MEASUREMENT OF TWO PHASE FLOWS IN GEOTHERMAL PIPELINES USING LOAD-CELLS: FIELD TRIAL RESULTS

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ABSTRACT

A method for the measurement of two phase flow has been tested, with the ability to provide continual monitoring of two-phase flow in geothermal or other pipelines. The sensor uses strain gage measurement on pipe supports to measure flow characteristics in a large volume of piping from one pipe support to another. Horizontal discharge well output tests were performed on wells at Wairakei geothermal field, New Zealand, with the sensor included during the tests for performance comparison and calibration to the standard output test. Early results show the sensor is able to track changes in the flow, with the advantage of simple construction, no direct contact required with internal pipe content, no restriction to the flow, and easy setup. The sensor is able to track changes in the percent of steam to water in the pipe, for the calculation of enthalpy in the pipes and wells in real time. The method has the potential to complement (improve) the accuracy of existing two-phase orifice plates, or as a stand-alone method for the measurement of total mass flow rate and enthalpy in geothermal pipelines and wells. Accurate tracking of changes to dryness fraction were observed, as well as detection of other phenomenon. Results of field trials and calibration methods are presented.

1. INTRODUCTION

1.1 Geothermal steam field management

Development of electrical power from geothermal sources requires continual monitoring and planning to maintain or improve the energy output from such facilities. In New Zealand, continuous fluid flow measurement and monitoring is also a primary condition for resource consent and compliance. Maximizing the production from a field full of wells and sources is a balancing act of knowing how the available wells will perform, when to plan for additional wells, and how to determine the most effective time to perform maintenance or other required operations. The more that can be known about well output performance, the better such plans can be made. Two important parameters to determine from each well are flow rate and enthalpy, and how these may change over time either by themselves or by interaction with other wells in operation. Various techniques have been devised to determine these two parameters, with most methods are complicated by the fact that well production is often two-phase. These techniques do allow determination of the necessary parameters, but are not suited to continual measurement on a minute or hourly basis. The common practice is to perform such tests only quarterly or longer, due to expense of testing or the requirement that the test be performed while the well is out of service. Changes occurring in the wells, or interaction between wells, may be missed with such long timespans between test results. The sensor method discussed here can provide data through these long timespans, providing results minute by minute, and may help improve the activity of tuning the steam field system for maximum performance and efficiency.

1.2 The sensor method

Piping in geothermal fields is often held above ground on pipe supports. Supports in some locations are allowed to slide to accommodate thermal expansion/contraction. This aspect of steam field design is used to allow for a measurement of pipe and fluid weight by monitoring the overall weight seen at one or more sliding pipe supports. The supports monitored by the sensor are chosen based on available field piping geometry. One or two sensors are attached to one or two pipe supports of a well output, and calibrated to the specifics of the pipe geometry. Then data can be taken continuously.

In the analysis below, results of field trials taken during four horizontally discharged well output tests are included and discussed.

2. MEASUREMENT WITH LOADCELLS

2.1 Introduction

This sensor method necessarily relies on determining the contents of the pipe by weighing the overall structure. Many factors may affect the weight reading detected such as pipe stresses, support from other locations, and properties of the water itself. Computer models of piping structures were created to allow study of various potential stresses such as pipe geometry and support, internal pipe pressure, and temperature. Various pipe geometries similar to those expected at the field trial locations were modelled and studied.

2.2 Pipe geometries

Steel piping used in steam fields is a strong element, able to support itself between pipe supports. A simple static load model (without pipe stress being considered) can help determine the expected weight seen at a center support in a pipe supported at each end, such as that shown in Figure 1 below.

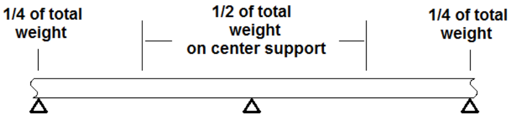

Figure 1: Simple static model

In this simple model, without taking pipe strength into account, the weight measured at the center would be expected to be one half of the total weight of the structure.

In a circumstance where the center support is offset a small amount from center, this simplistic model of weight would still be the same, as shown in the Figure 2.

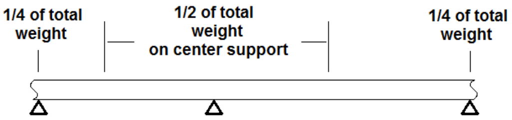

Figure 2: Simple static model with minor offset of center support

Actual structures would be expected to have pipe stresses that may affect the weight seen on a centralized support. If for example the pipe is fixed to a rigid support at one or both ends, this may affect the weight seen on a central support. In most geothermal steam fields pipes are supported by a rigid fixed position in a few locations and supported on sliding supports in other locations to allow for thermal expansion and contraction. A rigid support near the sensor location may allow the pipe itself to hold much of the weight of the unsupported span, similar to a cantilever, whereas a sliding support will not.

2.3 Simulation of piping geometries and determination of load cell requirements

Piping structures similar to those expected at the field trial locations were studied with Solidworks™ Simulation to determine the extent of support that may be expected from a fixed location as well as effects of offset center supports. The simulation model includes necessary parameters such as steel type, pipe diameter, wall thickness, distance between supports, support type (whether fixed or sliding), extra weight of insulation, weight of insulation protective covers, and material properties of all structural elements as well as for the water in the pipe. Material properties were adjusted for performance in the expected temperature range of operation.

Results appear to show that pipe stresses do not contribute major support capability to the pipe. The simulations show that the long distances between pipe supports allow for an accurate measurement of weight at the center of the span without significant effects from fixed supports or other pipe stresses. In simulation, all effects from such stresses do not contribute more than a 1% change in water content in the piping, and such effects are able to be predicted if needed. Of the stresses simulated, pressure in the pipe may have a larger effect on pipe strength that the effect of a fixed support on one end, or operation at increased temperature. This effect of pressure appears to increase as the pipe diameter increases.

Yet in all cases the simulations suggest that a simple calculation as shown in Figure 1 is sufficiently useful for determination of the expected weight in the center of a span. From this calculation, the necessary load cell maximum capacity was determined, as well as the expected weight of a 1% change in water content.

Simulations of field piping geometries with pipes at 'maximum weight', fully filled with cold water, all showed expected weights under 5000 kg. A load cell of 5000 kg capacity should be able to measure differences of 2.5kg. The weight of a 1% change in water content in the pipes for various field trial locations was determined from the simulation studies, and is summarized below:

Expected weights for a 1% change in water volume:

Location 1 and 3: 1% water volume = 7.78 kg

Location 2: 1% water volume = 5.94 kg

Location 4: 1% water volume = 18.1 kg

Therefore, a 5000 kg load cell with an accuracy of 2.5 kg should provide the ability to measure less than .5% change in water volume at all field trial locations. 5000 kg load cells were used for the field trials.

2.4 Field installation

With the expected weight determined, suitable mounts for the sensors were designed and fabricated to match the various possible sizes and shapes of pipe supports, while also meeting the necessary safety requirements. The design allows the weight of the pipe to be on the load cell while still allowing the pipe support itself to be the main element responsible for pipe alignment, as shown in Figures 3 and 4.

Figure 3: Load cell on load cell stand

Figure 4: Load cell detail. Note small air gap between shoe and pipe support, showing that weight of pipe is on load cell and not pipe support.

Once in place the load cells did not experience any movement. There was no in-line pipe motion, and the simple straps held the load cell and stand firmly against the pipe supports. The roller-pivot scheme shown in Figure 4 allows for easy alignment with the direction of potential pipe movement, and allows for a relatively vertical load onto the load cell without undue side stress. A laptop computer was used for data acquisition and data was logged and reviewed after completion of tests. Data points were taken approximately 35 times per second (35 Hz).

3. FIELD TRIAL LOCATIONS

3.1 Initial results

The sensors were installed to pipe supports on wells that were undergoing standard horizontal discharge well outputs tests. Four separate locations were used. The four locations have different pipe geometries as explained below.

3.2 Location 1: wk260

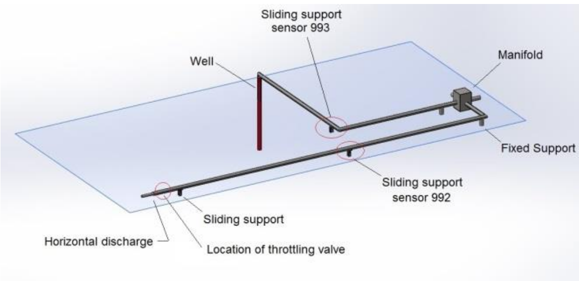

Figure 5: Location 1 (wk260) field piping

Two sensors were mounted. Sensor 993 is closest to the well and located at a position between two fixed supports: the well itself, and the fixed support near the manifold. Sensor 992 was located on a sliding support in the piping to the horizontal discharge as shown. In normal operation, well output flows through the manifold to a separator. The well output was diverted at the manifold into the horizontal discharge line for the well output test. Lip pressure data was taken at the horizontal discharge, and wellhead pressure controlled at the valve near the horizontal discharge. The well was allowed to run full then throttled in two steps, with sufficient time to allow for stable flow between steps. This created three different flow regimes, and well output data for the horizontal discharge test was taken for each regime. The sensor itself took data continuously, resulting in a dataset as shown in Figure 6.

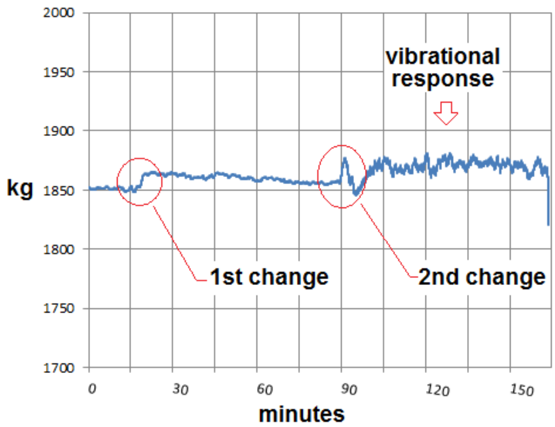

Figure 6: Location 1 (wk260) initial results. Total measured weight vs time.

The result shows an increase in weight throughout each change. After the second valve change the well piping was showing signs of vibration and was defined as ‘choked’, or close to the maximum discharge pressure (MDP). The Sensor registered an increase in vibration during this time, but an overall average increase in weight is still visible in the data.

Responses such as this were typical from all four test locations. Detailed datasets showing each valve change, and the resultant weights after each change, show the sensor’s ability to track changes in real time.

3.3 Location 2: wk253

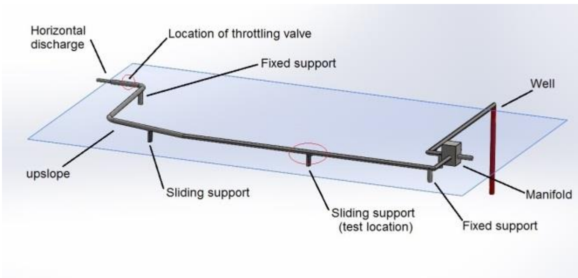

Figure 7: Location 2 (wk253) field piping

Location 2 has different pipe geometry, with piping that is fixed at two points. One fixed support is near the manifold and the other is located around a 90 degree bend near the horizontal discharge. Also, the piping actually measured by the sensor is not level, but has a rise in elevation that begins between the sliding supports, as seen in Figure 7. The sensor was installed to one sliding support in the discharge line where it would measure weight between the fixed support near the manifold and the sliding support near the upslope to the discharge. Like location 1 the well was allowed to run full, then throttled in two steps with a short time between steps to allow the flow to stabilize. This created three different flow regimes. Results of the raw data-set are shown in Figure 8.

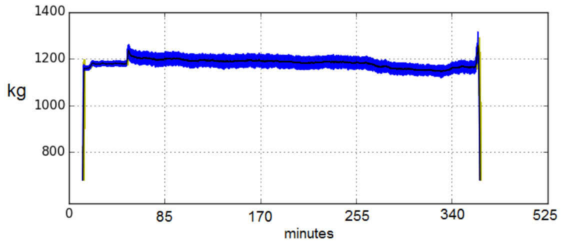

Figure 8: Location 2 (wk253) raw dataset

The first and second valve adjustments can be seen, and at approximately 15000 second a decrease in measured weight occurred. These changes are shown in details in Figures 9 and 10.

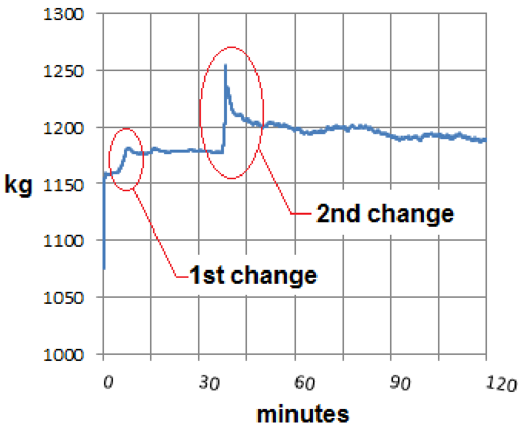

Figure 9: Location 2 (wk253) valve changes

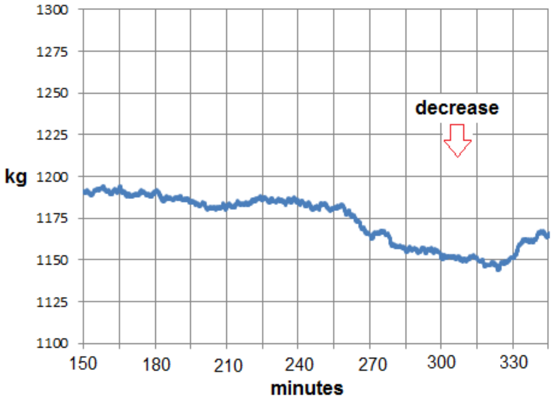

Figure 10: Location 2 (wk253) afternoon decrease

This decrease in weight apparently occurred on its own, and would indicate that the dryness fraction had increased. The well output may have changed, and contained more steam and less water.

3.4 Location 3: wk258

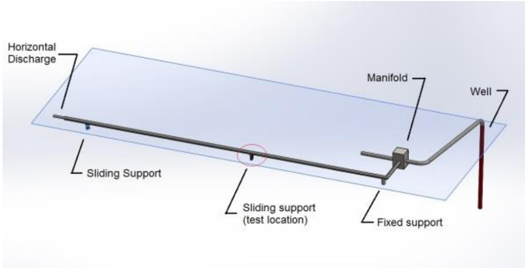

Figure 11: Location 3 (wk258) field piping

Location 3 (wk258) uses the same piping as location one. The sensor was placed on the same pipe support as in location 1, though the flow to the horizontal discharge is from a different well. The well was throttled in one step, creating only two different flow regimes. To determine effects of pipe stress, a weight of known amount was set on the pipe after the valve change. This 'standard weight' allowed for a determination of test accuracy, and whether or not pipe stress or other phenomenon where effecting the weight being measured. The addition of the standard weight can be seen the dataset shown in Figure 12.

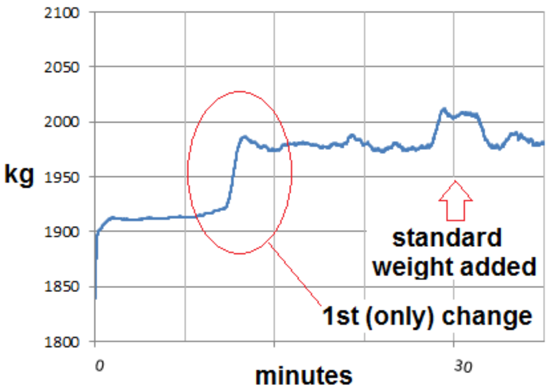

Figure 12: Location 3 (wk285) valve change and standard weight

The standard weight added to the pipe weighs 30.6kg. A review of the data shows that the increase in weight seen when the standard weight was added to the pipe was 30.8 kg. This would indicate that pipe stress has little effect on the overall weight measurement obtained from the sensor.

3.5 Location 4: wk222

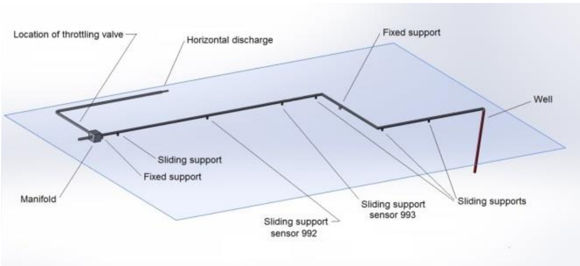

Figure 12: Location 4 (wk222) field piping

Test location 4 (wk222) is considerably different from test locations 1 through 3. Two sensors were placed on two pipe supports on the main line from the well, and not on a line to the horizontal discharge. The pipe diameter is larger than other tests, and has fixed supports in two locations. Sensors were placed on supports that lie between the two fixed supports. For normal operation, well output flows through the manifold to a separator. The well output was diverted to the horizontal discharge line for the well output test. Lip pressure data was taken at the horizontal discharge, and wellhead pressure controlled at a valve in the discharge line. The well was allowed to run full then throttled in two steps, with sufficient time between steps to allow the flow to stabilize. This created three different flow regimes. Like location 3 (wk258), a standard weight was added to the pipe for a few minutes at location 4 (wk222) to help determine if pipe stresses may be holding the pipe up more than expected. The same standard weights weighing 30.6 kg that were used at location 3 (wk358) were applied to the pipe at location 4 (wk222). With the standard weight added at sensor 1, the average increase in weight was 28.4 kg. With the standard weight added at sensor 2, the average increase in weight was 29.3 kg. The initial simulation studies for location 4 (wk222) suggest that the major factor for pipe stress is the internal pressure of 11 bar abs. The initial simulation studies would suggest that this pressure effect becomes a factor at location 4 due in large part to the larger pipe diameter at this location.

3.6 Field trial location summary

From the results it can be seen that the sensors registered a change in weight at every change made to the wells. As the wells were throttled the sensors registered an increase in overall weight in all cases accept sensor 2 at the first valve change at location 4 (wk222), where a small decrease in weight was measured.

Each of the field trial locations offered a different insight into sensor performance. Location 1 and 3 use the same physical piping. The use of standard weights for calibration at location 3 (wk258) seems to show that the piping geometry in that location is not affected by pipe stresses.
Results from location 2 (wk253), show a decrease in weight late in the test that would not have been measured otherwise. Review of WHP during this period does not show evidence of a change. This decrease might be due to an increase in the dryness fraction that occurred during that time, or less water and more steam in the pipe.
Location 4 (wk222), allows for additional analysis with the use of two sensors, and shows possible evidence of pipe stress due to pressure becoming an important factor for larger pipe diameters.

4. COMPARISON OF SENSOR DATA TO HORIZONTAL DISCHARGE DATA

4.1 Calculation of enthalpy and x from horizontal discharge test data

The results from the 4 locations were analysed using standard James Lip method. Calculated results are shown in table 1 below.

	James Lip	Atm =>	0.98		Pipe X sect	322.8262	<=tests 1-3		
					weir = .4				
wk260	**test 1**	**WHP (bar abs)**	**Lip (bar abs)**	**Weir (mm)**	**Rect Weir**	**Y**	**h**	**mass t/h**	**x**
1 % (kg) =>	7.78				w= .4m				
	1	10.98	3.33	190	198.77	0.19	**1131.38**	290.75	**0.176**
	2	11.28	3.08	180	183.28	0.19	**1135.16**	268.76	**0.175**
	3	11.98	1.88	110	87.56	0.15	**1300.90**	143.88	**0.253**
wk253	**test 2**								
1 % (kg) =>	5.94								
	1	11.38	2.88	195	206.66	0.23	**1024.53**	282.73	**0.119**
	2	11.98	2.68	180	183.28	0.22	**1054.57**	255.40	**0.129**
	3	13.73	2.28	165	160.86	0.23	**1039.98**	222.15	**0.109**
wk258	**test 3**								
1 % (kg) =>	7.78								
	1	9.18	2.98	200	214.66	0.23	**1021.48**	293.14	**0.136**
	2	12.4	2.08	194	205.08	0.31	**855.04**	254.43	**0.025**
wk222	**test 4**				Pipe X sect	178.18	<= (5.93 inch ID)		
1 % (kg) =>	18.09				weir = .3				
	1	7.38	2.03	110	65.67	0.19	**1154.74**	97.54	**0.218**
	2	8.88	1.95	98	55.22	0.16	**1238.70**	86.81	**0.245**
	3	11.18	1.53	94	51.88	0.19	**1132.83**	75.95	**0.175**

Table 1: Horizontal discharge data

4.2: Calculations of enthalpy and x from load cell data

The calculation of enthalpy and x from load cell data is complicated by the difficulty in obtaining a form of initial value for weight without detailed knowledge of the weight of structural components. Sensor values of weight cannot be directly converted into value of dryness fraction without knowledge of the weights of the rest of the structure, and it will be very difficult to determine such weights on structures currently in service. Instead, historical or current horizontal discharge data will be used for calibration. For example, the value of dryness fraction from the first data point taken for the horizontal discharge will be set to be first data point value of dryness fraction for calculation of load cell data. This assumes the value of dryness fraction calculated from the first dataset in each horizontal discharge calculation is the 'true' value, and the measured weight from the load cells at that point will be set to be the actual weight of that percent of water in the pipe. Then calculation of additional points will be based on that chosen dryness fraction.

4.3 Calculating changes in dryness fraction from changes in percent of water in the pipe

Dryness fraction (x) is defined as the proportion, by weight, of dry steam in a mixture of steam and water (Science Dictionary.2014). A 1% change in water weight in the pipe structure measured by a load cell would be equal to a 1% change in dryness fraction. Changes in dryness fraction can be calculated from the change in weight measured by the load cell at a pipe support as shown:

$$x(init) - \left(\frac{\Delta w}{w1*100}\right) = x\ (new)$$

$x\ (init)$ = initial value of x
Δw = change in weight (delta weight) seen after valve change
$w1$ = weight of a 1% change in water volume in the measured pipe length
$x\ (new)$ = new value of x
Δw = change in weight (delta weight) seen after valve change

Using this technique, and setting $x(init)$ equal to the initial value of x calculated from horizontal discharge data, values of x and enthalpy can be calculated from load cell data. Results are in table 2.

			Sensor							
			992	993	992	993	992	993	992	993
wk260	**test 1**	**WHP (bar abs)**	**Delta kg**	**Delta kg**	**Delta x**	**Delta x**	**x (new)**	**x (new)**	**h**	**h**
1 % (kg) =>	7.78									
	1	10.98					**0.176**	**0.176**	**1131.38**	**1131.38**
	2	11.28	4.86	4.701	0.006247	0.006042	**0.170**	**0.170**	**1125.35**	**1125.75**
	3	11.98	16.84	24.72	0.021645	0.031774	**0.148**	**0.138**	**1092.36**	**1072.65**
wk253	**test 2**									
1 % (kg) =>	5.94									
	1	11.38					**0.119**		**1024.53**	
	2	11.98	18.29		0.030791		**0.088**		**973.12**	
	3	13.73	10.16		0.017104		**0.071**		**964.97**	
wk258	**test 3**									
1 % (kg) =>	7.78									
	1	9.18					**0.136**		**1021.482**	
	2	12.4	68.49		0.088033		**0.047**		**898.99**	
wk222	**test 4**									
1 % (kg) =>	**18.09**									
	1	7.38					**0.218**	**0.218**	**1154.74**	**1154.74**
	2	8.88	50.58	-0.742	0.02796	-0.00041	**0.190**	**0.218**	**1125.92**	**1183.57**
	3	11.18	69.1	61.38	0.038198	0.03393	**0.152**	**0.184**	**1087.03**	**1151.38**

Table 2: Calculations of enthalpy and x from load cell data

Results of the load cell data based on this method of calibration are compared to the results from the horizontal discharge tests in the graphs below.

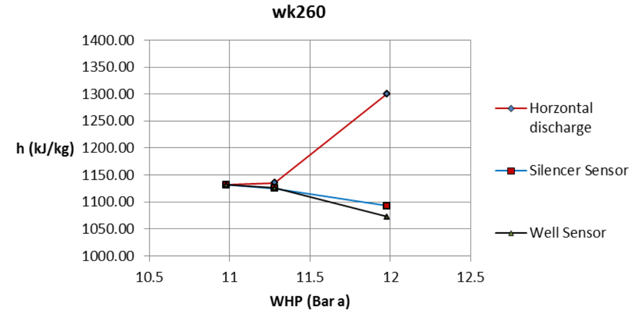

Figure 13: Enthalpy vs WHP. Location 1 (wk260)

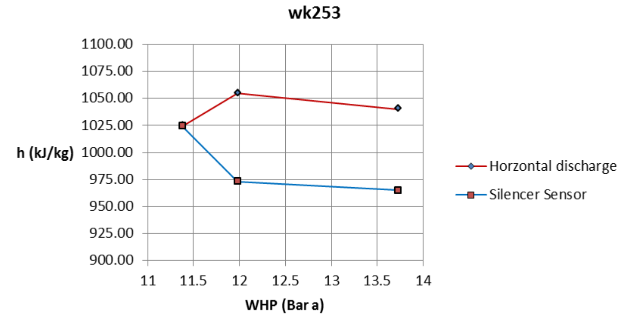

Figure 14: Enthalpy vs WHP. Location 2 (wk253)

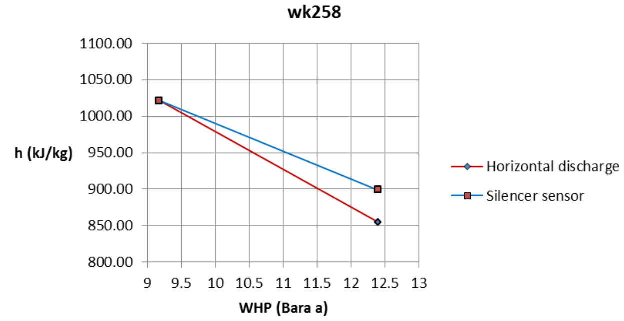

Figure 15: Enthalpy vs WHP. Location 3 (wk258)

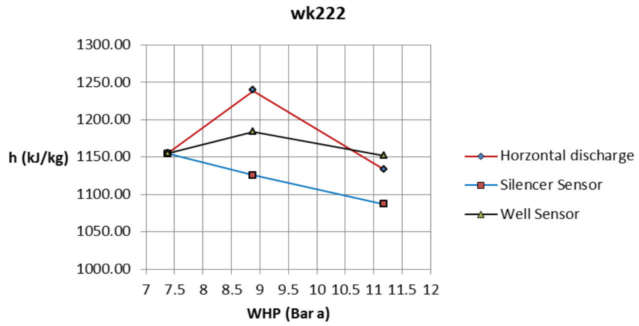

Figure 16: Enthalpy vs WHP. Location 4 (wk222)

4.4 Discussion

In review of the results, the slope of the enthalpy curves for load cell data appears to be a relatively close match to the slope of enthalpy curves from horizontal discharge data. This is interesting as the delta between readings, which defines the slope, is based on the calculation of dividing the actual measured weight difference between measurements by the theoretical weight of 1% of water. The volume of water used to define this 1% weight is based on the simple assumption that a load cell at a center support will measure the weight of ½ of the total weight of a full span.

Having obtained a relatively close match to slope of the enthalpy curves for both test methods, the difference in readings between the two methods may be more related to the choice of start point for the load cell calculations.

For location 1 (wk260), the first two test points are a good match. However the third shows a major shift in result.

For location 2 (wk253), the delta change from test point two to test point three matches the delta change seen in the horizontal discharge data, but the initial calibration of using the first horizontal discharge point as the starting point for the load cell data may not have been the best point to use for calibration. If the choice of calibration point had been chosen to be the second data point from horizontal discharge data instead of the first, the data may have a closer match.

For location 3 (wk258), results between the two methods show a relatively close match. A minor adjustment of only 1% to the initial dryness fraction chosen as the calculation point for load cell data creates quite close results as shown in the graph below.

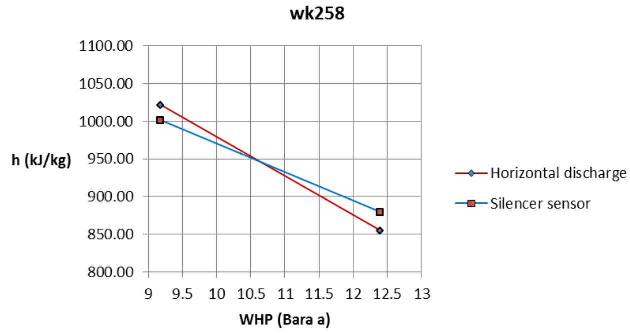

Figure 17: Location 3 (wk258). Load cell calibration point adjusted 1%

For location 4 (wk222), the two sensors measured different trends. The sensor near the well appears to match the rising and dropping enthalpy curve also seen in the horizontal discharge data, whereas the second sensor located closer to the silencer shows a more straightforward linear dropping curve. A comparison of both load cell enthalpy curves to the linear trend line of the horizontal discharge data is shown below.

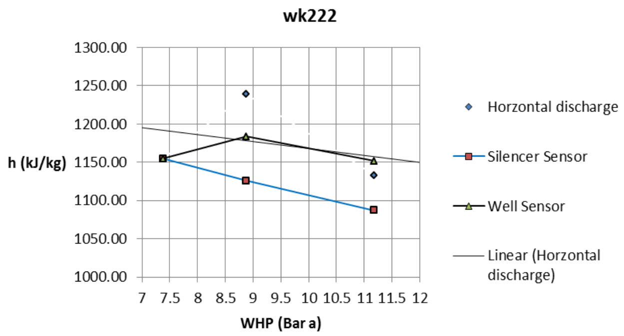

Figure 18: Location 4 (wk222). Load cell results compared to trend line of horizontal discharge data

Viewed in this manner, the result of the sensor near the well is a close match to the linear trend line of the horizontal discharge data. The sensor near the silencer is a close match in slope to the linear trend line, and could have an even closer match with a more suitable choice for the initial calibration value of x.

In general the load cell sensor method appears to be able to match trends in horizontal discharge data with a proper choice of calibration. Even without calibration it appears the sensor is able to be used to determine trends in change of enthalpy. The ability to provide trend data continuously would help improve the knowledge of well output during the time between calibrated well output tests.

5.0 FURTHER DATA ANALYSIS

5.1 Detection of slug flow

The previous analysis uses load cell data that has been averaged over one minute intervals to help dampen the rapid changes seen by the sensor. Further flow information, such as details of flow regime, may be able to be determined by analysis of the raw data directly. For example, analysis of the standard deviation of the raw data shows clear evidence of a major change in vibration after certain valve changes.

Location 1 and 3 use similar piping configuration. For both tests the load cell data show a major change in vibration when the wells were throttled to minimum flow. These flow rates were chosen because the output showed signs of slug flow, and the wells were therefore not throttled any further. Analysis of the raw data with a running standard deviation, set to one minute intervals, shows a clear pattern. This is shown for location 1 and 3 in Figures 19 and 20.

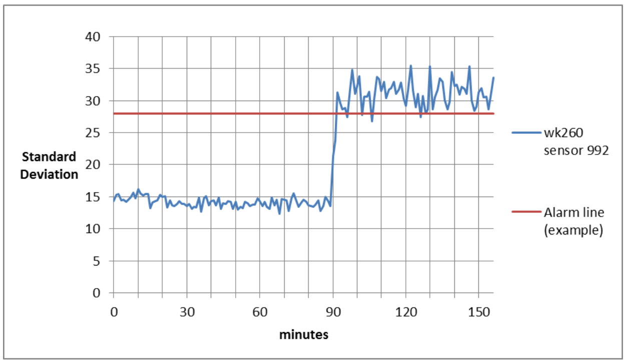

Figure 19: location 1 (wk260) standard deviations

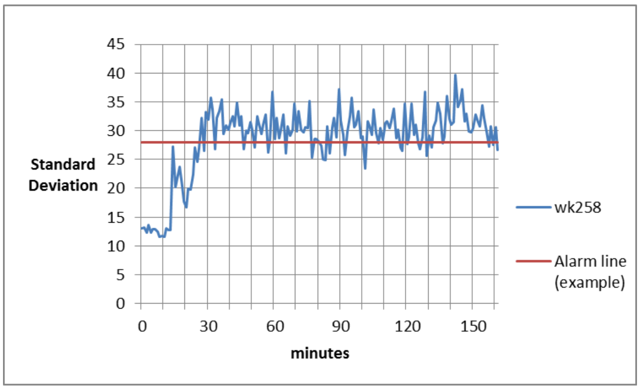

Figure 20: location 3 (wk258) standard deviations

The distinct difference in standard deviation after the valve changes on each well can be used as a means to detect undesirable flows such as slug flow. An 'alarm level' as shown in the graphs, could be defined, thereby allowing the sensor to act as a slug flow alarm.

6.0 CONCLUSION

Load cell sensors were successfully tested in multiple field trials at Wairakei steam fields, New Zealand. Suitable stands were built and modified as necessary to allow for the tests to proceed, and full datasets were taken from one and sometimes two load cell sensors at various field trial sites. Simulations of piping structures were completed and appeared to show that complex pipe stress phenomenon may not be a major contributor to load cell weight readings. Initial set values for the sensor may best be taken from historical information or standard well output tests, and from such values the sensor may be able to correctly track the trends of change taking place in the fluid flow. The four field trials all displayed different phenomenon, allowing for much knowledge to be gained on load cell sensor performance. The load cell sensor was able to measure results of every change done to the wells, with clear tracking of valve changes, and in at least one case was able to measure changes the well had undergone on its own. The sensor accuracy and data rate allow for determination of rapid transitions in value, from laminar flow to turbulent flow, and could be defined as a detector or alarm of such events. Full datasets were taken from four different field trial sites and will be used for further analysis. More information, such-as mass flow rate, may be determined from the datasets obtained.

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REFERENCES

Science Dictionary. (2014). Retrieved from http://thesciencedictionary.org/dryness-fraction/

Helbig, S., & Zarrouk, S. J. (2012). Measuring two- phase flow in geothermal pipelines using sharp edge orifice plates. Geothermics, 44, 52-64.

Grant, M., & Bixley, P. (2011). Geothermal Reservoir Engineering, second edition. Production Testing-Chapter 8 Elsevier Inc.

Arnold, W. a. (2013). Geothermal engineering : fundamentals and applications New York : Springer. 2013.

Outinen, J., & Mäkeläinen, P. (2004). Mechanical properties of structural steel at elevated temperatures and after cooling down. *Fire and Materials, 28*(2), 237-251.