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Evaluation and Comparison of Injection Indices and Production Characteristics of Feed Zones and Wells Obtained from Spinner Logs Measured During Injection and Production Testing

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ABSTRACT

The Theistareykir powerplant in N-Iceland started operation at 45 MW in 2018 after 8 production wells had been completed in the years 2016-2017. During the drilling of these wells extensive data was collected and all the wells were injection tested at the end of drilling. The injection testing involved spinner logging to map the flow characteristics of the wells, notably the feed zones. In this paper firstly, we describe the method used to process the spinner logs to produce downhole profiles of fluid velocity and mass flow. Secondly, we compare the injection indices of individual feed zones to the total injectivity index of each well. Thirdly, we compare the injection index and certain production characteristics of the wells to see how predictive the injection index is of the well´s production capacity. Lastly, we compare production and injection spinner logs in well ThG-15. This well was spinner logged while the well was discharging. The spinner logs are analyzed in the same way as the spinner logs during injection. The resulting fluid velocity profile is compared to the fluid velocity profile from injection testing. The outcome is evaluated to give an idea of the relationship between the wells flow characteristics during injection and production testing.

1. INTRODUCTION

In this paper spinner logs are used to evaluate permeability in wells and compared with the injectivity indices obtained from the step rate injection tests at the end of drilling. To obtain information on the location of feed zones and to estimate their permeability the well is spinner logged with two different injection rates. Ideally the two different injection rates are low to intermediate in the one case and high in the other. In practice the spinner logs are done just before starting the step rate injection test and again at the end of the step with the highest injection rate, after the pressure measurements of the step are completed. Logging the spinner at different injection rates creates a contrast in the pressure conditions in the well. The pressure contrast is reflected in the spinner logs since the pressure gradient between the well and the reservoir drives flow in and out of the feed zones. Certain feed zones will be masked by the pressure, i.e. those feed zones that are situated at the depth interval where the pressure in the well approximately matches that of the surrounding reservoir.

The injectivity index measures the amount of injected liquid the well will accept as pressure increases, typically in units of [L/s]/bar. The injectivity index is considered a good indicator of the overall permeability of a well. When drilling through a formation of varying permeability it is useful to be able to test the well and obtain the injectivity index. Nearing the end of drilling a short step rate injection test is often performed to assess if the permeability of the well is sufficient and thus if drilling can be stopped. If the injectivity is deemed too low drilling may continue or stimulation may be performed on the well to improve the injectivity index. It is worth noting that the acceptable range of injectivity indices varies from one geothermal field to the other. The relationship between the injectivity index and the production capacity of the well will be discussed in detail in section 3 of this paper. A case study from the high temperature geothermal field Theistareykir in Iceland is used to explore the predictive power of the injectivity index when it comes to the electrical output, thermal output or total flow from wells. Eight new wells were drilled in the field in 2017-2018 and all of the wells were logged and tested extensively during and at the end of drilling. The data accumulated during this drilling campaign serves as the basis of the case study undertaken in this paper. It worth mentioning that the production section of the wells was drilled with water and not with mud since doing so can cause the so-called skin effect, where permeable zones are blocked by drilling mud.

2. PROCESSING SPINNER LOGS TO OBTAIN DOWNHOLE PROFILES OF VELOCITY AND MASS FLOW

Each spinner log is run at a different logging speed. The spinner data itself is measured in rounds per minute of the impeller on the logging tool. Since the rate of the rotation of the impeller on the spinner tool is directly related to the logging speed, it is kept as close to constant as possible. To verify the integrity of the data the spinner logs and the tool velocity are plotted against depth. A visual assessment of the data at this stage helps to avoid false positives when analyzing inflow and outflow in the logs.

2.1 Effects of Well Width on the Logs

The well inner diameter directly affects the velocity at which the fluid flows inside the well and therefore the spinner impeller rate. Fluid flow is slowed down where the well widens and inversely speeds up where the well is narrower. Therefore, the well completion needs to be considered when evaluating the differences in velocity in the well. To do so the caliper logs are plotted alongside the spinner data, see Figure 1. Changes in the inner diameter of the well are compared to indications on the locations of feed zones from temperature logs, lithology or due to circulation loss to eliminate purely geometrical effects.

2.2 Depth Correction

A suggested method to correct for differences in depth in the logs is to shift the data up or down using the top of the liner as a reference point. As the spinner tool passes the top of the liner the wellbore radius suddenly gets smaller resulting in a change in flow velocity. This sharp change in velocity can be seen at around 780 m depth in Figure 1. If this sharp change cannot be seen in the spinner logs, perhaps because the fluid flow is slow, or the spinner logging speed is too low, it is possible to try to find another depth reference point but if one cannot be found then depth correction is best omitted. A typical depth correction in a high temperature well of about 2000 m depth is of the order of a few meters and the shift can be in either direction, upwards or downwards.

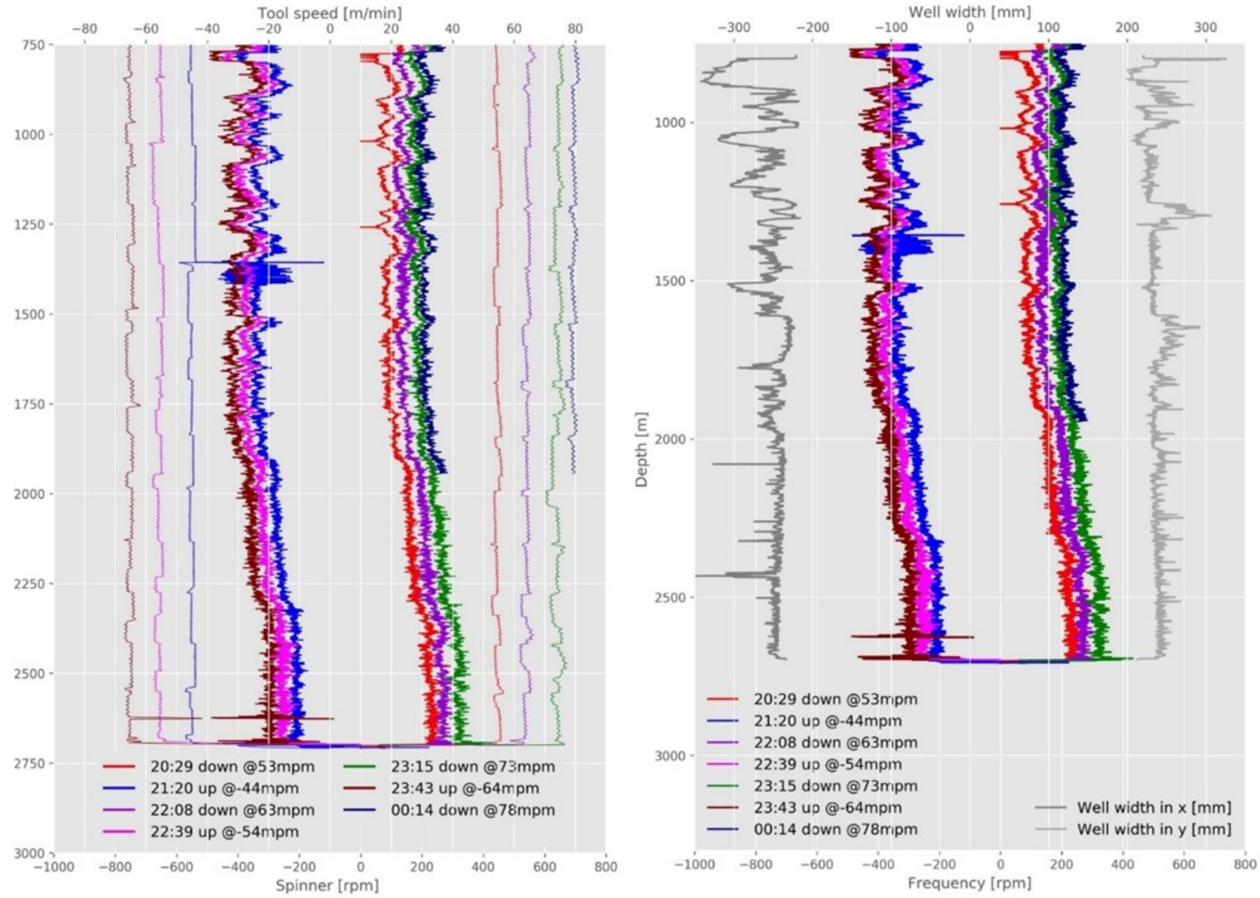

Figure 1. Left image: An example of raw spinner frequency data (rpm) and the tool speed in meters per minute (denoted mpm). The data on the edges of the plot represents the logging speed, which is relatively constant for each run. The more central data in the plot is the spinner rotation data. This data was logged in well ThG-12 on September 30th, 2016 (Ásgeirsdóttir et al., 2016). Right image: An example of spinner data plotted alongside the XY-caliper log shown in grey. The XY-caliper logs show a measurement of the well's inner diameter on two axes (Ásgeirsdóttir et al., 2016).

2.2 Noise and Outlier Filtering

The spinner logs are noisy and tends to contain outliers, see example in Figure 2. Outliers can occur e.g. when the impeller is blocked by rock chips, when there is an electrical issue in the tool or if there is a connection problem between the tool and the registration unit on the surface. To rid the data of outliers and noise a box filter and a gaussian filter are applied to the data.

2.3 Calculating Fluid Velocity from Spinner Logs

The fluid velocity is calculated using cross plots such as the one in Figure 3. A cross plot typically contains data from a 4-meter long depth interval, 2 meters above and 2 meters below a reference depth. The logging speed (meters per minute, mpm) over the selected interval is plotted on the y-axis and the impeller rotations (in rounds per minute, rpm) on the x-axis. A linear regression is used to fit a line through the data points. Where the regression line goes through zero on the x-axis, the value of the fluid velocity can be read off the y-axis. The idea being that where the frequency of the impeller is zero the tool is travelling at the same speed as the fluid in the well. (Grant and Bixley, 1995). It is suggested to run the spinner tool 4 times over a depth interval, in order to obtain a good dataset for the linear regression.

Spinner logs are usually done in the production part of the well, but it is good practice to run the tool about 80-100 m up into the production casing. This allows for the injection rate to be confirmed as described in section 2.6 of this paper.

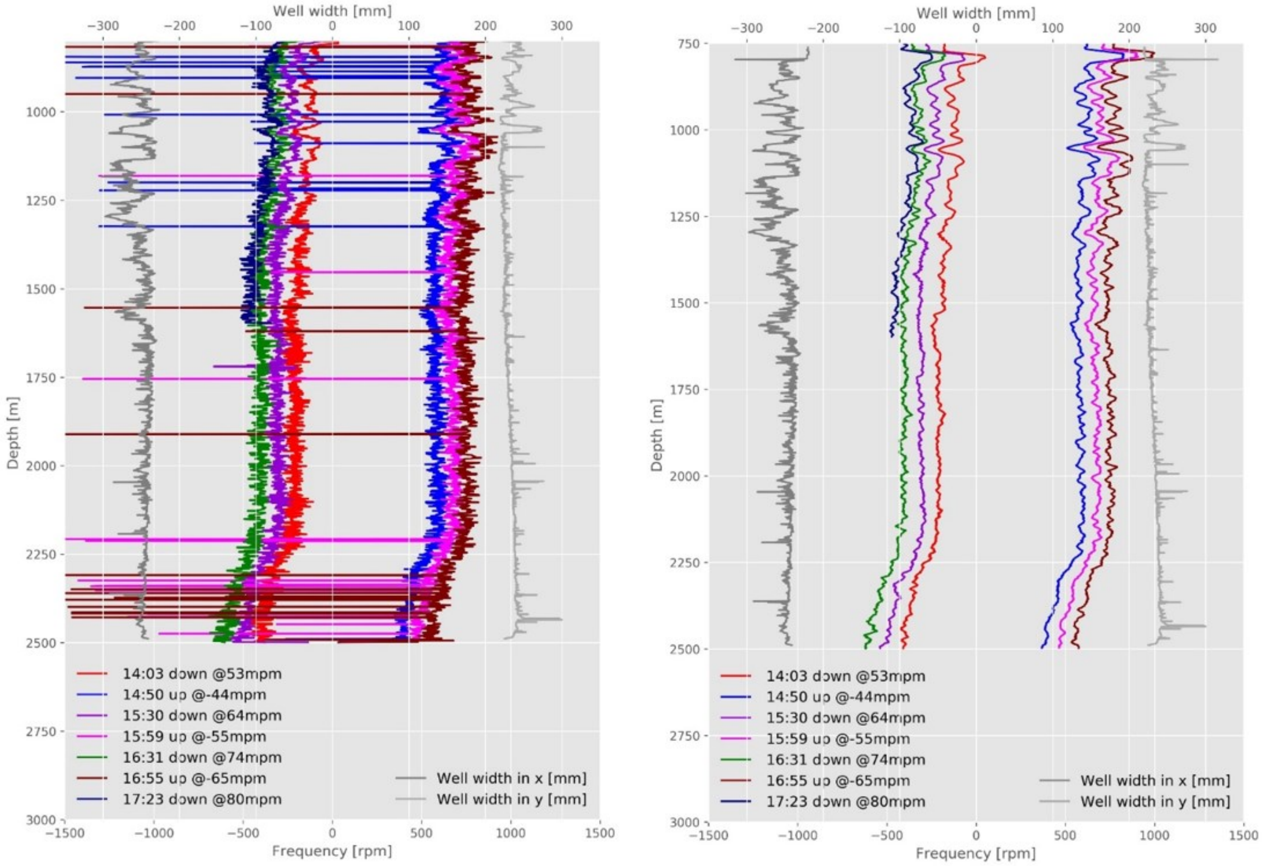

Figure 2: Image on the left: An example of noisy spinner logs with outliers (colored central data) plotted alongside XY-caliper logs (in grey) from well ThG-13 (Asgeirsdottir, 2017). Image on the right: An example of spinner logs that have been filtered to remove outliers and noise. The logs are plotted next to caliper log (in grey) for the visual evaluation of the effects of the well's width on the spinner impeller rate.

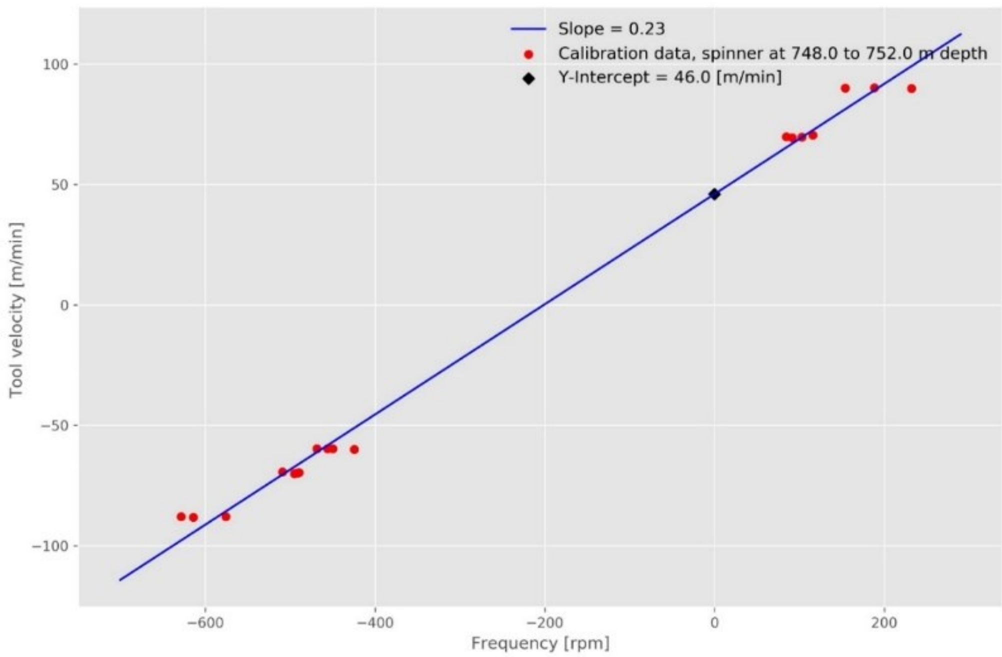

Figure 3: An example of a cross plot from the depth interval 748 m to 752 m. The tool velocity (in meters per minute, denoted mpm) is plotted against the impeller's frequency (in rounds per minute, denoted rpm). The red points represent the dataset. The blue line is a linear regression on those datapoints. The black point shows where x=0, the value of y at this point corresponds to the fluid velocity at this depth and at this injection rate in the well.

2.4 Creating Fluid Velocity Logs from Cross-Plots

It is suggested to generate cross plots at 1-meter intervals over the production section of the well. The fluid velocities obtained from these cross plots are then plotted against depth as a fluid velocity log, one for each injection flow rate applied during the spinner logging. The fluid velocity logs give a good picture of where inflow and outflow zones may be situated in a well and one such log is sufficient for the interpretation of the location of feed zones in a well.

2.5 Creating Volumetric and Mass Flow Logs

In addition to the fluid velocity log it is possible to create logs of the volumetric flow rate (L/s) and mass flow rate (kg/s). The volumetric flow rate is the product of the fluid velocity and the cross-sectional area at the same depth. If the well width has been logged, e.g. with a caliper log this can be used to estimate the cross-sectional area in the open hole. To convert from volumetric flow rate to mass flow rate the temperature of the injected fluid is used to obtain the fluid density (IAPWS 1997) and convert the flow from L/s to kg/s.

The assumption that the injected fluid flows down the entire cross section of the well becomes perhaps a little naïve when a well has been completed with a liner. The fluid is in that case flowing down a double annulus, the inner annulus being the liner and the outer annulus being the radius of the well, which can be quite irregular due to borehole breakout. Borehole breakout is more pronounced i.e. where the well has been drilled with a motor drill bit, where there is high stress in the formation, or where the drill bit has been passed through numerous times during the drilling operation. In addition to this irregular radius the well may collapse on the liner in parts. This creates a single annulus of flow over a depth range, which then becomes a double annulus again just below. We will discuss this further in section 3. Figure 4 shows two examples of mass flow logs. In one case (left image) the mass flow is calculated using the entire width of the well and matches the injection rate, depicted as a dotted line. This leads to the conclusion that in this well the fluid flows along the entire well bore. In the other case (image on the right) the mass flow is calculated using the liner cross sectional area and matches the injected flow rate. This indicates that in this well the fluid flows inside the liner and not the entire well bore.

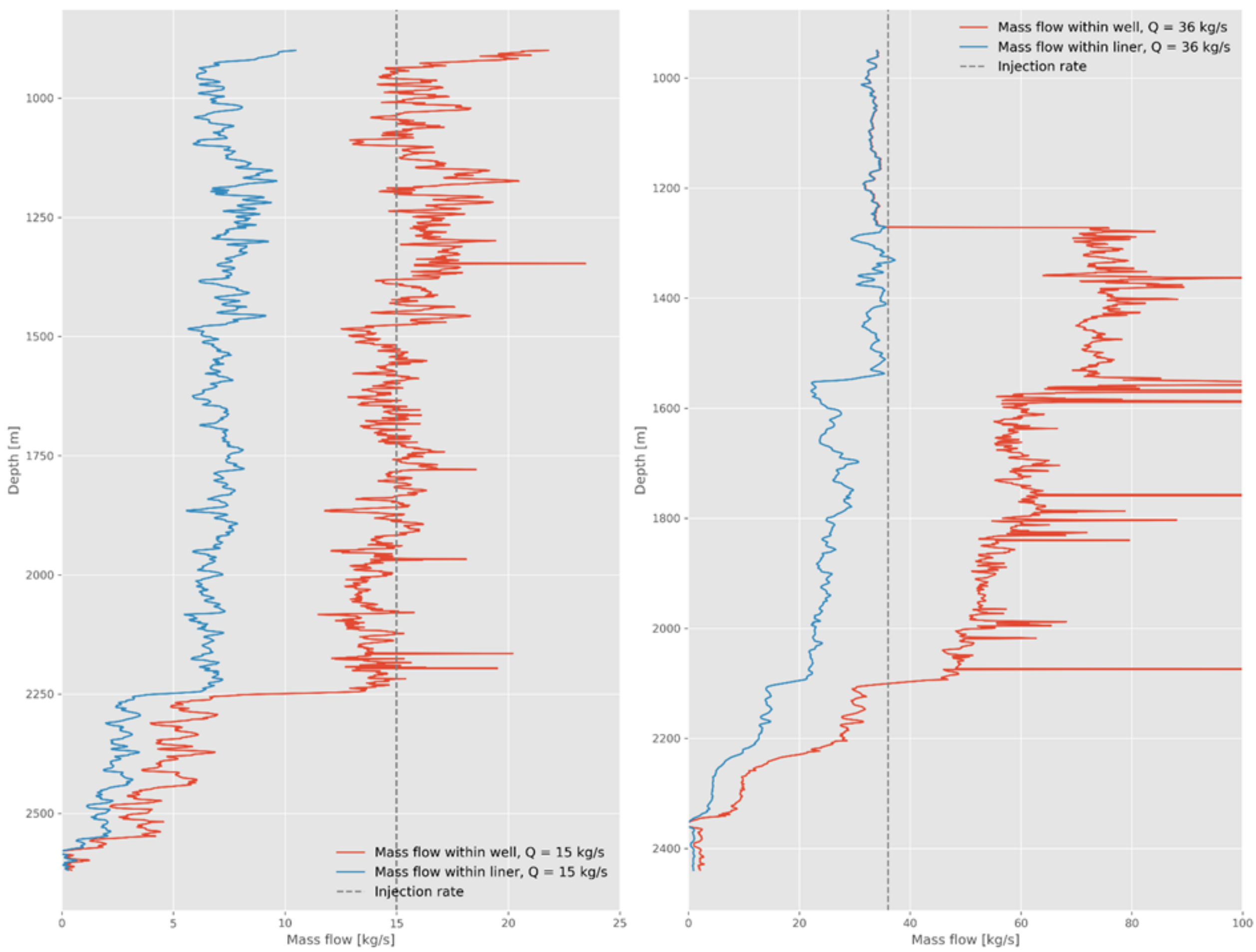

Figure 4. An example of the mass flow rate in well ThG-16 at injection rate 15 L/s and in ThG-14 at injection rate 36 L/s (Guðjónsdóttir et al., 2017a) (Guðjónsdóttir et al., 2017b). The mass flow rate is the product of the fluid velocity, fluid density and the cross-sectional area the flow goes through. The mass flow logs from these two wells appear to be giving information on whether the injected fluid flow is flowing along the entire wellbore (left image) or just inside the liner (right image).

2.6 Verification of the Injection Rate

A part of the suggested spinner logging protocol is to run the tool into the production casing, approx. 80-100 m above the casing shoe. This allows the fluid velocity and the flow rate in the casing to be calculated. This is an inexpensive way to verify the injection rate into the well and may be useful where the injection rate is obtained by an indirect measure, such as the pump rate.

This method entails identifying a 4 m depth interval in the casing where the tool speed and the impeller rate are stable, plotting a cross-plot over this interval and obtaining the fluid velocity from the regression line as described in the previous subsection. The volumetric flow rate is the product of the fluid velocity and the cross-sectional area and since the dimensions of the casing are well known this is straight forward to obtain and to convert to mass flow rate if needed.

2.7 Interpretation and Documentation of Feed Zones

At the end of drilling, spinner and temperature logs give valuable and complementary information on the presence of inflow and outflow zones in a well. Active feed zones are identified in the fluid velocity logs by the change in fluid velocity at a certain depth, after geometric effects have been excluded. In temperature logs feed zones are seen as either a change in slope of the log (outflow zones) or as a step in the log (inflow zones), see Figure 5. The results from the interpretation of the spinner and temperature logs may be summarized in a table of feed zones for each well. The table should contain the depths where feed zones were detected, an estimate of the relative size of the feed zone e.g. the injectivity index (see section 2.8), and what downhole logs the feed zone was seen in (e.g. temperature, spinner, geophysical logs). Additionally, it is recommended to note any drilling parameters that may have changed at the depth of the feed zone (e.g. loss of circulation, ROP), any changes in the lithological logs or fractures that might explain the permeability of the well at the depth of the feed zone. The table of feed zones serves as a reference for further study of the reservoir and its permeability. Moreover, the table of feed zones should be updated as more relevant information becomes available, e.g. during warm-up after drilling, during flow testing of the well or later in the lifetime of the well.

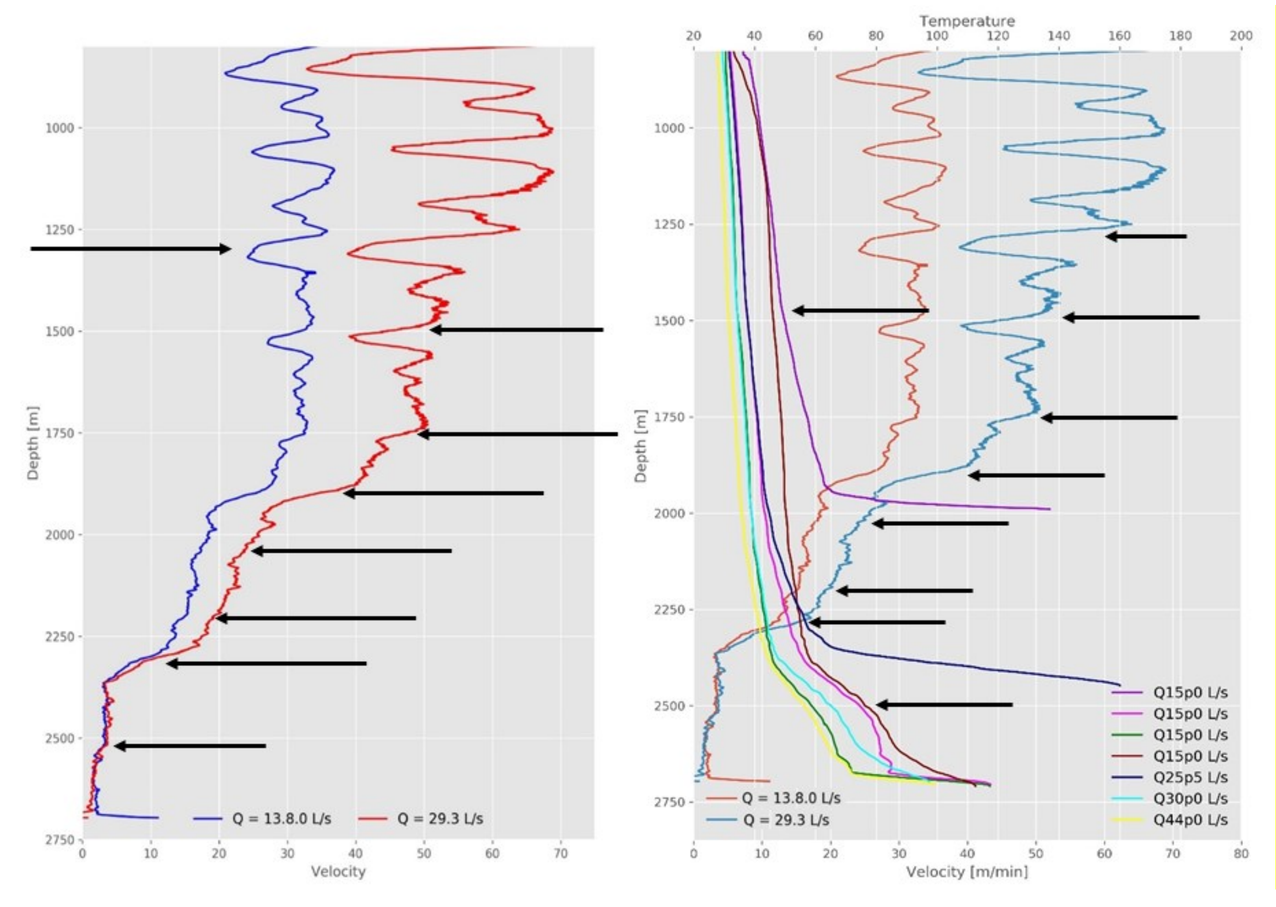

Figure 5. Locating feed zones in fluid velocity logs (left image) entails looking for changes in flow velocity. Locating feed zones in temperature logs (right image) entails looking for changes in the gradients of the temperature logs. The feed zones have been highlighted with black arrows.

2.8 The Calculation of Injectivity Indices of Individual Feed Zones

Fluid flow into the well or out of it is governed by pressure difference. In order to affect the pressure inside the well the injection rate is changed which causes flow change at each individual feed zone. With corresponding fluid velocity profiles and pressure profiles, an injectivity index for each individual feed zone is calculated using a method described by Egilson (2020).

3. A CASE STUDY: INJECTIVITY INDICES AND PRODUCTION CAPACITY IN THEISTAREYKIR GEOTHERMAL FIELD IN ICELAND

The spinner processing chain described in section 2 was tested on eight new wells drilled at Theistareykir in Iceland. The injectivity indices calculated for individual feed zones were compared to the injectivity indices obtained from the step-rate injection tests and the correlation between the injectivity indices and the production capacity of the wells was investigated.

3.1 The Feed Zone Injection Indices in Wells ThG-11 to ThG-18 in Theistareykir

Out of these eight new wells two had insufficient data for injectivity indices to be calculated for individual feed zones. In both cases spinner logging had failed. The first case was due to malfunctioning pumps at the drill rig which resulted in that half of the spinner logs being taken with a zero injection rate. The second case was due to an electrical connectivity problem between the tool and the acquisition computer.

The injectivity indices were determined for individual feed zones for the 6 wells where data was sufficient. The distribution of the sizes of the injectivity indices against depth in the wellbore (measured depth) is seen in Figure 6.

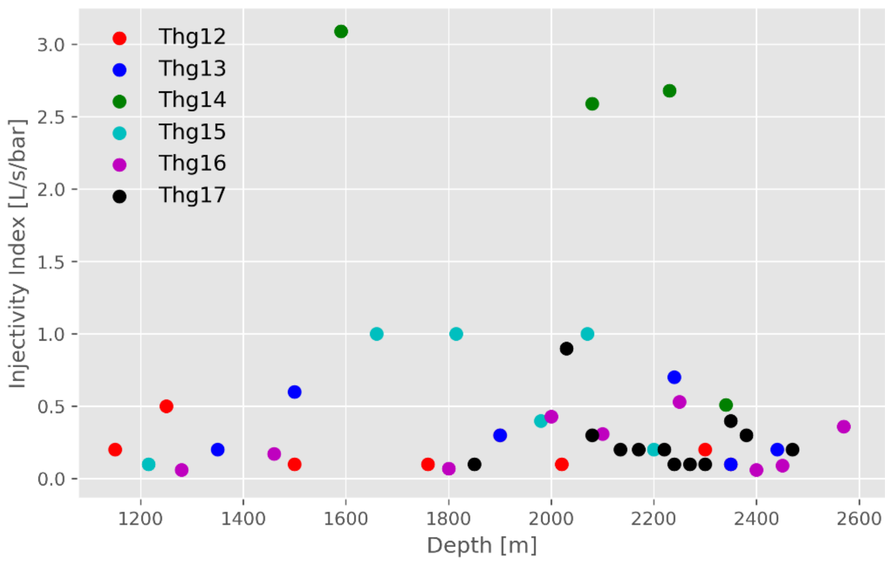

Figure 6. The injectivity indices of individual feed zones in wells ThG-12 to ThG-17, plotted against their approximate depth (measured depth) (Guðmundsdóttir, 2018b).

3.2 A Comparison of Individual Feed Zone Injection Indices to the Injection Indices of Wells

Table 1 below shows how the sum of the injection indices of feed zones in each well compared with the injection index obtained from the step-rate injection test at the end of drilling. The last column shows the relative difference (in percent) between the sum of the injection indices and the injection index obtained from the step test. The difference is the greatest for well 13 but in this well there were problems with the pumps on the rig during the injection test and the pressure did not stabilize during any of the steps of the step rate injection test.

Table 1. A comparison of the injectivity indices obtained from step-rate injection tests and the sum of the injectivity indices of individual feed zones.

Well	Injection Index from step test [(L/s)/bar]	Sum of Injection Indices of Feed Zones [(L/s)/bar]	Difference in Injectivity Indices [%]
ThG-12	2.2	1.6	27
ThG-13	3.6*	2.1	42*
ThG-14	7.8	8.9	14
ThG-15	3.9	3.7	5
ThG-16	2.2	2.1	5
ThG-17	2.8	3.1	11

3.3 Correlating the Injectivity Indices and the Total Flow from Wells

According to Grant (2009) the injectivity index has a lognormal distribution. Similarly, Sveinbjornsson and Thorhallsson (2014) show that both the total flow from wells and their injectivity indices have a lognormal distribution. Grant and Bixley (2011) put forward a non-linear relationship between the injectivity index and the expected maximum discharge of an 8-inch wide well. Additionally, Combs and Garg (2000) compare the injectivity and the productivity indices of wells on a log-log scale and find a log-linear trend between the two. Their study has a larger set of single-phase wells than of two-phase wells and the log-linear trend in the single-phase case is more pronounced than in the case of the two-phase wells.

All of the eight new wells have been flow tested and data from all eight wells was thus included in the following analysis.

In the present study, the correlation coefficient between the $\log_{10}$ of the injectivity index and the $\log_{10}$ of the total flow is 0.75, compared to 0.53 in the linear case (when the $\log_{10}$ is not taken). When looking only at the wells that produce at 12 bar-a separation pressure (six out of the eight wells) the correlation coefficient is higher between the $\log_{10}$ of the total flow and the $\log_{10}$ of the injectivity index, or 0.83. While this is interesting, the subject of this study is the predictive power of the injectivity index at the end of drilling and since a wells capacity to produce at a given separation pressure only becomes known after discharge testing, weeks or months after the end of drilling, this will not be discussed further here.

One of the wells has a much greater flow than the others relative to its injectivity index and thus the corresponding data point on the plot in Figure 7 lies quite far from the remaining data points and the regression line, see Figure 7. This well has both high enthalpy and favorable reservoir conditions, which, as Sveinbjornsson and Thorhallsson (2014) point out, are the other two important parameters when predicting a wells capacity for power production based on it´s injectivity index.

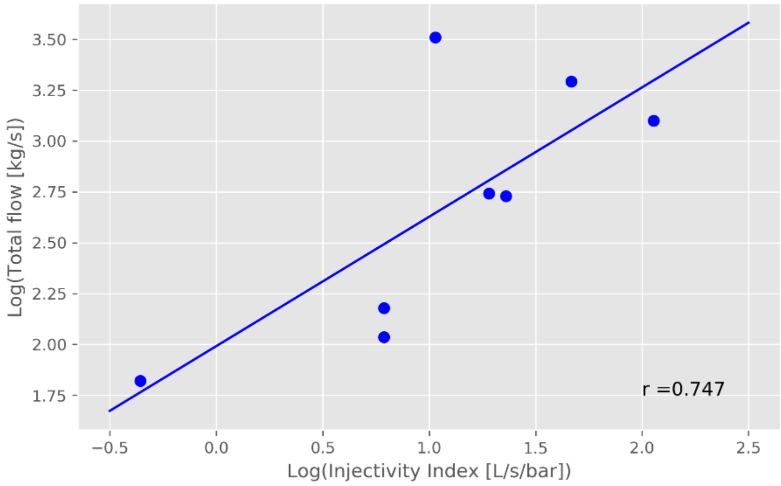

Figure 7. The $\log_{10}$ of total flow (in kg/s) plotted against the $\log_{10}$ of the injectivity index (in L/s/bar) of each well.

3.4 Correlating the Injectivity Indices to the Electrical and Thermal Output from wells.

Out of the eight new wells six produce at 12 bar-a. The following analysis was done only on those 6 wells. The correlation between the $\log_{10}$ of the electrical power output of the wells (in MWe) and the $\log_{10}$ of the injectivity index is 0.737. A similar correlation exists between the $\log_{10}$ of the thermal power output of the wells (in MWth) and the $\log_{10}$ of the injectivity index or 0.743. Figure 8 shows the thermal and electrical power output of wells plotted against their injectivity indices on a log-log scale.

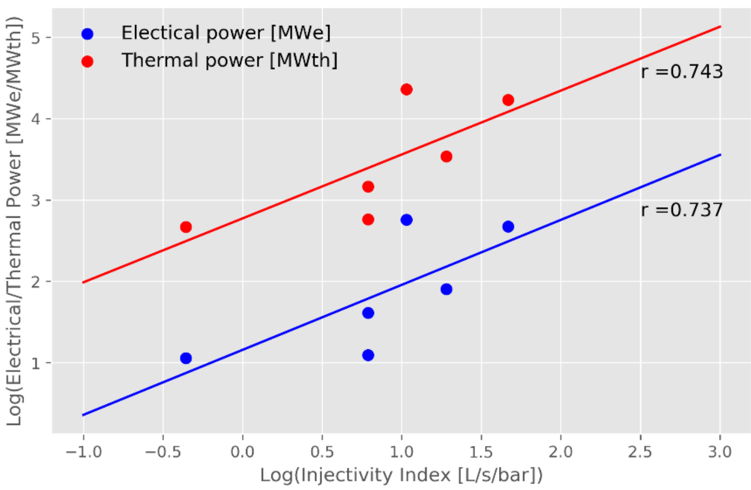

Figure 8. The electrical output of wells (in MWe) plotted against the injectivity index of each well (in L/s/bar) on a log-log scale.

4. A COMPARISON OF SPINNER LOGS TAKEN DURING INJECTION AND DISCHARGE IN WELL THG-15 IN THEISTAREYKIR

We have described how spinner logs taken at the end of drilling are used to locate feed zones in a well. In the case study in the previous section injectivity indices of individual feed zones added up to give an overall injectivity index close to that of the step rate injection test itself. The question of how representative these feed zones located in the well after weeks of cold-water injection are of the production conditions in the well remains unanswered. Very little spinner data has been collected from wells in a production state but out of the eight wells of the case study in the previous section one was spinner logged while discharging. This logging took place as a part of a PTS logging session. The tool went through a boiling surface at around 500 m depth, inside the production casing. Therefore, the fluid in the production part of the well was in the liquid phase during logging. Due to unfavorable weather conditions the logging was cut short after one set of spinner logs. Therefore, it was only possible to calculate one velocity log and estimating the production indices of the individual feed zones was not possible, since this requires at least two velocity logs.

4.1 A Comparison of Spinner Logs Taken During Discharge and Injection

After processing the spinner logs taken during discharge in the same way as the logs taken during injection, as described in section 2 of this paper, one velocity log was obtained. Figure 9 shows a comparison of the velocity logs from the injection test and the velocity log calculated from spinner data during discharge. For ease of comparison the discharge log has been flipped over the y-axis, since due to the reversed direction of flow during discharge the velocity has opposite signs to that during injection.

The question we look to address with this comparison is what difference there is in the outflow zones in the well during discharge compared to the inflow zones identified in the spinner logs from the injection test. In the case of this well, ThG-15, which has a single-phase flow below 500 m, the feed zones detected at the end of drilling are very similar to the feed zones visible in the discharge velocity log, see

Table 2. A slight shift upwards in the location of the feed zones in the discharge logs is noticed compared to the injection logs which may be explained by the reversed direction of flow. This result is encouraging with respect to the interpretation of the spinner logs taken at the end of drilling (Guðmundsdóttir, 2018a).

The velocity log at the higher injection rate (35 L/s) is more comparable to the discharge velocity log. A further look into the pressure logs taken simultaneously to the logs shows that the pressure gradient from the wellbore to the reservoir are of similar proportions although of opposite signs. The velocity log taken with a lower injection rate (10 L/s) shows less contrast in the velocity log making the detection of feed zones in this log more difficult, see Figure 9. This further reinforces the argument of using a high injection rate when spinner logging.

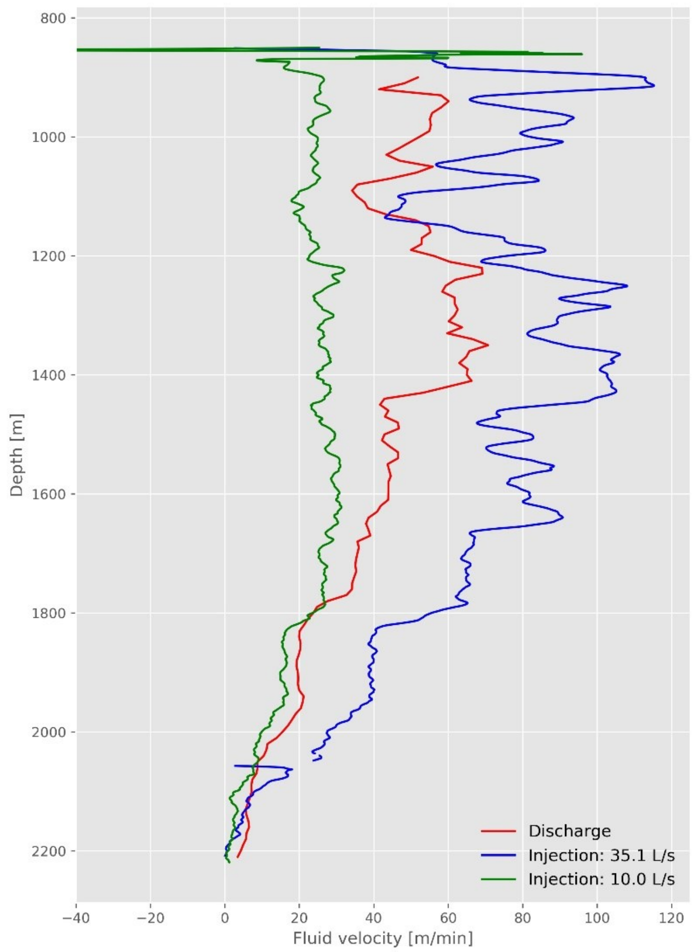

Figure 9. The velocity logs from the injection test in the well (in blue and green) and the velocity log obtained from spinner logs during discharge (in red).

Table 2. A comparison of the feed zones identified in well ThG-15 from spinner logs during discharge and during injection.

Depth of inflow zones from spinner logs during discharge [m]	Depth of outflow zones from spinner logs during injection [m]
1410-1440	1457
1670-1680	1670
1770-1830	1730, 1800-1830
1970-2020	1980
2050	
2080	2090
	2250?

5. CONCLUSION

In this paper we have described a logging protocol and a spinner log processing chain, based on the works of Grant and Bixley (1995), which leads to the creation of a list of feed zones in a well and their individual injectivity indices, based on the method by Egilson (2020). We have shown that for the field of Theistareykir in Iceland the injectivity indices of feed zones add up to a total injectivity index close to that estimated by the step-rate injection test at the end of drilling.

We have investigated the predictive power of the injectivity indices when it comes to estimating what a well's production capacity will be. Our results from the analysis of eight new wells in the high temperature geothermal field of Theistareykir, Iceland, show that the $\log_{10}$ of the injectivity index correlates reasonably with the $\log_{10}$ of total flow from a well, with a correlation coefficient of 0.75 and slightly better even with the $\log_{10}$ of the output of the well at 12 bar-a separation pressure (kg/s), with a correlation coefficient of 0.84. Our results confirm those of Sveinbjornsson and Thorhallsson (2014) where the area under study was the high temperature geothermal field of Hellisheidi, Iceland. Additionally, they concluded that to obtain a reliable prediction of steam mass flow on the basis of the injectivity index one must also consider reservoir conditions and enthalpy. In Rutagarama (2012), the relationship between the injectivity index and the productivity index is studied for 28 wells from 5 geothermal fields worldwide. Although no obvious relationship is seen in the data on a linear scale, a second look at the data on a log-log scale reveals that the injectivity index and the productivity index are reasonable correlated, with a correlation coefficient of 0.68, which is in line with the results discussed here.

A suggestion to improve on the current comparison would be to include an uncertainty in the estimate of the injectivity indices in the analysis since it is not uncommon to see step-rate injection tests where the injection index has been estimated despite the fact that the pressure does not appear to stabilize during the testing. This can occur i.e. when logging with a memory tool, since the step length needs to be fixed before the logging and may turn out to be insufficient.

A comparison of the results of spinner logging during discharge with spinner logging during injection in a single-phase flow well shows that the feed zones identified at the end of drilling match those identified in logs during discharge, an encouraging result with respect to the predictions made by the spinner logging at the end of drilling. It is not unlikely that the picture looks more complex in the case of two-phase flow. To further study the differences in feed zone productivity when two-phase flow occurs in a well we suggest simulating such a scenario in a well bore simulator.

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