Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Experiments for Real-Time Measurement of Well Output

Erlingur Geirsson, Egill Júlíusson

Landsvirkjun, Háaleitisbraut 68, 103 Reykjavík, Iceland

Erlingur.Geirsson@landsvirkjun.is

Egill.Juliusson@landsvirkjun.is

Keywords: well output, real-time measurement, sensors

ABSTRACT

Landsvirkjun has formed a project to work on real-time measurement of well output. The aim is to run a number of experiments on wells with varying output, steam quality, chemical composition etc. The experiments will be set up such that real-time output can be measured in a separator at the end of a flow line. The flow line will contain several types of sensors that might be utilized to estimate total flow and enthalpy of the two-phase fluid. Interested parties are invited to work with Landsvirkjun on solving this challenge by testing data processing algorithms and various measurement types in the flow line. The goal is to come up with a simple and robust set of sensors for the task, which eventually could be utilized by geothermal power producers for real-time well output monitoring.

1. INTRODUCTION

Most geothermal wells produce a two-phase mixture of steam and water at the wellhead. The measurement of two-phase mass flow rate and enthalpy of the produced fluid from each production well can be used to calculate the total available power. Continuous monitoring of these two parameters is therefore important for day-to-day field management.

There have been some difficulties associated with real time measurement of two-phase (steam/water) flow from geothermal wells. A method commonly used today to measure the power production involves tracer dilution. These tests are time consuming, relatively expensive and only provide point measurements. Another option is to take the well offline for measurement, but that is also expensive and cumbersome. Therefore, these tests are typically only done 1-2 times each year. Changes occurring in the wells – or interaction between wells – may be missed with such long timespans between test results.

Landsvirkjun is now developing an experiment to measure these two parameters (mass flow rate and enthalpy) and evaluate the power production on a continuous basis, while the well is in use. This could then generate detailed data sets about the production, which in turn could lead to a more resourceful way to manage the reservoir and to optimize production. The data collected from the experiment can be compared to recent studies and used separately to search for a potential empirical relationship between the measurements and power production.

Landsvirkjun invites interested parties to cooperate and participate in this experiment. Other Icelandic power companies have also indicated interest in collecting data from their geothermal wells in follow-up experiments of the one described here.

2. EXPERIMENT

2.1 Objective

The purpose of this experiment is to apply and try different measurement techniques in a geothermal setting where two-phase flow conditions are present. The ultimate goal is to develop a method to measure real-time well output monitoring from a geothermal well with two-phase fluid (steam and water) in production with a simple and robust set of sensors which could eventually be exploited by energy companies for real-time well output monitoring. The data gathered and obtained will be used to test recent two-phase correlations and possibly develop new ones. These data will be made available to universities or other interested parties.

Should this goal be reached, the method would promote a more resourceful way to manage the reservoir. Detailed data sets about the production offers the possibility to strengthen the ability to optimize the production and the yield. It also gives information on how to utilize the geothermal reservoir in a sustainable way. The data sets could monitor the individual well performance more efficiently which strengthens the ability to detect technical problems in the well, such as scaling or boiling in the formation, which in turn motivates early execution of appropriate intervention. The interaction between individual wells in a geothermal system could also be comprehended more thoroughly.

2.2 Setup

The experiments will take place at Þeistareykir located in the Northeastern part of Iceland. Real-time output will be measured in a steam separator at the end of a flow line where different pipe diameters will be used. For the first phase of the experiment, two different pipe diameters (DN200 and DN250) will run from the well to the steam separator where the two-phase fluid will be separated into steam and liquid. Figure 1 shows the steam separator used in this experiment. The steam, escaping to the atmosphere, will be measured with a Vortex meter while the separated water will flow into a water weir where the volumetric flow is measured. The flow line will contain several types of sensors that might be exploited to estimate total flow and enthalpy of the two-phase fluid. Chapter 3 discusses sensors that appear promising for the task. Figure 2 and figure 3 show the site used for the first phase of the experiment and figure 4 shows an aerial view of the site. Single-line diagrams of the setup are shown in figure 5, where the figure to the right shows the setup for the first phase of the experiment and the figure to the left is an example of a setup with a variety of different sensors.

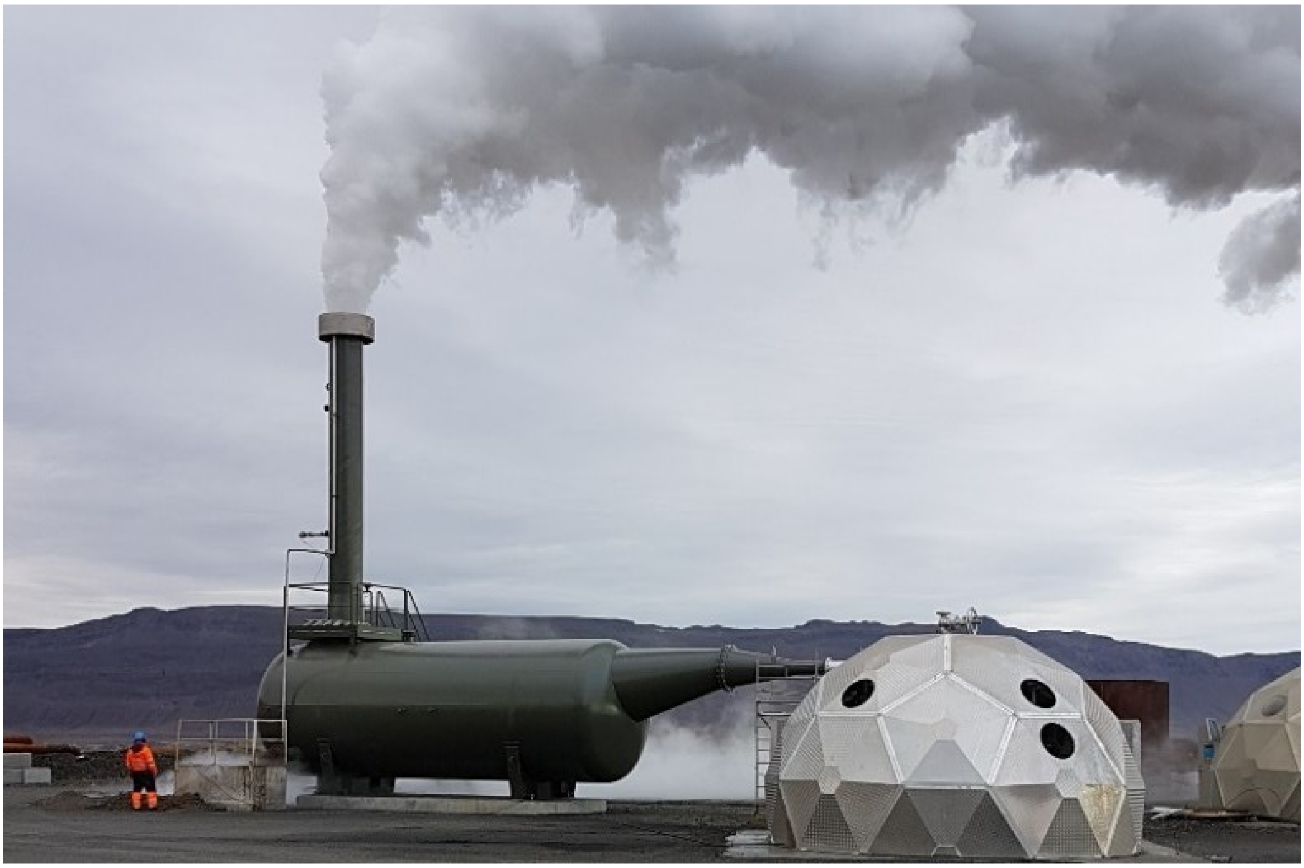

Figure 1: The steam separator used for the experiment.

Figure 2: Apparatus used for the first-phase of the experiment at Þeistareykir, Iceland.

Figure 3: Apparatus used for the first-phase of the experiment in Þeistareykir, Iceland. The pipeline can be seen connecting the geothermal well ÞG-18 and the steam separator.

Figure 4: Aerial view of the apparatus in Þeistareykir, Iceland. The flowline follows the piping from hole ÞG-18 to the steam separator.

2.3 Flow conditions

In geothermal applications, the two-phase flow of steam and liquid water can be at variable conditions. The aim with this experiment is to find a method that would work in the following range of conditions:

Media:	Two phase flow of steam and liquid water
Steam quality:	0.05-0.99
Pressure:	2-40 bar-a
Temperature:	120 - 250 °C
Steam quality:	0.2 – 1
Flow range:	5-100 kg/s
Pipe diameter:	200-700mm

In the first phase of the experiment, well ÞG-18 in Þeistareykir will be used with the following expected conditions:

Temperature:	120-250°C
Pressure:	2-40 bar-a
Steam quality:	0.7-0.9
Flow range:	5-100 kg/s
Pipe diameter:	200 and 250 mm

2.4 Timeline

The experiment will be divided into different phases as shown in table 1. In the first run, orifice plates and venturi meters will be used and the reference measurements coming from the steam separator will be validated by comparison to tracer dilution and lip-pressure measurements. After that, other experimental devices will be tested.

Table 1: Timeline for the experiment

Experiment on one well at Landsvirkjun	Orifice Plates, Venturi	2019
Experiment on two wells at Landsvirkjun	Orifice Plates, Venturi	2020
Experiment on two wells at Landsvirkjun	Alternative devices from partners	2020
Experiment on two wells at Landsvirkjun	Orifice Plates, Venturi meter	2021
Experiment on two wells at Landsvirkjun	Alternative devices from partners	2021

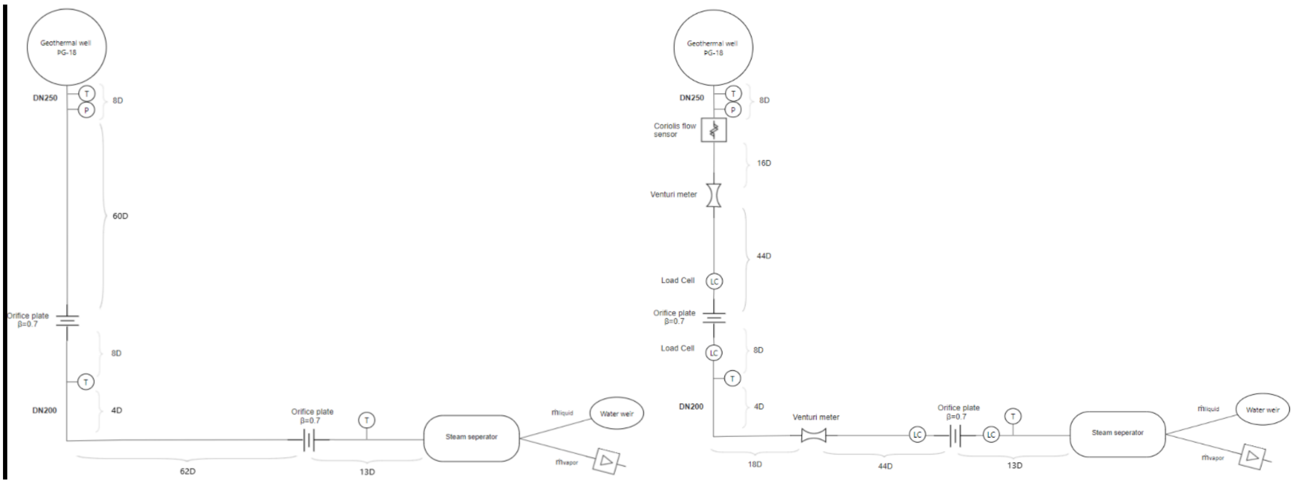

Figure 5: Single-line diagrams for the setup. The first phase of the experiment showed on the left and an example of a setup with various sensors on the right.

2.5 Data sampling and handling

The data will be sampled at high frequency and stored. The data and associated metadata (e.g. orifice sizes, pipe diameters, gauge locations etc.) will be aggregated into a large data set or database. The obtained data offers the possibility to compare the results with earlier studies or find new empirical relationships between the measurements and the well output. The data will be accessible for universities and research partners.

3. MEASUREMENTS

The measurements here can be divided into two categories: experimental and reference measurements. The experiments will be set up such that real-time output can be measured in a separator at the end of a flow line where the reference measurements take place. The reference measurements are comprised of: steam mass flow measurement with a Vortex meter in the steam separator, water level measurement in the separator and a separated water discharge measurement in the water weir.

The experimental measurements consist of several types of sensors that might be utilized to estimate total flow and enthalpy of the two-phase fluid in the flow line. These measurement methods have not been established in a geothermal setting. The most promising sensors to use in this experiment include orifice plates, venturi meters, Coriolis meter, load cell sensors and radio frequency sensors. These experimental measurements could potentially unlock a robust method that can be applied to geothermal systems in order to measure and monitor the well output in real-time. The data gathered from the experiments will be used for further exploration where the experimental measurements can be compared to the reference measurements.

In order to develop a method to monitor the well output in real-time, two things will be done. Recent correlations will be tested with the gathered data and an empirical correlation between experimental measurements and reference measurements will be pursued.

3.1 Reference measurements

3.1.1 Vortex meter

A vortex meter is used to measure the mass flow rate of steam leaving the steam separator. Vortex meters detect fluid oscillation and can measure the flow of gas, steam, or liquid. Their advantages for reasonably clean fluids include good accuracy and repeatability, high rangeability, low maintenance and the ability to provide frequency or linear analog outputs (Lipták, 1995).

The vortex meter used in this experiment is an InnovaMass 241i Insertion from Sierra Instruments Inc and will be installed at the steam outlet of the steam separator.

Figure 6: Vortex meter used in the experiment. Picture to the left shows how the Vortex meter is connected to the steam separator.

3.1.2 Weir

Weirs are apertures in the top of a dam, across a channel through which flows are to be measured. A weir may be rectangular, trapezoidal (used for larger flows) or V-notch (for smaller flows). A water weir allows for easy and accurate flow measurements. They are durable, easy to build and require limited maintenance (Lipták, 1995).

For a fully contracted 90-degree V-notch sharp crested weir, as used in this experiment, the volumetric flow Q [m^3/s] over the weir is found with the Cone equation (in S.I. units):

$$Q = 1{,}36H^{2{,}48} \tag{1}$$

where H is the head over the weir [m].

This equation is reliable for small, fully contracted weirs where free flow conditions persists and the head over the weir fulfills the requirement: $0{,}06<H<0{,}381$ m.

Figure 7: The water weir used in the experiment. The separator water from the separator flows into the weir.

3.1.3 Uncertainty and sensitivity analysis

The mass flow in the steam separator can be written as:

$$\dot{m}_{total} = \dot{m}_s + \dot{m}_{w1} \tag{2}$$

Where $\dot{m}_{total}$, $\dot{m}_s$ and $\dot{m}_{w1}$ are the total mass flow rate into the steam separator, the steam mass flow rate from the separator and the mass flow rate of the separated water from the steam separator, respectively. Evaporation in the water weir is negligible.

Flash correlation factor

The flash correction factor, FCF, can be used to correct water flows measured at atmospheric pressure at some higher separation pressure. Namely, after separating steam and water at some higher pressure, the separated water is flashed to the atmosphere and the water flow from this second flash is measured in the water weir. To correct for the steam flashed off between the separator and the atmospheric pressure we can use (Grant and Bixley, 2011):

$$\dot{m}_{w1} = \dot{m}_{w2}\, FCF \tag{3}$$

where

$$FCF = \frac{1}{1-X} \tag{4}$$

where $\dot{m}_{w1}$, $\dot{m}_{w2}$ and X are the mass flow rate from the separator [kg/s], mass flow rate from the V-notch in the water weir [kg/s] and the dryness of the second flash, respectively. X is calculated from saturated liquid enthalpy at the separator pressure P1 and the atmospheric pressure P_{atm}.

The mass flow rate from evaporation that takes place in the water weir is negligible.

Fully contracted 90° V-notch weir

A fully contracted 90° V-notch weir will be used in this experiment for the separated water. The Cone equation, given by Equation (1), used to calculate the discharge, where Q and H are respectively the volumetric flow of water from the water weir [m^3/s] and the head over the weir [m].

Q can be expressed as:

$$Q = \frac{\dot{m}_{w2}}{\rho} \tag{5}$$

so

$$\dot{m}_{w2} = \rho Q \tag{6}$$

where ρ is the saturated liquid density (of the separation water) at atmospheric pressure that can be written here as:

$$\rho = \rho_{L@atm} \tag{7}$$

The uncertainty of $\dot{m}_{w2}$ can be expressed as:

$$\Delta\dot{m}_{w2} = \sqrt{\left(\frac{\partial \dot{m}_{w2}}{\partial \rho}\Delta\rho\right)^2 + \left(\frac{\partial \dot{m}_{w2}}{\partial Q}\Delta Q\right)^2} \tag{8}$$

which is equivalent to

$$\Delta\dot{m}_{w2} = \sqrt{(Q\Delta\rho)^2 + (\rho\Delta Q)^2} \tag{9}$$

The saturated liquid density's uncertainty can be expressed as:

$$\Delta\rho = \frac{\partial \rho_{L@atm}}{\partial P_{atm}}\Delta P_{atm} \tag{10}$$

ΔQ can be found by taking the partial derivative of Q with respect to H

$$\Delta Q = 3{,}37H^{1{,}48}\Delta H \tag{11}$$

Thus, the uncertainty of $\dot{m}_{w2}$ can be calculated with:

$$\Delta\dot{m}_{w2} = \sqrt{\left(1{,}36H^{2{,}48}\ \frac{\partial \rho_{L@atm}}{\partial P_{atm}}\Delta P_{atm}\right)^2 + (\rho_{L@atm}3{,}37H^{1{,}48}\Delta H)^2} \tag{12}$$

The uncertainty $\Delta\dot{m}_{w1}$ can be calculated with the following equation:

$$\Delta\dot{m}_{w1} = \sqrt{\left(\dot{m}_{w2}\frac{\partial}{\partial h_{w1}}\left(\frac{1}{1-X_{h_{w1};P_{atm}}}\right)\frac{\partial h_{w1}}{\partial P_1}\Delta P_1\right)^2 + \left(\dot{m}_{w2}\frac{\partial}{\partial P_{atm}}\left(\frac{1}{1-X_{h_{w1};P_{atm}}}\right)\Delta P_{atm}\right)^2 + \left(\left(\frac{1}{1-X_{h_{w1};P_{atm}}}\right)\Delta\dot{m}_{w2}\right)^2} \tag{13}$$

where h_{w1} is the saturated liquid enthalpy at the separator pressure P_1:

$$h_{w1} = h_{L@P1} \tag{14}$$

Total available power

The total available power P_{th} can be determined with:

$$P_{th} = h_s\dot{m}_s + h_{w1}\dot{m}_{w1} \tag{15}$$

Where h_s, $\dot{m}_s$, h_{w1} and $\dot{m}_{w1}$ are respectively the enthalpy of steam, mass flow rate of steam, enthalpy of separated water at the separator pressure and the mass flow rate of the separated water leaving the steam separator.

The uncertainty of P_{th} can be written as:

$$\Delta P_{th} = \sqrt{\left(\frac{\partial P_{th}}{\partial h_g}\Delta h_s\right)^2 + \left(\frac{\partial P_{th}}{\partial \dot{m}_g}\Delta \dot{m}_s\right)^2 + \left(\frac{\partial P_{th}}{\partial h_{w1}}\Delta h_{w1}\right)^2 + \left(\frac{\partial P_{th}}{\partial \dot{m}_{w1}}\Delta \dot{m}_{w1}\right)^2} \tag{16}$$

where Δh_s $\Delta \dot{m}_g$ $\Delta h_{w1}\Delta \dot{m}_{w1}$ are the uncertainties of the parameters defined above.

The calculated uncertainty of the total available power ΔP_{th}, based on the reference measurements, is shown in figure 8 and figure 9 with respect to the expected total mass flow rate of the two-phase fluid and its total enthalpy.

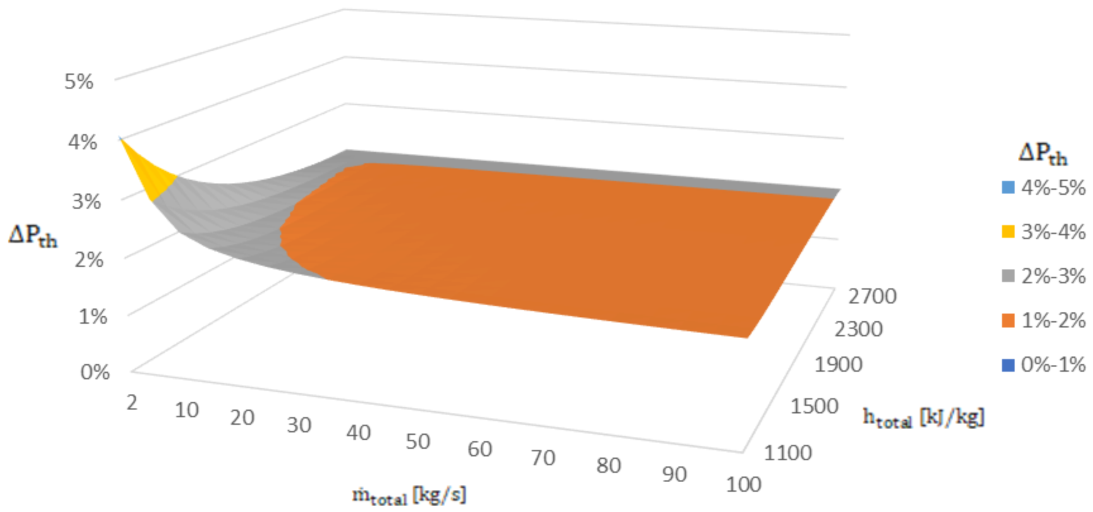

Figure 8: Calculated uncertainty of the total available power with expected range of total mass flow of the two-phase fluid and its enthalpy.

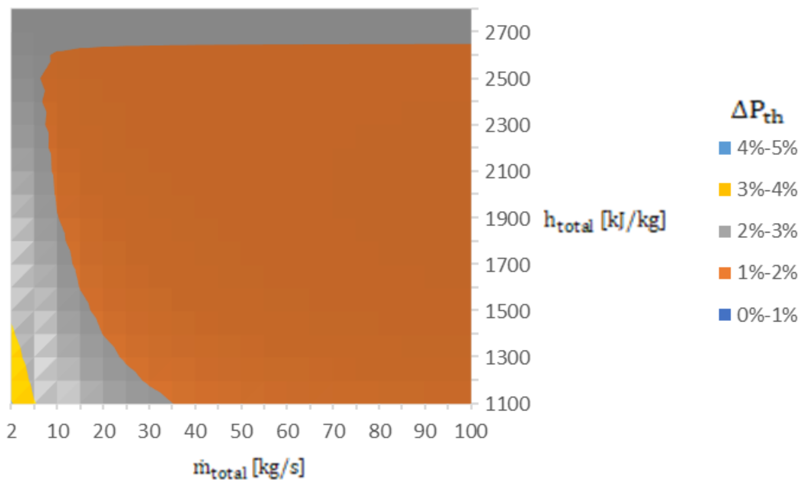

Figure 9: A contour plot of figure 8, the calculated uncertainty of the total available power with expected range of total mass flow of the two-phase fluid and its enthalpy.

3.2 Experimental measurements

3.2.1 Orifice plate

An orifice plate, a thin plate with a hole in it, is a device used for measuring the rate of flow using differential pressure. It uses the Bernoulli's principle which states that there is a relationship between the pressure and the velocity of a fluid. The fluid is forced to converge to pass through the hole, increasing flow velocity and causing a corresponding decrease in pressure. A little downstream of the orifice, where the velocity reaches its maximum, the minimum pressure can be measured (The American Society of Mechanical Engineers, 2004 (Reaffirmed 2017)).

Known for its durability and simplicity, orifice plates can be used in a wide range of applications. They are very economical and are used for robust applications. They are available in a variety of materials and in many designs, such as concentric, segmental or eccentric. Badly worn or damaged, the orifice plate can still provide a reasonably repeatable output, although significantly inaccurate (The American Society of Mechanical Engineers, 2004 (Reaffirmed 2017)).

Two-phase flow correlations

Normally orifice plates are used to measure single-phase liquid or vapor. They have been used for flow rate measurements by the geothermal industry for decades now (Mubarok, Zarrouk, & Cater, 2018). Normally used for single phase fluid, two-phase orifice plate is the most widely examined alternative method to measure mass flow rate and enthalpy from two-phase geothermal wells. Measurements using orifice plates can cover a wide range of two-phase geothermal mass flow rates and enthalpy values not captured by some of the existing measurement techniques used in industry (Mubarok, Zarrouk, & Cater, 2018). Two-phase fluid measurements with orifice plates have however not been well established in the geothermal industry due to the associated difficulties.

Two-phase flow correlations for sharp-edge orifice plates use have been developed by Mudock; James; Lin; Zhang et al.; Helbig and Zarrouk and Campos et al. All of these methods are based on either homogenous flow or separated models and require an estimated enthalpy, which is taken from an earlier horizontal discharge or separator testing data. Therefore, on-going validation of enthalpy measurement is required to avoid increasing error (Mubarok, Zarrouk, & Cater, 2018). Recently, a new two-phase orifice flow rate correlation was developed by Mubarok, Zarrouk & Cater (2018) using a concentric sharp-edge orifice plate. This correlation was calibrated using 2000 field test data sets from 56 geothermal wells in multiple fields in New Zealand, Indonesia and the Philippines with different measurement instrumentation/technology and for different size orifice plates. The advantages of this new correlation are an improvement in accuracy and the ability to use data from other enthalpy measurement techniques easily. The two-phase flow rate estimation is improved by using the two-phase fluid enthalpy, which is more suitable for geothermal applications, instead of dryness (X) as some of the previous two-phase correlations have done. The dryness can be sensitive to changes in the operating pressure and consequently introduce additional errors (Mubarok, Zarrouk, & Cater, 2018). This new correlation offers a straight-forward way to calculate the fluid enthalpy by measuring the real-time mass flow rate and vice versa. Furthermore, this new correlation has lower error relative to field data (1.01%) than other correlations, indicating that it can be used to calculate the two-phase mass flow rate of geothermal fluid with higher accuracy and performance. Indeed, it shows higher accuracy for a wider range of measurements than previously developed two-phase flow rate correlations (Mubarok, Zarrouk, & Cater, 2018).

The new correlation that Mubarok, Zarrouk and Cater (2018) developed shows that the two-phase orifice mass flow rate can be found with:

$$\dot{m} = \frac{a\left(\frac{\pi d^2}{4}\right)C_h\sqrt{2\Delta p}}{\left(\sqrt{1-\beta^4}\right)} \tag{17}$$

The pressure coefficient of modified correlation a is defined as:

$$\mathrm{a} = \left(\frac{\mathrm{p1}}{\mathrm{p2}}\right)^{D\sqrt{\frac{(10^{-5}\Delta p)}{D}}} \tag{18}$$

The enthalpy coefficient C_h can be found with Mubarok's, Zarrouk's and Cater's (2018) power curve fit model for the relationship between C_h and the enthalpy h:

$$\mathrm{C_h} = (9{,}7 \times 10^5)(h)^{-1{,}72} \tag{19}$$

Therefore, the two-phase orifice mass flow rate can fundamentally be determined as:

$$\dot{m} = f(p_1, p_2, D, d, h) \tag{20}$$

where $\dot{m}, p_1, p_2, D, d, h, \Delta p$ and β are respectively the mass flow rate, pressure upstream of the orifice plate, pressure downstream of the orifice plate, inside pipe diameter, orifice diameter, enthalpy, pressure drop across the orifice plate and the ratio of the orifice diameter d to the inside pipe diameter D ($\beta = d/D$). By knowing the enthalpy, it is possible to determine the mass flow rate and vice versa.

The use of two-phase orifice plates has not been universally adopted due to difficulties with scaling and the need for maintenance that can only be performed with the well off-line. A pressure drop forms when the fluid flows through the orifice plate, creating a pressure differential at the plate itself, which may create issues with scaling. Being internal to the pipe structure itself, maintenance of such plates requires a shutdown of the flow (Sisler J. R., 2018).

Wet-gas orifice plate

The oil and gas industry have slowly been moving towards a wet gas orifice meter design. Substantial evidence has recently shown that the performance of orifice meters is relatively good in wet gas flows, opposite what was previously thought. Masses of data sets from different test facilities, from various orifice meter designs by different manufacturers, researched by different groups over many years show a remarkable reproducibility. This irrefutable independent evidence has led ISO to publish orifice meter wet gas equations quantifying the orifice meters wet gas performance (Richard Steven, Clyde Shugart, Ray Kutty, 2018).

Across the wet gas range, for a known liquid loading, the most advanced multiphase wet gas flow correlation predicts the gas flow to 2% uncertainty at 95% confidence. The wet gas flow performance of orifice is repeatable, reproducible and hence predictable. The limiting factor for most generic gas meters with a wet gas correlation is knowing the liquid loading from an external source. There is no unique solution to a wet gas correlation algorithm without the external liquid loading knowledge. However, the orifice meter has the ability to internally predict the liquid loading by having three pressure taps around the orifice plate. The additional downstream pressure port allows for internal prediction of the liquid loading. This, in turn, makes the problem solvable with a unique solution. The orifice meter can then directly predict the gas flow and liquid loading with no required end user liquid loading keypad entry. This kind of wet gas orifice meter for deliberate continuous use in wet gas flow applications has been developed. A wet gas flow calculation algorithm can predict the wet gas flow and estimate liquid loading from the wet gas correlation. It can predict the gas flow to <4% uncertainty for wider wet gas flow and orifice meter geometry ranges, and <2,5% uncertainty for some wet gas flow conditions without knowledge of the liquid flow being required (Richard Steven, Clyde Shugart, Ray Kutty, 2018).

The additional use of the third pressure tap gives the wet gas orifice meter some system verification capability. The use of diagnostics gives a differential pressure (DP) reading integrity check and allows an easy visual way to monitor changes in wet gas liquid loading. The systems additional reading of the recovered DP (measured at the third pressure tap) gives three different DP ratios instead of one. Each of these three DP ratios has a physical reproductible relationship with the liquid loading. Thus, if one of the systems DP transmitters fails, it can still operate (Richard Steven, Clyde Shugart, Ray Kutty, 2018).

Number of pressure meters and mass flow rate

Two pressure meters are commonly used with orifice plates, located upstream and downstream from the orifice plate. The differential pressure between the two is then measured. Mubarok, Zarrouk & Cater (2018) used this setup with good results for their two-phase flow correlation in geothermal wells. Stevens, Shugart & Kutty (2018) placed a third pressure tap downstream of an orifice meter for a wet gas flow. By adding an additional downstream pressure tap to an orifice meter, it is possible to read three different differential pressures (DPs) from the three pressure taps. The relationships between these DPs can be used as an integrity check on the reading. Each of the three DPs can individually meter the gas flow whereas the three flow predictions can be inter-compared. Reading three DPs produces three DP ratios that are reproducible in orifice meters and can be predicted from data fits (Richard Steven, Clyde Shugart, Ray Kutty, 2018).

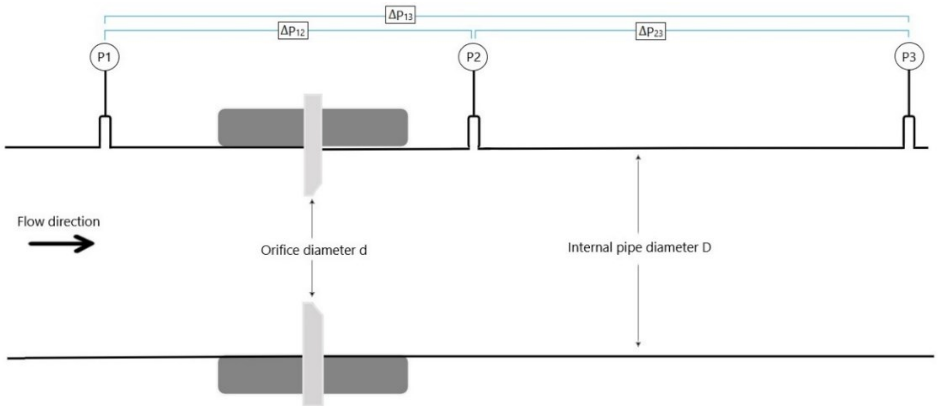

Figure 10: Orifice plate with three pressure meters

This experiment will test the possibility of determining the mass flow rate for two-phase fluid flows in geothermal wells by adding a pressure sensor downstream of the orifice plate, using three pressure sensors instead of two like Mubarok, Zarrouk & Cater (2018) did for their correlation. The mass flow rate could then potentially be determined as:

$$\dot{m} = f(p_1, p_2, p_3, D, d) \tag{21}$$

The real-time mass flow rate can thus potentially be determined without providing an explicit enthalpy value, making the orifice plate an autonomous measurement device that can measure two-phase mass flow in geothermal wells. Once the mass flow has been determined, the enthalpy can be found, e.g. based on equation (17).

3.2.2 Venturi meter

Venturi tubes are simple, robust and cost-effective flow meters. Like orifice plates, a venturi tube is a meter design within a general group called the Differential Pressure ('DP') meters operating under Bernoulli's principle. The shape of venturi tubes and nozzles have taken its form by minimizing the pressure drop across them. In contrast with the sharp edge orifice, they are resistant to abrasion and can also be used to measure the flow of dirty fluids and slurries (Lipták, 1995). venturi meters form the main component in the majority of commercial wet-gas and cost-effective flow meters. From a limited data set, it has been shown that the current wet-gas over-reading correlation in ISO/TR 11853, derived for venturi meters, can be used with reasonable accuracy for 3-phase wet-gas flows with water cuts from 0-100% (Graham, et al., 2015). A venturi meter with three pressure sensors will be used in this experiment.

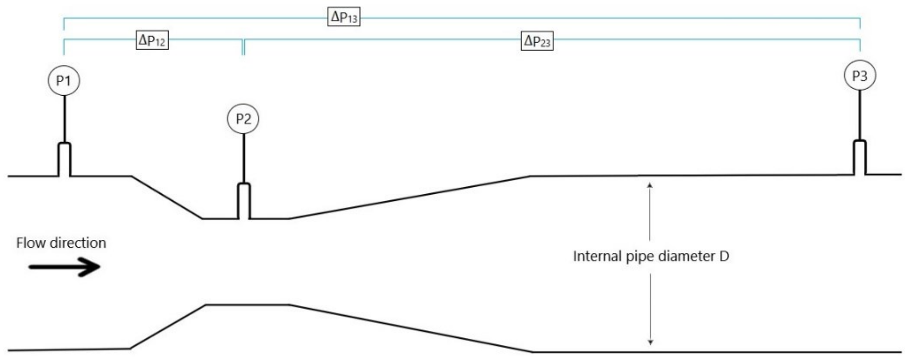

Figure 11: Venturi meter with three pressure meters

3.2.3 Coriolis meter

Coriolis meters are mass flowmeters that can directly measure mass flow, volume flow, density and temperature (Lipták, 1995). There is limited material available on measuring two-phase mass flow in a geothermal setting with such meters. They are relatively expensive and may have trouble dealing with pulsing flow. Landsvirkjun is, however, interested in testing a Coriolis meter in this experiment.

3.2.4 Load cells

The most practical means of weighing with measurements are by using strain gauge load cells. There is a wide variety of strain gauge load cells that are accurate, stable and reliable for nearly all applications (Lipták, 1995). Recently, Sisler et al. (2015) have tested a new application of strain gauge load cells with the attempt to develop a method to measure two-phase flow in geothermal pipelines for continual monitoring. Multiple fields trials were taken during four horizontally discharged well output tests at Wairakei steam fields in New Zealand. Full datasets were taken from one, sometimes two, load cell sensors (Sisler, et al., 2015). The LC sensor was installed at pipe supports of a well output, with no contact to the geothermal fluid within the pipe, using strain gauge measurement to measure flow characteristics in a large volume of piping. The sensors are calibrated to the specifics of the pipe geometry where the initial set values for the sensor may best be taken from historical information or standard well output tests. From such values the sensor may be able to track the trends of change taking place in the fluid flow correctly (Sisler, et al., 2015).

The pipe and fluid weight are measured in real-time by monitoring the overall weight of the pipelines with LC sensors. This sensor method relies on the determination of the contents of the pipe stresses, support from other locations, and the water properties inside the pipe. The sensor was able to track changes in the steam quality in real time, which can be used to calculate the enthalpy of the fluid within the pipes. The sensor appears to be able to determine trends in change of enthalpy, even without calibration of the sensor. Continuous trend data for enthalpy could help improve the knowledge of well output between calibrated output tests. The accuracy of existing two-phase orifice plates could potentially be complemented or improved with this method. It could even be used as a stand-alone method for the measurement of total mass flow rate and enthalpy in geothermal pipelines (Sisler, et al., 2015). Flow information can be determined if two sensors are used together on the same well, which can initiate calculations of water mass flow (Sisler J. R., 2018). Further analysis of the datasets obtained from the field tests is however required (Sisler, et al., 2015). LC sensors are also able to track vibrational events in the piping (Sisler J. R., 2018).

The early results from Sisler et al. (2015) shows promising results but the method is still in its development stage. The advantages of using LC sensors includes an easy setup and simple construction, no direct contact with the internal pipe content and accordingly no restriction to the flow (Sisler, et al., 2015).

3.2.5 Radio frequency

This method, like the load cell method, is still in its development stage and is specifically developed to allow installations with minimal or no pipe modification. The instruments are located outside the pipes, so the use of these sensor methods does not affect pipe pressure. The installation and maintenance of RF sensors can therefore be performed without shutdown of the flow. RF sensors are installed through standard pipe tap ports that allows a probe to be injected into the volume of the pipe. It requires a pressure seal at the actual installed antenna but is less affected by environmental effects or pipe stresses (Sisler J. R., 2018).

The radio frequency sensor measures water content inside the pipe by evaluation of internal pipe impedance in real-time. Like load cell sensors, the radio frequency method puts an emphasis on software analysis and minimal installed hardware. The data obtained can be described as a measurement of open-air space in the pipe (void fraction), instead of an actual dryness fraction value. The analysis of data has shown that the RF sensors can track changes in the flow and water content in real time. The water flow velocity, and in turn the water volume flow rate as the pipe internal cross section is known, could be determined by finding the time offset of variances between the distance of two RF sensors in the pipe (Sisler J. R., 2018).

4. DISCUSSION & SUMMARY

Landsvirkjun has formed a project to conduct experiments on wells with varying output, steam quality, chemical composition etc. to work on real-time measurements of well output. Many difficulties are associated with measuring the parameters needed to evaluate the well output. These include mass flow, steam quality and enthalpy.

Two options are most commonly used today in the geothermal industry to evaluate well output: tracer dilution tests and horizontal discharge tests. These tests are time consuming, cumbersome, relatively expensive and only provide point measurements. These tests are therefore typically done only 1-2 times each year. Methods for two-phase flow measurements in geothermal settings are available, mainly for orifice plates but also with some other methods as mentioned in chapter 3.2. These methods have however not been well established in the industry and are in their development stage. Landsvirkjun wants to accelerate this process by conducting these experiments with the goal to develop a robust set of sensors that can execute the task and could eventually be utilized by the energy companies for real-time well output monitoring.

Landsvirkjun will provide wells, separators and reference measurements for the experiment. In the first phase, geothermal well ÞG-18 in Þeistareykir will be used with a steam separator at the end of the flow line where the real-time output can be measured. Reference measurements will be taken at the steam separator to measure steam mass flow with a Vortex meter and volumetric mass flow of the separated water at a water weir. As figure 8 and figure 9 show, the calculated uncertainty for the reference measurement is acceptable for the expected range in total mass flow and enthalpy of the two-phase fluid, ranging from 1% to 4%. The reference measurements can then be compared with experimental measurements in the flow line with devices and sensors such as orifice plates, venturi meters, Coriolis meters, load cell sensors and radio frequency sensors. By applying many different devices and sensors at once, new empirical relationships could be discovered. The devices and sensors could complement each other to arrive at the most robust and accurate measurement of two-phase flow. Recent two-phase correlations will also be tested with the obtained data and new correlations will potentially be determined. Landsvirkjun invites interested parties and manufacturers to cooperate in these experiments that offer a unique chance to test different devices and methods in the same well simultaneously.

Real-time well output measurement is an industry wide challenge where the solution accommodates great benefits. Real-time well output monitoring would give information that can be applied in the management of the reservoir. The ability to optimize the production and yield would be significantly strengthened. Monitoring individual well performance and its effect on other wells in the system would lead to a more sustainable utilization of the reservoir. In addition, the real-time well output would help to detect technical problems in the wells, such as scaling, that can trigger a quick reaction of appropriate intervention. Thus, real-time well output measurements would promote a more resourceful way to manage the geothermal reservoir.

REFERENCES

Graham, E., Reader-Harris, M., Ramsay, N., Boussouara, T., Forsyth, G., Wales, L., & Rooney, C. (2015). Impact of Using ISO/TR 11583 for a Venturi Tube in 3-Phase Wet-Gas Conditions. *33nd International North Sea Flow Measurement Workshop 20-23 October.*

Graham, E., Reader-Harris, M., Ramsay, N., Boussouara, T., Forsyth, G., Wales, L., & Rooney, C. (2015). Impact of Using ISO/TR 11583 for a Venturi Tube in 3-Phase Wet-Gas Conditions. *33nd International North Sea Flow Measurement Workshop 20-23 October.*

Grant and Bixley, P. (2011). *Geothermal Reservoir Engineering 2nd edition.* Elsevier Inc.

Lipták, B. (1995). *Instrument engineer's handbook. Process Measurement and Analysis 4th edition.* CRC Press.

Mubarok, M., Zarrouk, S., & Cater, J. (2018). *Two-phase flow measurement of geothermal fluid using orifice plate: Field testing and CFD validation.* Renewable Energy.

Richard Steven, Clyde Shugart, Ray Kutty. (2018). *Orifice Meter Multiphase Wet Gas Flow Performance – The Pressure Loss Ratio Solution to the 'Ill-Posed' Problem.* North Sea Flow Measurement Workshop 22-24 October 2018.

Sisler, J. R. (2018). Real-Time Sensors for Multi-Phase Flows: Results of Field Trials and Further Study. *43rd Workshop on Geothermal Reservoir Engineering.* Stanford, California.

Sisler, J. R., Zarrouk., S. J., Urgel, A., Lim, Y. W., Adams, R., & Martin, S. (2015). Measurement of two phase flows in geothermal pipelines using load-cells: Field trial results. *37th New Zealand Geothermal Workshop.* Taupo, New Zealand.

The American Society of Mechanical Engineers. (2004 (Reaffirmed 2017)). *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi.* CRC press An American National Standard, . ASME MFC-3M-2004 (reaffirmed 2017).