are picked manually from the fluid velocity profiles. Each black line is drawn over corresponding feed zone and shows the estimate of the fluid velocity above and below it.

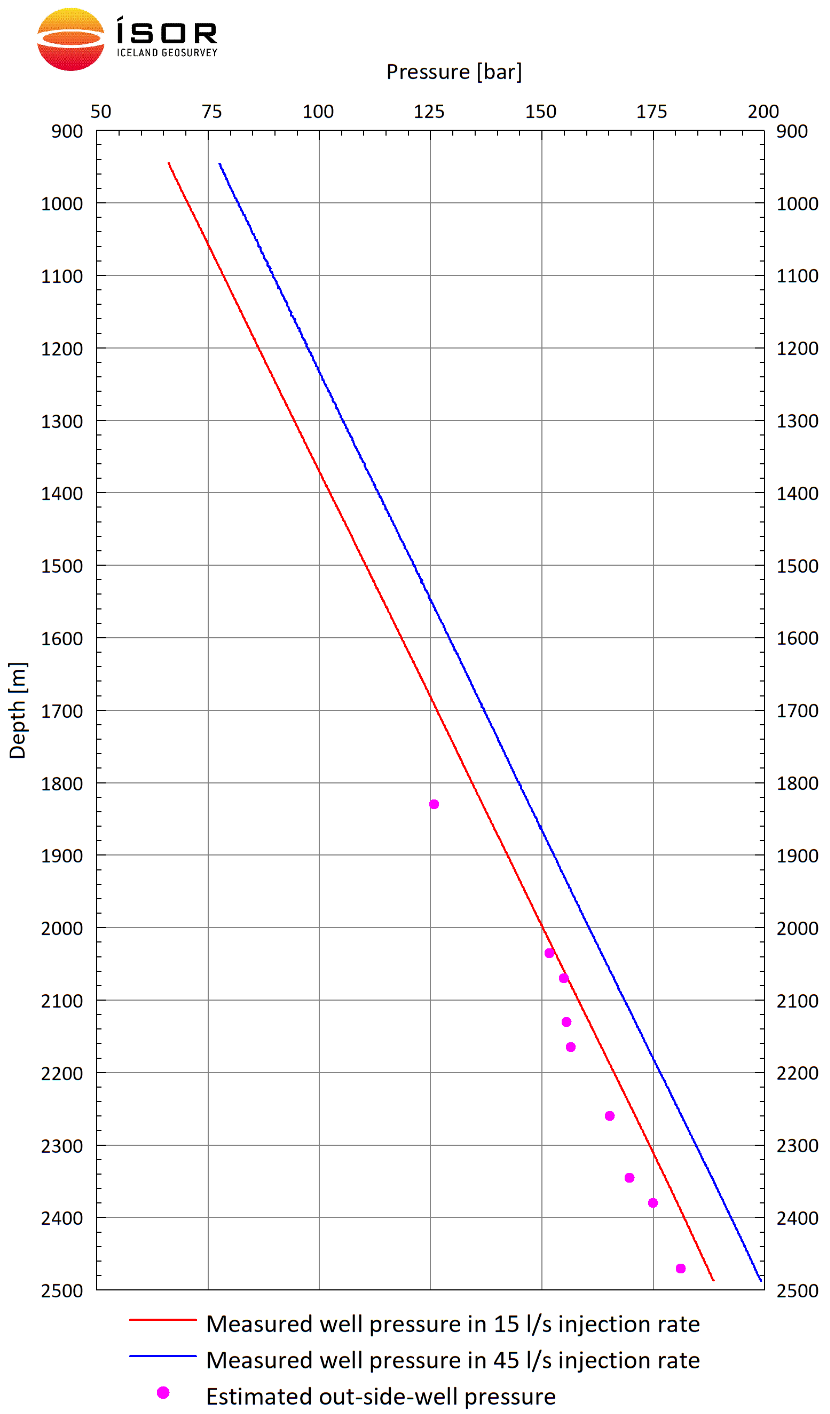

Figure 7. The measured pressure profiles in 15 l/s and 45 l/s injection rates. Also, the out-side well pressure output parameter of the feed zone analysis is drawn on the graph.

The feed zone analysis results are listed in table 1. The total injectivity index for the picked feed zones is 2.98 l/s/bar which lies close to the injectivity index of 2.8 l/s/bar which was obtained in a conventional multi rate injectivity test at 2000 m (Asgeirsdottir et.al., 2017). The first approved feed zone is at 1830 m. The best feed zone is located at 2035 m depth with estimated injectivity index of 0.90 l/s/bar, double as large as the second best over the zone of 2200 m-2320 m. According to this analysis the deepest feed zone is at 2470 m and there below no flow is detected. The out-side-well pressure from the feed zone analysis (see Table 1) is graphed with the measured well pressure in 15 l/s and 45 l/s injection rates. It is a temptation to regard what I call outside-well pressure as the reservoir pressure at each feed zone, but it must to taken into account that at the time of the completion test, the well has been injected for many days so the pressure field around the well is disturbed from the original state.

Table 1. The complete feed zone analysis. The input parameters are the fluid velocities above and below each feed zone with corresponding inside-well pressure in two different injection rates. The outcome parameters are injectivity index, outside-well pressure and effective well diameter.

			14.9 l/s injection rate			45 l/s injection rate			Fluid control at feed zones				Feed zone analysis		
Feed zone depth	$Q_{1,a}$	$Q_{2,a}$	$V_{1,a}$	$V_{1,u}$	$P_{1,fz}$	$V_{2,a}$	$V_{2,u}$	$P_{2,fz}$	$\Delta Q_{1,fz}$	$\Delta Q_{2,fz}$	$Q_{1,u}$	$Q_{2,u}$	Injectivity index	Outside-well pressure	Effective well diameter
[m]	[l/s]	[l/s]	[m/min]	[m/min]	[bar]	[m/min]	[m/min]	[bar]	[l/s]	[l/s]	[l/s]	[l/s]	[l/s/bar]	[bar]	[in]
1830	14.9	45	35.5	32.8	136.7	110.5	105.2	147.2	1.1	2.2	13.4	42.8	0.10	125.8	6.9
2035	13.4	42.8	31.8	26.5	154.2	103.1	75.6	164.5	2.2	11.4	11.2	31.4	0.90	151.7	7.0
2070	11.2	31.4	27.6	27.0	155.8	75.6	67.7	166.2	0.2	3.3	10.9	28.1	0.29	154.9	7.0
2130	10.9	28.1	26.5	24.4	160.6	67.8	61.4	171.0	0.9	2.7	10.0	25.5	0.17	155.5	7.0
2150-2180	10.0	25.5	23.9	20.7	162.2	64.0	55.0	172.6	1.3	3.6	8.8	21.9	0.22	156.5	6.9
2200-2320	8.8	21.9	19.6	13.3	171.1	51.9	34.5	181.5	2.7	7.3	6.1	14.6	0.45	165.2	7.1
2330-2360	6.1	14.6	13.3	6.5	177.8	34.5	19.1	188.2	2.9	6.5	3.2	8.1	0.35	169.6	7.1
2360-2400	3.2	8.1	6.5	2.7	180.4	19.1	8.0	191.0	1.6	4.7	1.6	3.4	0.29	174.9	7.1
2470	1.6	3.4	2.7	0.0	186.6	8.0	0.0	197.1	1.1	3.4	0.5	0.0	0.21	181.2	7.1
												Total	2.98		

CONCLUSION

The approach introduced with this paper to estimate feed zone size quantitative with combined spinner and pressure logs in two different flow rates is valid when fluid velocities are picked at equal diameters above and below each feed zone. However, feed zone recognition is often difficult from noisy spinner data and appropriate smoothing is of great help. Also, by using two different flow rates helps to distinguish between flow through feed zones and irregular caliper (Grant et.al., 2006).

As seen, not only the fluid velocity shows fluctuations in its profile, also the tool constant is dynamic which expresses the importance of using the generalized method for interpreting spinner data into fluid velocity profile inside the well (Grant, M.A. and Bixley, P.F., 1995) to avoid biases that follow the when the fluid velocity profile is generated from a single cross-plot (Grant and Bixley, 2011). However, single cross-plots at certain locations inside the well can be used to confirm fluid velocity. At ÍSOR it is a standard procedure to measure for cross-plot to conform fluid velocity inside the production casing with known diameter for two flow rates and also to measure for a single cross-plot close to the bottom section of a well to confirm flow or not flow in high flow rate.

The data from well ÞG-17 in Þeistareykir used to demonstrate the feed zone analysis described is of moderate to good quality, i.e. the pick of feed zones was clear in many places but at others not. Also, a feed zone interval has been chosen when necessary. A very important cross-check for a feed zone to be picked is the resulting out-side well pressure since wrong picks easily reverse the pressure. The output of effective diameter lies close to the 7” diameter of the perforated liner which also is a cross-check for the results. At last, the added injectivity indices to 3 l/s/bar is similar to the injectivity index of 2.8 l/s/bar obtained with a conventional multi-rate injectivity test of the well during the its completion test (Asgeirsdottir et.al., 2017).

The procedure described to distinguish feed zones in terms of flow indices is here only tested for injected well in volumetric sense which can easily be converted in mass sense since temperature is usually available. No changes need to be made to it for discharge tests with single phase liquid to obtain productive indices but as far as I have experienced spinner logs in two phase fluids are hard to interpret but according to method introduced by Acuña and Arceder (2005) it provides an alternative way to check consistency of feed zone location, enthalpy and mass flow rate contributions found with our conventional trial and error wellbore simulator based method.

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REFERENCES

Acuña, J.A. and Arcedera, B.A.: Two-Phase Flow Behavior and Spinner Data Analysis in Geothermal Wells. *Proceedings 30th* Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford CA (2005).

Asgeirsdottir, R.S., Magnús Á. Sigurgeirsson, Sylvía R. Guðjónsdóttir, Hörður H. Tryggvason, Þorsteinn Egilson, Valdís Guðmundsdóttir, Friðgeir Pétursson, Sigurjón Vilhjálmsson, Halldór Ingólfsson, Halldór Ö. Stefánsson: *Þeistareykir-Well ÞG-17. Phase 3: Drilling for 7“ perforated liner down to 2500 m*. Iceland Geosurvey, ÍSOR-2017/062 (2017).

Gonzalez, R. and Woods, R.: *Digital Image Processing.* Addison Wesley Publishing Company (1992).

Grant, M.A. and Bixley, P.F.: *Geothermal Reservoir Engineering*, 2nd ed. Academic Press, USA (2011).

Grant, M.A., Wilson, D. and Bixley, P.F.: Spinner Data Analysis to Estimate Wellbore Size and Fluid Velocity. *Proceedings* 28th NZ Geothermal Workshop (2006).

Grant, M.A. and Bixley, P.F.: An Improved Algorithm for Spinner Profile Analysis. *Proceedings* 17th NZ Geothermal Workshop (1995).

D. C. Montgomery, D.C. and G. C. Runger, G.C.: (2011) Applied *Statistics and Probability for Engineers*, 3rd ed. John Wiley & Sons, Inc., New York (2003).