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Real-Time Monitoring of Geothermal Wells using the Dual-Differential Pressure Method

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ABSTRACT

Landsvirkjun has performed experiments on several methods for measuring production from geothermal wells in real-time. A differential pressure method was tested using an orifice plate and three pressure ports. The method was set up in collaboration with Tek DPro Flow Solutions, and yielded promising results. The experimental conditions spanned a total flow rate of 5 to 35 kg/s and enthalpy from 1000 to 2800 kJ/kg.

We discuss the experimental setup, data collection, analysis and results in brief. Our main conclusion is that the method can be used to estimate well output in real-time with reasonable accuracy. Another advantage of the method is that the functionality of the sensors and orifice plate can be evaluated by means of a real-time diagnostics algorithm derived from the measurements.

INTRODUCTION

A plan for the experiments discussed in this paper was introduced in a publication presented at the 2020 World Geothermal Congress (Geirsson and Juliusson, 2020). The aim of the project was to find a practical method to measure geothermal well output (flow rate, enthalpy and thus thermal power) in real-time. Such continuous monitoring could open the doors to further optimizing well field operations with online control valves and dynamic models for fluid flow though the reservoir and steam-gathering system.

The experiments were carried out in the Þeistareykir geothermal field in the summers of 2019, 2020 and 2021. Several types of multi-phase flow meters were tested – some appeared to work, while others were less successful in dealing with the conditions tested. Due to confidentiality agreements, these cannot all be discussed. In this publication we will only discuss the results of the Dual-Differential Pressure (DDP) method. The DDP method is well known in the oil and gas industry and consists of a single orifice plate, one pressure probe upstream, and two pressure probes downstream of the orifice plate, as shown in Figure 1.

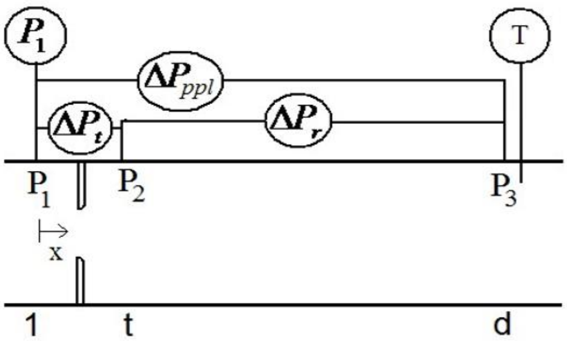

Figure 1: Setup for a Dual-Differential Pressure orifice meter.

The key to the DDP method is to collect a wide-ranging set of data and find the relationships between flow rate, steam quality (or gas volume fraction) and the pressure drop values across the orifice plate, as shown in Figure 1.

Much of the data analysis done to date was performed in the fall of 2021. After cleaning and quality control of the data, two separate data analysis methods were applied. One was based on standard oil and gas analysis method which focuses on the gas mass flow and Lockhart Martinelli parameter with proprietary modifications for steam and water. The results were presented by Steven and Juliusson in the 2023 Stanford Geothermal Workshop. The second method, which is the one discussed here, is based on using the large data set collected to machine learn the relationship between the steam quality and the various other parameters collected for the DDP method.

OVERVIEW OF EXPERIMENTS

The aim with the experiments was to create a practical range of experimental conditions in terms of flow-rate, enthalpy and pipe size. Based on the experience of operating conditions at Landsvirkjun's geothermal power plants, each well would seldom produce more than 35 kg/s, and the enthalpy would generally be between 1000 and 2800 (dry steam) kJ/kg. A snapshot of the operating conditions for each well run by Landsvirkjun in March 2020 is shown in Figure 2. The most common pipe sizes were DN250 and DN350, covering 75% of all wells in operation.

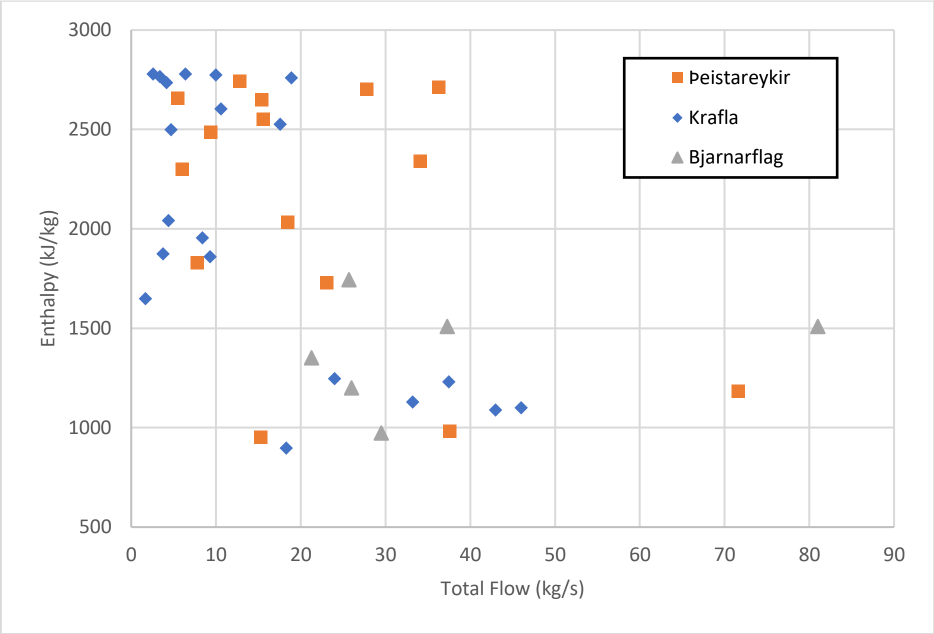

Figure 2: A snapshot of the operating conditions of wells run by Landsvirkjun in March 2020.

The operating conditions can be viewed somewhat more abstractly by converting the flow and enthalpy values to Froude numbers for the vapor and liquid phase. The Froude number relates inertial forces in a system to gravitational forces and is defined as

$$Fr = \frac{inertial\ forces}{gravitational\ forces} = \frac{v}{\sqrt{gL}} \tag{1}$$

where v represents velocity, g is gravitational acceleration and L is a characteristic length scale for the system.

The vapor specific Froude number for two-phase flow in a pipe depends on the superficial flow velocity of vapor

$$v_{vap} = \frac{x}{\rho_{vap}} \frac{\dot{m}}{A} \tag{2}$$

where x is the steam quality, ρ_{vap} is the density of the vapor phase, $\dot{m}$ is the total mass flow rate and A is the cross-sectional area of the pipe.

The Froude number for the vapor phase is then defined as

$$Fr_{vap} = \frac{v_{vap}}{\sqrt{gD}} \sqrt{\frac{\rho_{vap}}{\rho_{liq} - \rho_{vap}}} \tag{3}$$

where D is the diameter of the pipe and ρ_{liq} is the density of the liquid phase.

Similarly, for the liquid phase, the superficial flow velocity of liquid is

$$v_{liq} = \frac{1-x}{\rho_{liq}} \frac{\dot{m}}{A} \tag{4}$$

And the Froude number for the liquid phase is then defined as

$$Fr_{liq} = \frac{v_{liq}}{\sqrt{gD}} \sqrt{\frac{\rho_{liq}}{\rho_{liq} - \rho_{vap}}} \tag{5}$$

The operating conditions for Landsvirkjun's wells in terms of Froude numbers are shown in Figure 3. Flow regime dividers have been overlain on the chart, which indicate that most of the wells operate in the *stratified-wavy, annular-dispersed*, or *mist* flow regime.

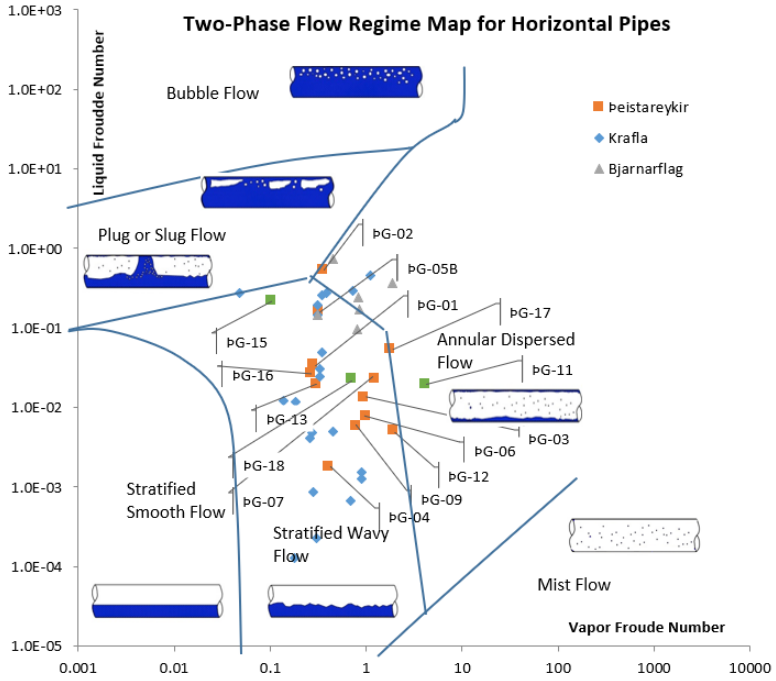

Figure 3: Overview of flow conditions in pipes leading from wells in operation by Landsvirkjun in 2021 in terms of Froude number for vapor and liquid. Approximate flow regime dividers have been added to the chart. Wells marked in green were the ones used to collect data in this experiment.

The experiments were carried out in two separate locations in the Þeistareykir field; on well pad F with fluid from well ÞG-18; and on well pad B with a mixture of fluids from wells ÞG-11 (enthalpy ~2800 kJ/kg) and ÞG-15 (enthalpy ~1000 kJ/kg). Four test runs were carried out on well pad F and six runs were carried out on well pad B. A timeline for the work is presented in Figure 4.

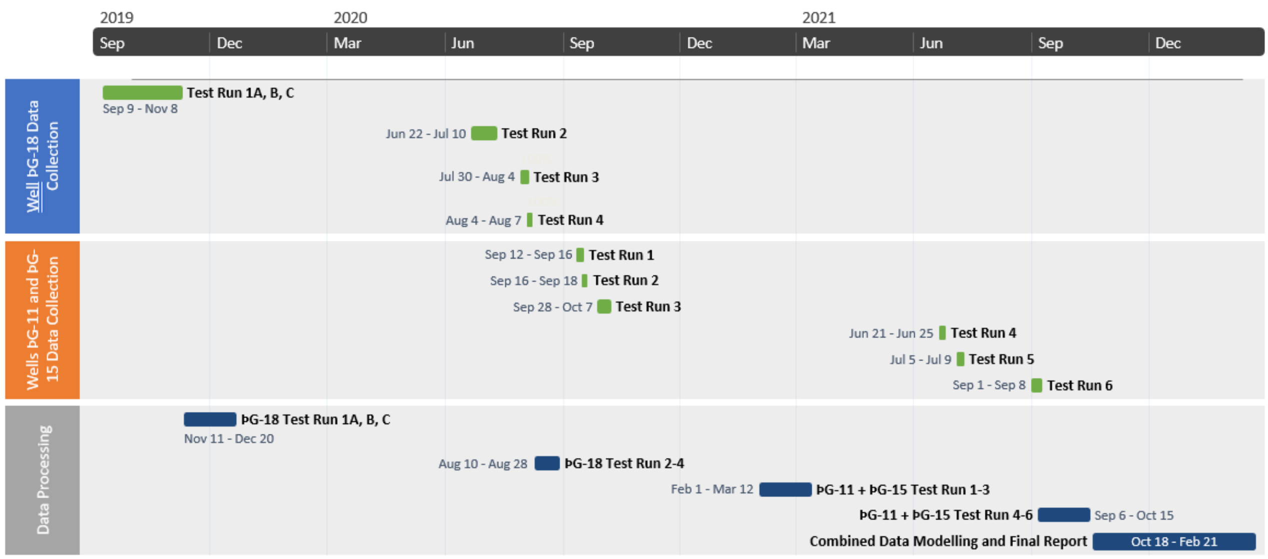

Figure 4: Timeline for data collection and data analysis carried out for the project.

The experiments were carried out outdoors in the highlands of NE Iceland (Þeistareykir field) and therefore weather conditions, logistics and general working conditions were at times challenging. Several lessons were learned from the various test runs and each opportunity was used to improve the experimental setup to the extents possible. Following is a brief discussion of the test runs.

Test runs on well ÞG-18 (well pad F)

Four test runs were carried out on well ÞG-18, located on well pad F. A single line diagram, and an aerial photograph of the setup is shown in Figure 5.

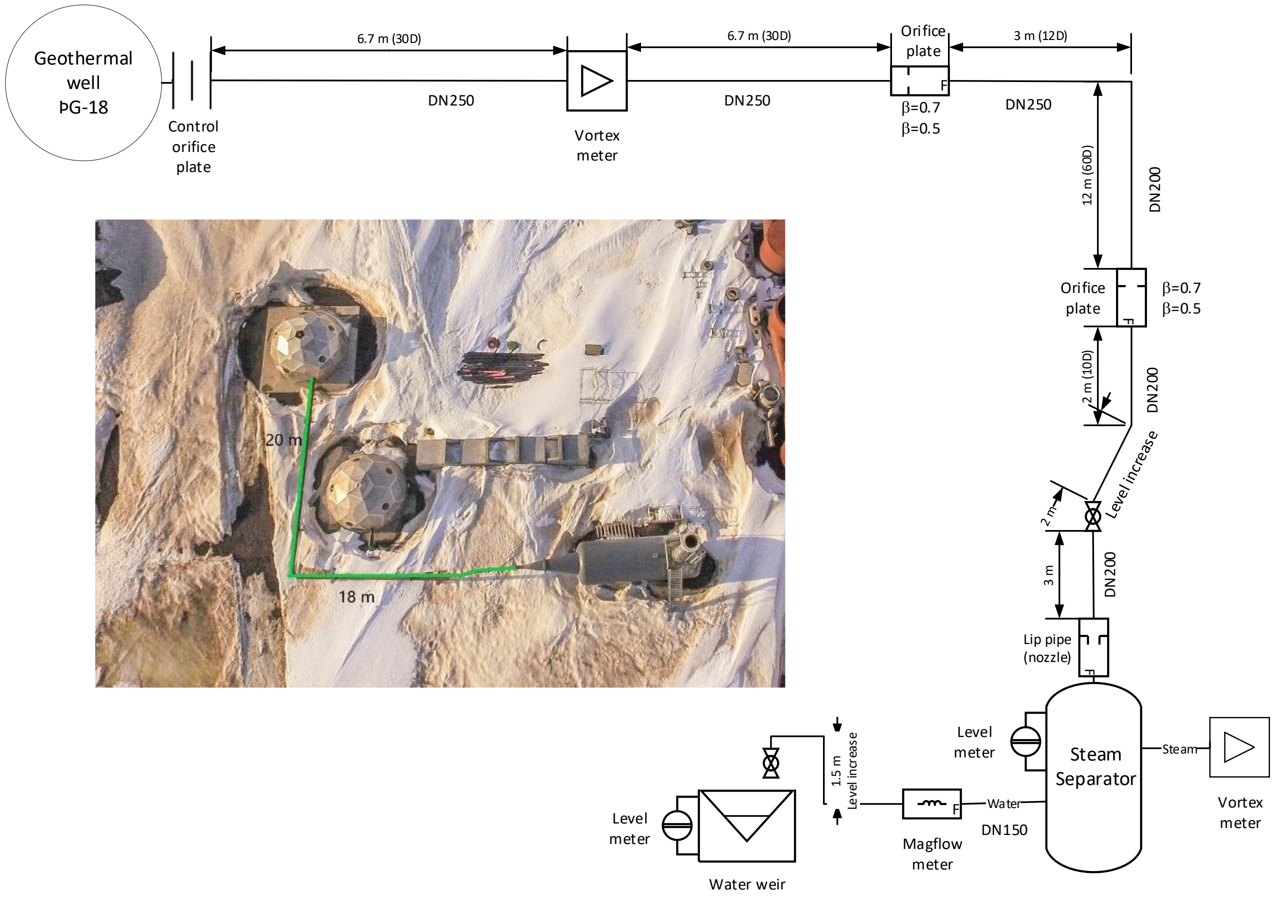

Figure 5: Setup of experiment carried out on well ÞG-18, well pad F, at the Þeistareykir field.

ÞG-18 test run 1A, B and C

The first test run was performed in the fall of 2019, from 18.09.2019 until 16.11.2020. The test configuration was set up with the well connected to a steam separator via a 40 m long pipe. The first 20 m had a diameter of 250 mm and after that there was a 90° bend in the pipe and it narrowed to 200 mm. A two-phase vortex meter was placed 6.7 meters downstream of the control orifice plate on the well. Measurement orifice plates were placed in each pipe section, with pressure gauges 1D upstream (P1), 1/2D downstream (P2), and XD downstream (P3). Measurements were collected, first at 1 sec intervals, but later (after Sept. 30) at 10 sec intervals. In hindsight this high sampling rate was not necessary, and in production an output interval of 1 to 10 minutes or more should be sufficient.

This test run was used to try different data collection methods, test various types of gauges, orifice plate setups, reference measurement methods and well controls. Some valuable lessons learned were that the differential pressure between pressure ports needs to be measured with accurate single membrane DP sensors and temperature probes need to have a robust thermowell.

It also became clear that water-level of the separator could affect the estimated water output from the well, and adjustments had to be made to the water output reference measurement. Minor flaws in the design of the inlet to the separator were also identified and corrected.

The data gathered for the first orifice plate was useful and was collected with an orifice to pipe diameter ratio β=0.54 and 0.59. The second (downstream) orifice plate data could not be used because of measurement inaccuracies.

Because of problems with measurements on the second orifice plate, the lip-pipe and vortex meter measuring steam flow from the separator, it was decided to repeat this experiment in early summer 2020.

ÞG-18 test run 2

The second test run on well 18 was carried out from June 22nd until July 10th. The orifice to pipe diameter ratio was β=0.7 for each plate.

In this test run the control valve at the inlet to the separator had been moved down before the level increase, further away from the inlet to the lip-pipe. The diameter of the lip-pipe had also been reduced, thus making the lip-pipe reference measurement more reliable.

Problems with the water output measurement had also been fixed and a correction method was derived to account for fluctuations in the water level of the separator.

After reviewing that data collected, it turned out that a key parameter for the orifice plate measurements (P1) had not been logged by the flow computer and therefore all of the data collected had to be discarded.

ÞG-18 test run 3

The third test run was carried out from 30.7.2020 to 4.8.2020. The orifice to pipe diameter ratio was again β=0.7 for each plate. The data collected spanned a flow rate from 10 to 18 kg/s and enthalpy from 1900 to 2400 kJ/kg.

Again, the data collected for orifice plate 2 was corrupted due to sensor issues and had to be discarded.

ÞG-18 test run 4

The fourth and final test on well ÞG-18 ran from 4.8.2020 to 7.8.2020. This time the orifice to pipe diameter was β=0.5 on each pipe. Data from each pipe (i.e. each orifice meter) were successfully collected and usable this time.

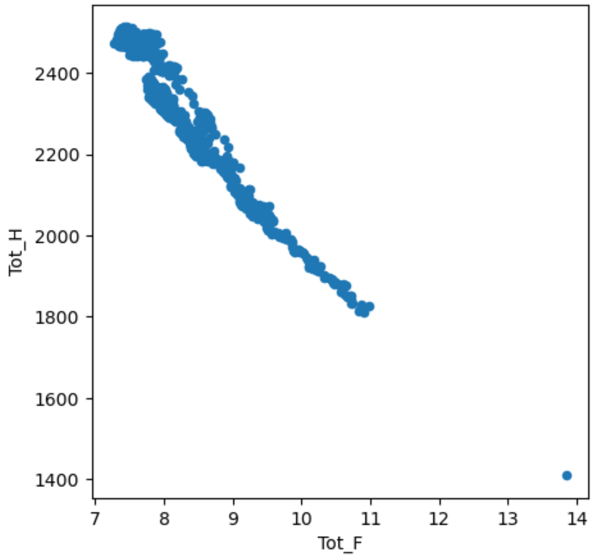

Figure 6: Flow rate vs enthalpy reference data points collected during test run 4 on well pad F.

Test runs on wells ÞG-11 and ÞG-15 (well pad B)

Six test runs were carried out on the combined output from wells ÞG-11 and ÞG-15, located on well pad B. A single line diagram, and an aerial photograph of the setup is shown in Figure 7. The combined stream from the wells first flowed along a DN350 pipe line, with a DDP orifice meter located approximately 16 m downstream of the mixing point. After that there was a 90° pipe bend and the pipe narrowed down to a DN250 line. The DN250 line had a two phase vortex meter and then a DDP orifice meter located 7.5 and 11 meters down stream of the bend, respectively.

The two wells were very different in their characteristics as ÞG-11 produced up to 30 kg/s of dry steam with enthalpy at around 2800 kJ/kg, but well ÞG-15 produced fluid at around 950 kJ/kg and was very sensitive to wellhead pressure. By mixing the fluid from these two wells there was an opportunity to create fluid mixtures that would range in enthalpy from 950 kJ/kg to 2800 kJ/kg, which is a range that covers more-or-less all the wells in operation by Landsvirkjun.

Since ÞG-15 would choke at pressures above ~10 bar-g, some care needed to be taken in how to connect it to ÞG-11 to get the two streams to mix. The output from the two wells was combined with a ejector that was built from two consecutive pipe constrictions welded to a flange. This rudimentary ejector design worked well enough for the purpose of drawing some of the fluid from well ÞG-15 into the combined output stream. More analysis of this ejector and a research project derived from this work can be found in other publications in the World Congress (Andal et al., 2023 and Muguroza et al., 2023).

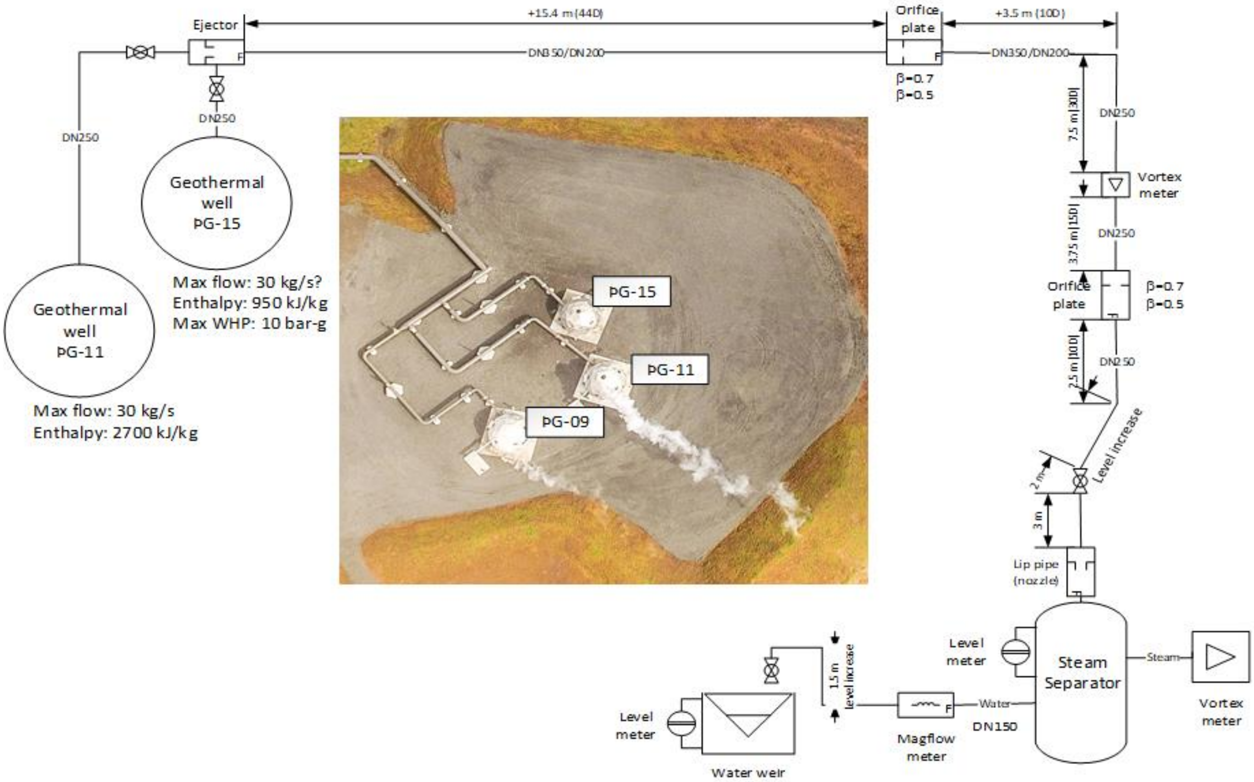

Figure 7: Setup of experiment carried out on wells ÞG-11 and ÞG15, well pad B, at the Þeistareykir field.

The flow from the two wells could be controlled either by the wellhead valves or the inlet valve to the steam separator. The inlet valve to the steam separator was usually set such that the pressure at the meters being tested was in the range of 7-12 bar, i.e. close to typical pressure in the steam gathering system.

ÞG-11 and 15 test run 1

Test run 1 for wells ÞG-11 and 15 ran from 12.09.2020 to 16.09.2020. The orifice to pipe diameter ratio was β=0.7 for each orifice plate. In this run, only well ÞG-15 was open. The high water content in the fluid caused slugging, pressure pulses and vibrations in the system.

Considerable effort was spent on replacing or reconfiguring sensors that came loose due to vibration or other issues that resulted from the high water content in the fluid.

Several data points were collected successfully for the DDP meter on the DN250 pipe, although these were eventually discarded due to limits on the enthalpy range that the DDP meter could cover reliably (in our estimate). The data are shown in Figure 8.

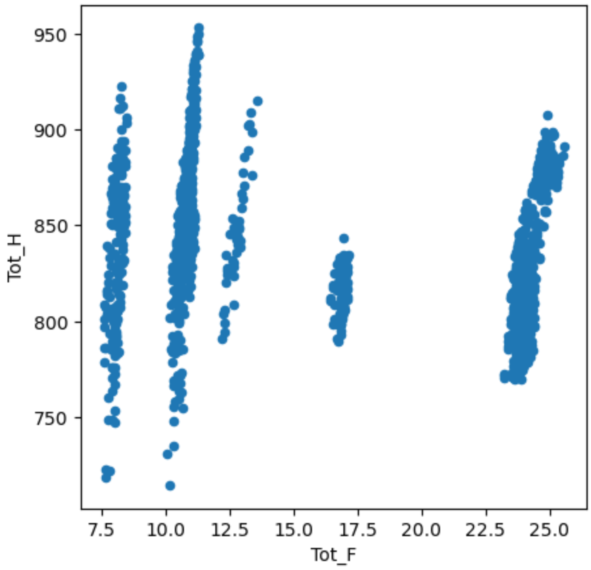

Figure 8: Flow rate vs enthalpy reference data points collected during test run 1 on well pad B.

<u>ÞG-11 and 15 test run 2</u>

Test run 2 for wells ÞG-11 and 15 ran from 16.09.2020 to 18.09.2020. The orifice to pipe diameter ratio was β=0.7 for each orifice plate. In this run, only well ÞG-11 was open. The test ran considerably more smoothly with the dry steam from well 11, as compared to the low enthalpy fluid from well 15.

Data were collected successfully with both DDP meters. Here an issue of varying pressure at the reference vs. wellhead and DDP meters was encountered. When samples were taken from the wellhead at 30 bar-g it turned out that there was not water at all in the steam, and hence the enthalpy around 2800 kJ/kg or more. The reference measurement, however, was taken close to atmospheric conditions (0-1 bar-g) which meant that the maximum possible enthalpy that could be measured (assuming saturated steam) was 2674 kJ/kg. It also proved very difficult to use the thermocouple on the DDP meters to measure the superheat in the steam. Thus, all the data were eventually discarded in the data processing phase.

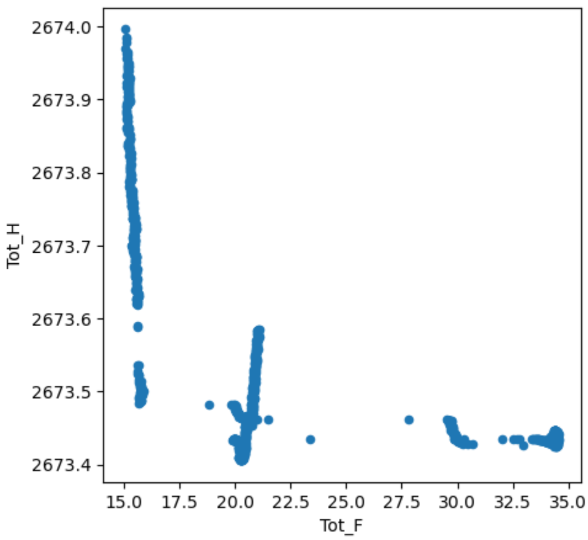

Figure 9: Flow rate vs enthalpy reference data points collected during test run 2 on well pad B.

<u>ÞG-11 and 15 test run 3</u>

Test run 3 for wells ÞG-11 and 15 ran from 28.09.2020 to 07.10.2020. The orifice to pipe diameter ratio was β=0.7 for each orifice plate.

Data from the flow computer on the DDP meter in the DN350 line was not logged correctly in this run an thus had to be discarded. The data on the DN250 line turned out to be useful though. An overview of the reference data points collected is shown in

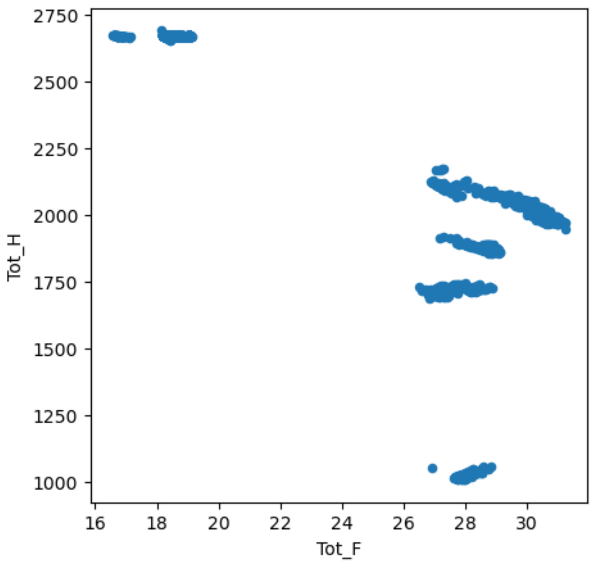

Figure 10: Flow rate vs enthalpy reference data points collected during test run 3 on well pad B.

ÞG-11 and 15 test run 4

Test run 4 for wells ÞG-11 and 15 ran from 21.06.2021 to 25.06.2021. The orifice to pipe diameter ratio was β=0.7 for each orifice plate.

A very wide array of data was gathered this time, with flow rate spanning from 4 to 38 kg/s and enthalpy from 900 to 2700 kJ/kg. After reviewing the data, everything from June 21st to the 23rd had to be discarded due to sensor malfunctions, the rest of the data set was stored for further evaluation. An overview of the resulting reference points is shown in Figure 11.

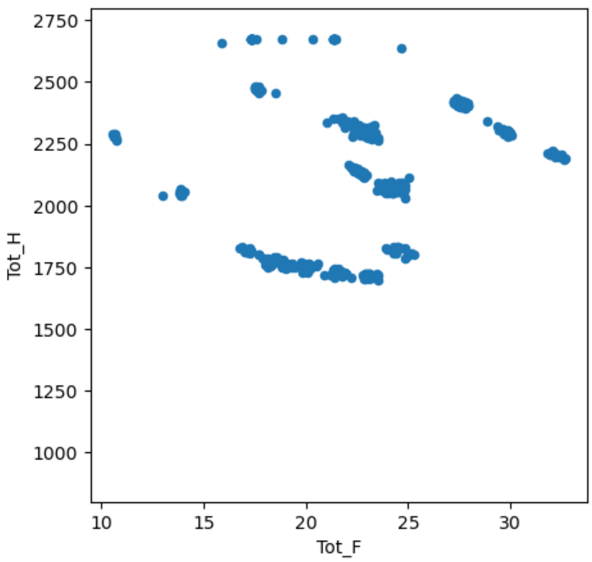

Figure 11: Flow rate vs enthalpy reference data points collected during test run 4 on well pad B.

ÞG-11 and 15 test run 5

Test run 1 for wells ÞG-11 and 15 ran from 05.07.2021 to 09.07.2021. The orifice to pipe diameter ratio was β=0.7 for each orifice plate.

With the success of the previous run, the aim was to gather more details and fill in the gaps seen in Figure 11. The resulting data set for run 5 is shown in Figure 12. This time an enthalpy range of 1350 to 2700 was covered and flow rates from 8 to 38 kg/s

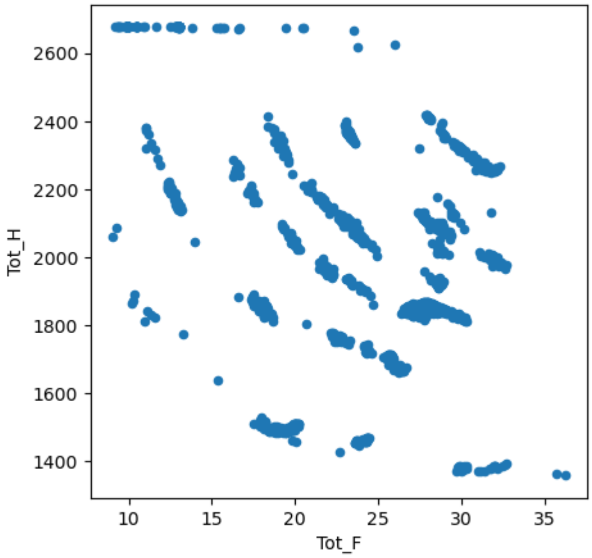

Figure 12: Flow rate vs enthalpy reference data points collected during test run 5 on well pad B.

<u>ÞG-11 and 15 test run 6</u>

Test run 1 for wells ÞG-11 and 15 ran from 01.09.2021 to 08.09.2021. This time the orifice meter on the DN250 pipe was replaced with another meter in development by a private party. The DDP orifice meter on the DN350 pipe was still in place with an orifice to pipe diameter ratio of β=0.5.

Figure 13 shows the distribution of the reference measurements collected. The values spanned an enthalpy range of 1000 to 2750 kJ/kg and flow rates from 4 to 38 kg/s.

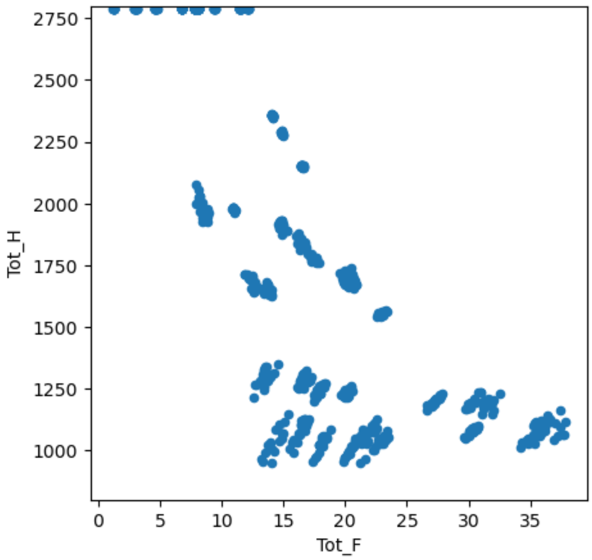

Figure 13: Flow rate vs enthalpy reference data points collected during test run 6 on well pad B.

OVERVIEW OF DATA

After having collected and cleaned a large amount data in several test runs over three summers (2019-2021), it was time to compile the results and view the data coverage. After cleaning the data there were 19,454 measurement points in the data set. The distribution of these points in terms of flow rate and enthalpy is shown in Figure 14, and in terms of the Froude number for vapor and liquid in Figure 15.

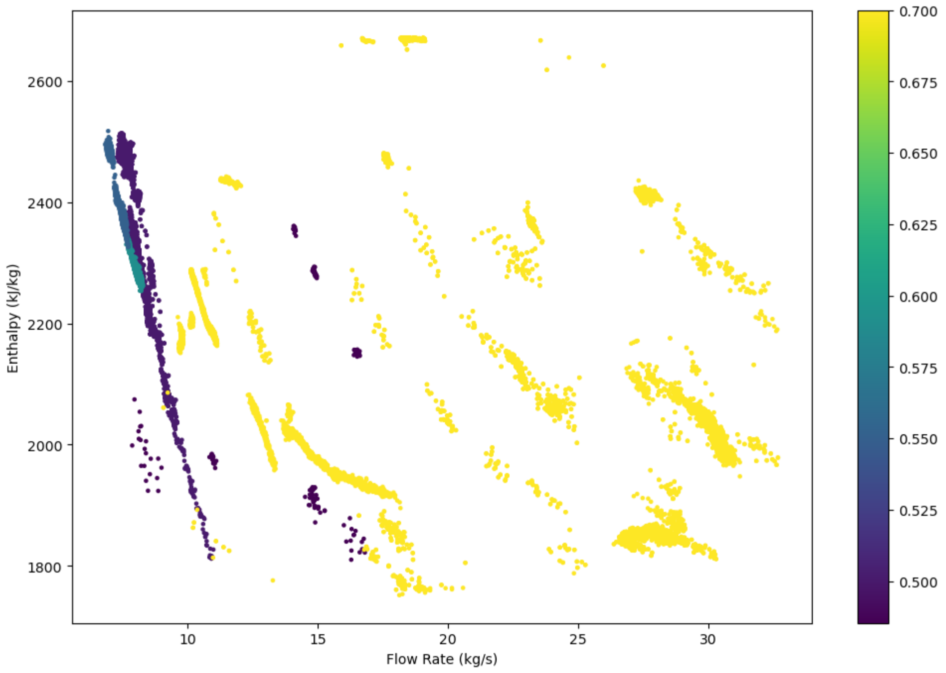

Figure 14: Distribution of all data points in terms of flow rate and enthalpy. The color of the points is determined by the β ratio.

Comparing the results to Figure 2 and Figure 3 shows that the reference points cover most of the range in operation conditions, in particular for β=0.7. Much fewer data points were collected for other β ratios, both because of lack of time and resources, but also because β=0.7 is was considered a convenient size to focus on. With that particular ratio the pressure-drop over the orifice is limited but measurable (good signal to noise ratio). Moreover, as β approaches 0.5 the relationship between the pressure loss ratio, $PLR = \Delta P_{ppl}/\Delta P_t$, and the steam quality becomes less unique, as illustrated in Figure 16. It is also apparent that the measurement noise increase as the beta ratio increases, and as the steam quality becomes lower.

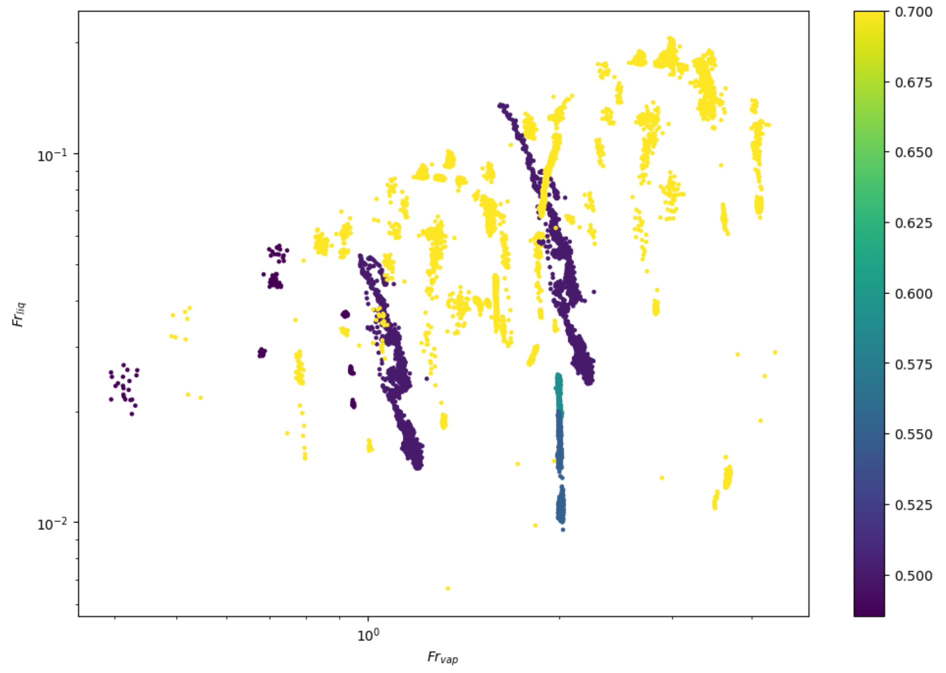

Figure 15: Distribution of all data points in terms of Froude number for vapor and liquid phase. The color of the points is determined by the β ratio.

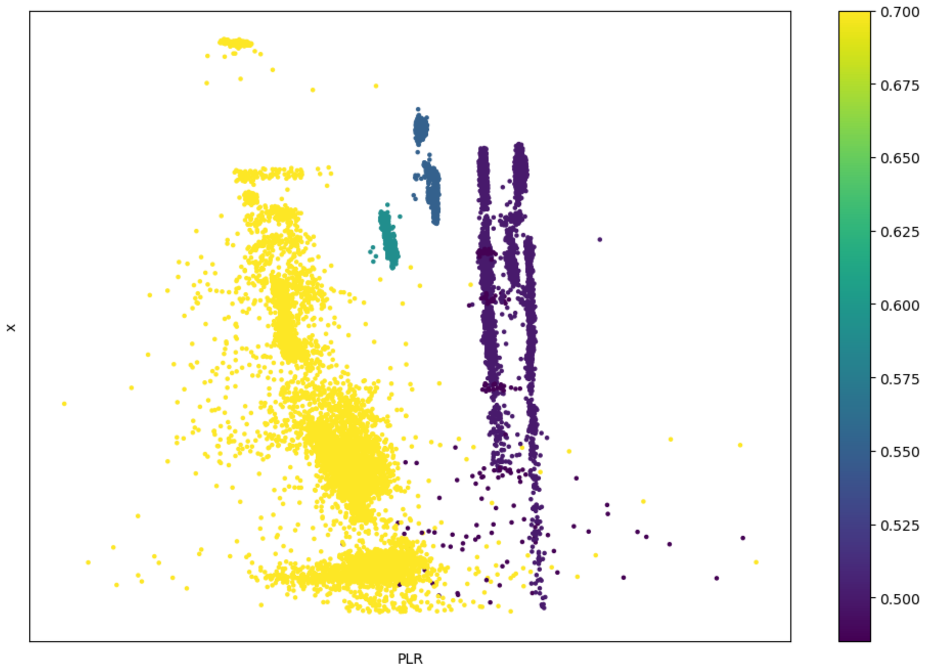

Figure 16: Distribution of measurements of pressure loss ratio (PLR) and steam quality. The color of the points is determined by the β ratio.

Scrutinizing Figure 16 it appears that more than just the beta ratio and the PLR measurement would be required to estimate the steam quality. For example, this could be the pipe diameter, the upstream pressure, total pressure drop over the orifice plate, or some combination of parameters relating to the measurement conditions. A pair plot of the total flow rate (Tot_F), enthalpy (Tot_H), β ratio, pipe diameter (D) and pressure drop over the orifice plate (DP12) is shown in

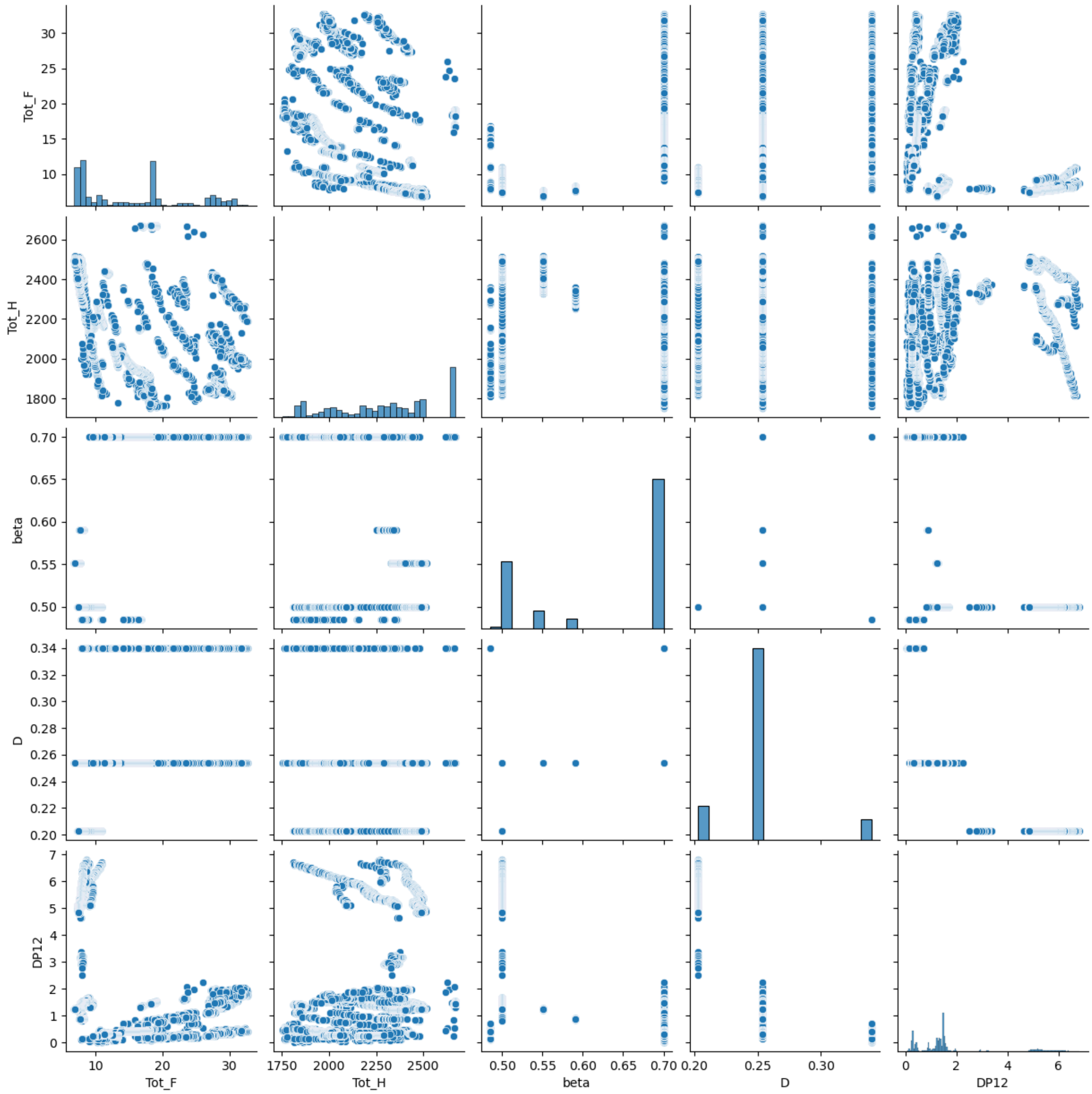

Figure 17: Pair plot of total flow rate (Tot_F), enthalpy (Tot_H), β ratio, pipe diameter (D) and pressure drop over the orifice plate (DP12) for the collected and cleaned data set.

MODELLING AND PREDICTION

Data modelling and prediction steps were taken with a view of the Masters Thesis work of Einarsson (2021). His work was based on a subset of the data collected for this project, i.e. the data available in the fall of 2020.

In the view of the authors, the relatively comprehensive data set described in the chapters above, needed to be clustered into representative points and then used to create a model, to avoid biases in the modelling process. This is the main difference between our approach and that of Einarsson.

Data reduction

Two methods were employed for data reduction. The first method was to set up a grid and pick one data point from each block on the grid. The second method employed was K-means clustering, which is an iterative process of assigning each data point to a group and slowly getting them clustered based on similar features.

Grid method

The aim of the grid method was pick one data point from each block (the point closest to the center) on a grid. The grid was defined in four dimensions, flow rate, enthalpy, pipe diameter and β ratio. The flow rate and enthalpy grid spacing were defined as 1 kg/s and 50 kJ/kg, respectively. There were only seven overall combinations of pipe diameter and β ratio with available data, therefore, all these values were used to define the grid in those dimensions.

Table 1: Overview of data reduction via the grid selection method.

Pipe Diameter (D) [m]	Beta [-]	Full Num. Samples	Reduced Num. Samples	Ratio
0.254	0.50	2600	16	0.6%
0.254	0.70	10312	144	1.4%
0.254	0.59	774	5	0.6%
0.254	0.55	1440	7	0.5%
0.34	0.70	1498	108	7.2%
0.34	0.49	151	18	11.9%
0.203	0.50	2679	21	0.8%
Total		**19454**	**319**	**1.6%**

The grid method reduced the data from 19,454 to 319 data points, or only about 1.6% of the total amount, as illustrated in Table 1. Out of those 319 data points, there were 252 points left for β=0.7. The distribution of the selected points for the (DN250, β=0.5) and (DN250, β=0.7) data sets are illustrated in Figure 18.

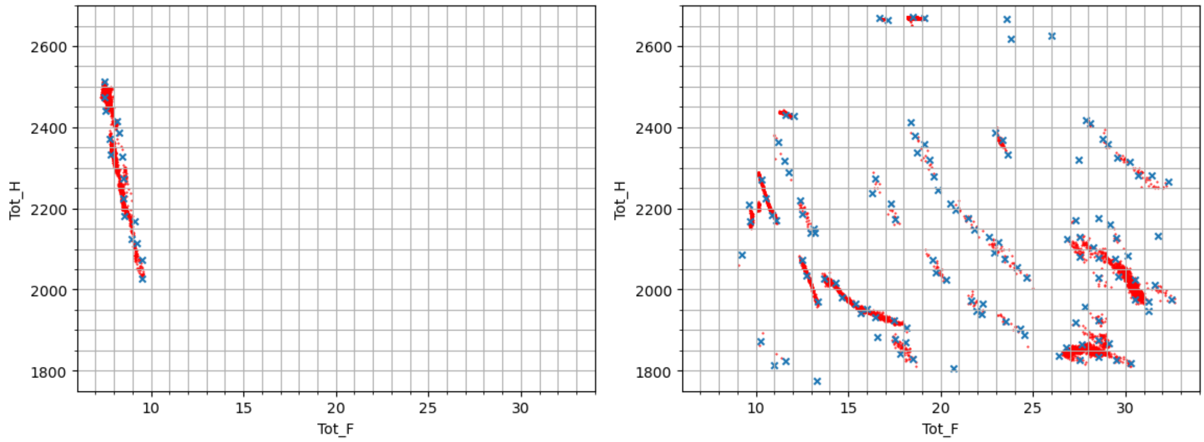

Figure 18: Result of grid clustering method shown for (DN250, β=0.5) and (DN250, β=0.7) data sets. The selected data points after reduction are shown as blue x's.

<u>K-means clustering</u>

K-means clustering is a method of vector quantization, originating from signal processing, that aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean (cluster centroid), serving as a prototype of the cluster.

The K-means clustering algorithm built into the scikit-learn machine learning library for Python was used in this case. The algorithm was used to create 300 clusters out of the full data set, using pipe diameter, beta ratio, upstream pressure (P1), pressure drop across the orifice (DP12) and the pressure loss ratio (PLR=DP13/DP13) to define the clusters. The results of the K-means clustering are shown for the (DN250, β=0.5) and (DN250, β=0.7) data sets in Figure 19, where the center of each cluster is shown with a blue x.

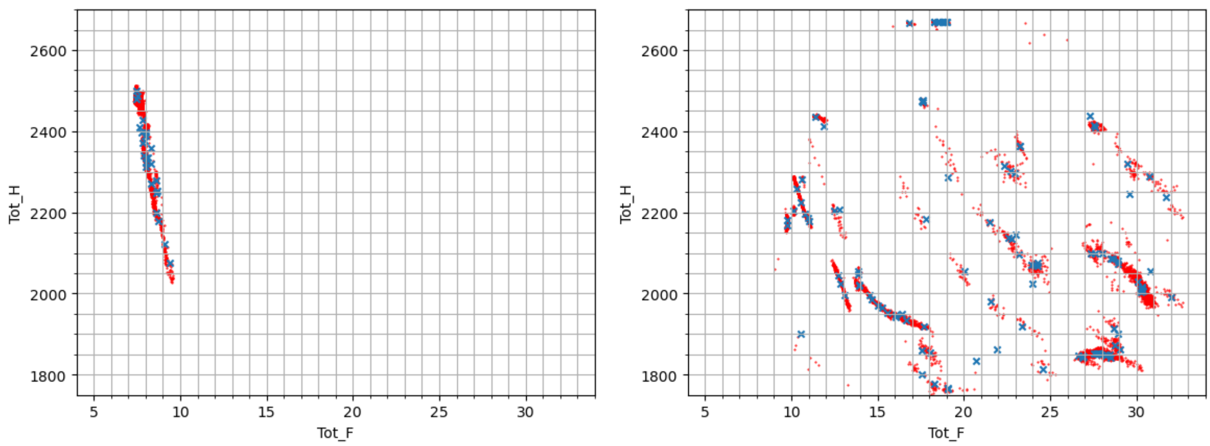

Figure 19: Result of K-means clustering method shown for (DN250, β=0.5) and (DN250, β=0.7) data sets. The centers of each cluster are shown as blue x's.

Feature Selection

Feature selection was performed based on a mixture of insight into the data and the results of a linear regression algorithm. The final data set used for the model contained the following features to predict the steam quality:

1. Pressure upstream of the orifice (P1)
2. Traditional differential pressure over the orifice (DP12)
3. Pressure loss ratio (PLR=DP13/DP12)
4. Pipe diameter (D)
5. Orifice to pipe diameter ration (β)

Modelling

Several machine learning algorithms were tested for predicting steam quality. The method that gave the best performance was Random Forest Regression. Random Forest Regression is a supervised learning algorithm that uses ensemble learning for regression, i.e. a technique that combines predictions from multiple machine learning algorithms to make a more accurate prediction than a single model.

In a Random Forest Regression, the algorithm creates an ensemble of decision trees, where each tree is trained on a different subset of the data and uses a random subset of features. During training, the algorithm builds each decision tree by recursively partitioning the feature space based on the selected features. The splitting process continues until a stopping criterion is met, such as reaching a maximum depth or minimum number of samples in each leaf node. The predictions from all the individual trees are then averaged to obtain the final prediction. This ensemble approach helps reduce overfitting and improves the model's generalization ability.

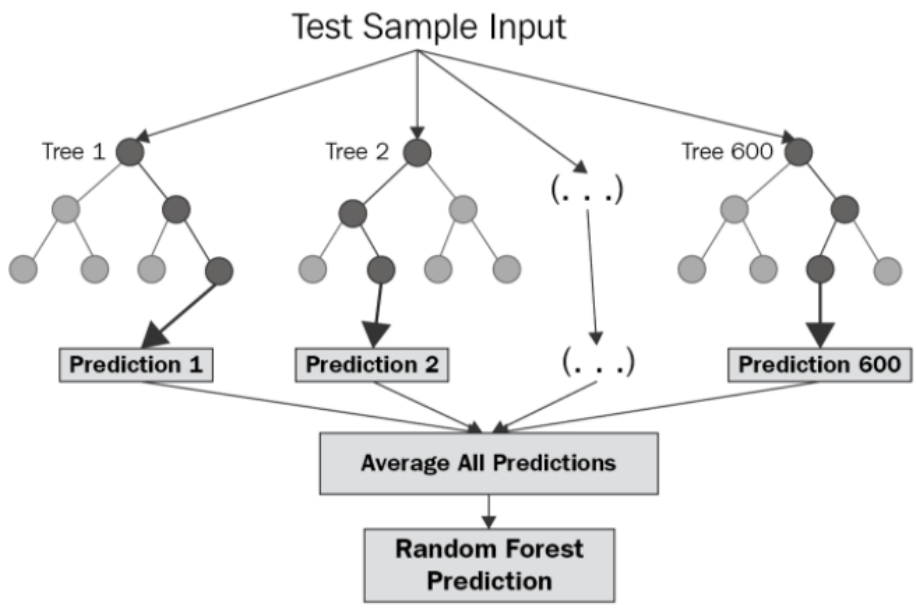

Figure 20: Explanatory figure for random forest regression.

Figure 20 shows several decision trees within the Random Forest ensemble. Each decision tree is trained on a different subset of the data and uses a random subset of features. The final prediction is obtained by averaging the predictions from all the decision trees in the ensemble. The combination of multiple decision trees improves the model's accuracy and robustness for regression tasks.

The RandomForestRegressor algorithm provided by the Python sklearn library was used to train the model, and some hyperparameter adjustment was made using the GridSearchCV alorightm from sklearn. For the model where the grid selection method was used, the best root mean square error (RMSE) obtained was around 0.075 (depending on the random seed for the algorithm), when using the k-means clustering with 300 samples, the RMSE was reduced to around 0.03

When training on 80% of the entire data set an even lower RMSE was obtained, or around 0.023. This, however, may not be a fully valid prediction of the error rate as many of the points in the data set were very close or essentially the same point.

A good way to visualize the quality of the predictions the measured and predicted steam quality can be plotted as a 2D histogram using contour lines. Such diagrams for the predictions based on the grid method data, and the k-means clustered data are shown in Figure 21 and Figure 22, respectively. When visualizing the data prediction quality this way it becomes much more clear how well the k-means clustering helps create a good subset of data to base predictions on.

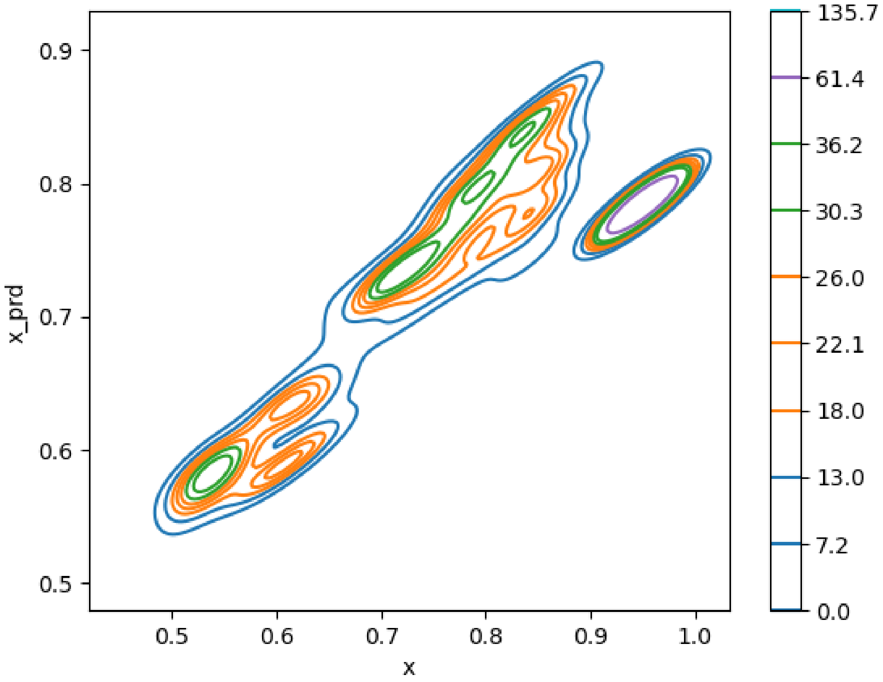

Figure 21: Histogram of measured vs predicted steam quality based on grid sampling.

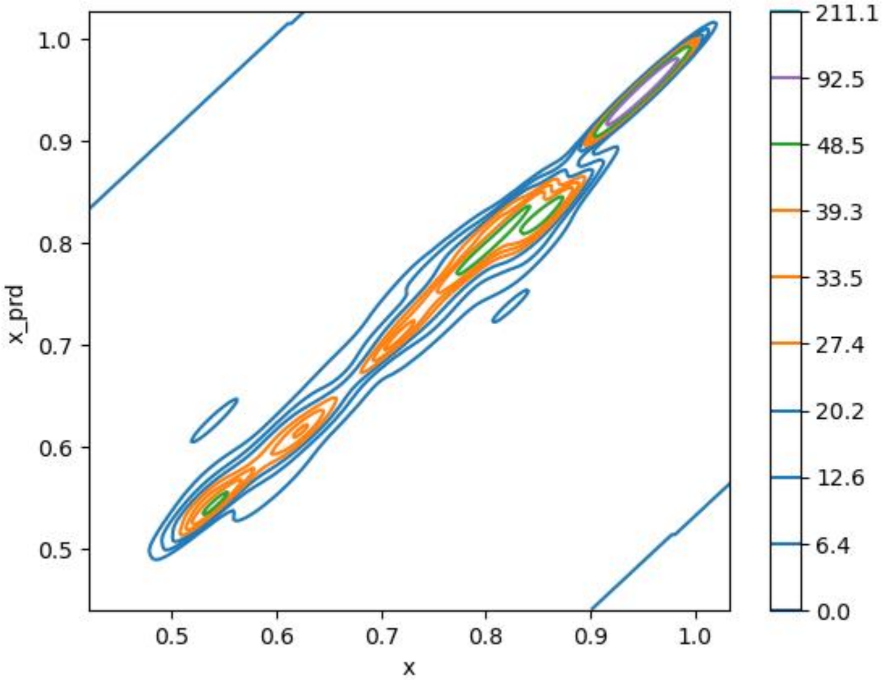

Figure 22: Histogram of measured vs predicted steam quality based on k-means clustering sample.

CONCLUSION

In this paper reviews a considerable amount of data that was collected in the summers of 2019 to 2021 in order to find a way to measure steam-water flow in pipes in real-time using the Dual Differential Pressure method. After processing and cleaning the data, the it is clear that the most comprehensive set of points is available for a beta ratio of 0.7, although several data points are also available for beta ratios of 0.59, 0.55, 0.5 and 0.49. Steven and Juliusson (2023) presented an empirical model to predict the total flow and enthalpy based on these data. Here we have explored machine learning methods to predict the steam quality, which is the key to being able to predict two phase flow through an orifice plate. Mubarok et al. (2018) and Einarsson (2021) cover many of the methods known to predict two phase flow using orifice plates.

The machine learning method that was found most promising was the random forest regressor. Although this regressor proved powerful for predicting the data we tested, there is likely that can be done in feature selection, model exploration, training and hyper parameter selection.

As the data overview shows, there is good coverage of measurements for beta ratios equal to 0.7. This is a practical beta ratio that is often applied in industry as it strikes a balance between limiting permanent pressure loss and getting a measurable signal. Given the pipe sizes used as well it is assumed that many practical real-time steam-water measurements for geothermal applications can be performed with the random forest regressor presented here.

Moving to other beta ratios, e.g. some as low as 0.5 may cause difficulty as the PLR predictor shows a less unique correlation to the steam quality, but perhaps other features can cover that gap. There is yet much to be gained from collecting more data for a wider variety of conditions such that a more comprehensive model can be created.

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