Investigation and Application of Flashing Flow Nozzles to Mitigate Geothermal Turbine Life Reduction at Te Mihi Power Station

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Keywords: *steam impurities, turbine, flashing nozzle, steam separation, steam scrubbing*

ABSTRACT

Because flash steam is not completely dry after processing in the separation equipment, pipelines and demisters are used to remove the remaining moisture together with condensation formed during transmission. If they are not fully effective, the result is scaling of turbine inlet nozzles, erosive wear of turbine internals, corrosion of alloy blade paths and rotor forgings. This significantly reduces the economic life of steam turbines. This issue of poor steam quality and purity is common to many geothermal plants worldwide, and prevalent in stations with separators nearby.

Investigation determined that significant moisture travels downstream of the separators as droplets less than 10 micrometers in size. Preventing the formation of these small sized droplets results in a significant reduction of mist borne-impurities that are resistant to conventional methods of gravity, centrifugal or impingement separation.

Using the TRIZ (Theory of Inventive Problem Solving) methodology, a systematic review of 34 engineering options to improve the steam purity at Te Mihi Power Station was conducted. Importantly, this drew on knowledge from outside the geothermal industry. The main solution selected was the application of flashing flow nozzles instead of orifice plates, or control valves, to minimise the creation of droplets < 10 micrometers in diameter when producing flash steam. Plant tests following installation measured a significant reduction in the total mass of mineral impurities flowing through the Te Mihi Power Station low pressure steam system.

This was a low cost but effective improvement, avoiding invasive modifications to the steam system. Minimising the creation of droplets smaller than 10 micrometers is an important design consideration for future steam field and station developments around the world. Furthermore, the internal design of cyclone separators and transmission systems should avoid sharp edge flow shedding which can increase creation and entrainment of small droplets.

1. PROBLEMS FOR STEAM TURBINES

Scaling, corrosion, and erosion problems have been well documented in geothermal steam turbine installations (Morris and Mroczek, 2016). Effort has been made in many cases to reduce these problems by means of pipeline and turbine steam washing, or to manage their impact by selecting corrosion resistant materials. The International Association for the Properties of Water and Steam (IAPWS) provides guideline documents (IAWPS Technical guidance Document 5-13, 2013) based on years of research on conventional steam plant as to the conditions necessary to avoid scaling problems. The physical side of the problem is the same in any steam turbine – 1 gram of scale added to the turbine inlet is still 1 gram of scale no matter the steam source. While it is not possible to closely control water chemistry in geothermal steam as it can be in conventional steam plants, these guidelines do point at what is needed to avoid, or at least minimize, scaling rates. Doing so will increase availability at rated output, over the long periods between internal inspections and cleanings.

2. SEPARATION, DEMISTING, AND SCRUBBING

Generally the main consideration to steam cleanliness in geothermal installations is around the performance of separation, scrubbing, and demisting equipment (Mubarok and Zarrouk, 2016). Primary considerations in the design are usually around flowrate, pressure drop, and velocities. It is not clear in most post installation documentation how much consideration designers have given to droplet size and two phase flow regime when specifying separation equipment, process piping, control valves, and orifices.

The benefits of pipeline scrubbing to the cleanliness of geothermal steam have been known for some time (Stacey, Bacon and Empson, 1981). More recently, Arifen, Zarrouk and Kuriawan (2015), calculated how droplet size affects the removal of moisture in pipelines. The calculations demonstrated droplets smaller than 25 micrometers required excessively long pipelines to scrub out. Reviewing documentation from scrubbing and demisting equipment suppliers (Coastal technologies, ACS Separators, FILTERS®), their performance is also affected by droplet size and velocity. Separation efficiency falls rapidly for droplet sizes smaller than 10 micrometers when utilising density based separation such as centrifugal or vane type equipment. Filter based separation can remove smaller droplets, but at a large cost in pressure drop.

Washing systems need a significant water flow, often greater than 1% of steam flow rate. This is required to give sufficient spray coverage of the entire pipe flow, so small droplets can merge with the larger wash water droplets. The associated heat loss also allows smaller droplets to grow larger, improving the effectiveness of any density based separation downstream. There are costs to running wash water systems, sufficient clean low oxygen water is needed, the heat loss reduces the steam available for use, and the wash water can cause erosion to pipework and vessels.

3. MEASUREMENT OF SATURATED STEAM QUALITY AND PURITY

Measuring the steam quality and purity performance of the system is a difficult task, with it near impossible to get a true representative sample. Values measured only apply to the portion measured – assumptions must be made to infer the total mineral and moisture content in the system (Misa and Mroczek, 2017). Given the moisture content is not evenly distributed in a saturated steam system, results based on steam and condensate mineral concentrations are the best case scenario, assuming all of the liquid flow inside the pipe is being measured. The reality is actual mineral and moisture content in the pipe will always be more than that measured, as the film on the pipe wall cannot be fully accounted for. The best method for comparing the performance of a given system under varying conditions, is a combination of measuring bulk steam flows (Richardson, Addison and Thompson, 2013) and their mineral concentrations, plus measurement of condensate drain flows, and their mineral concentrations (Morris, Mroczek and Misa, 2019). The combination gives a total measured mineral content flow, indicating the minimum amount of carryover from the separators occurring. If this figure reduces, while liquid condensation rates remain constant, the steam purity has improved.

4. TE MIHI LP STEAM TURBINE SCALING

Te Mihi Power Station consists of two 83.5MW three flow turbines. Each unit has a dual flow IP turbine and a single flow LP turbine, all exhausting into a common direct contact condenser. The IP steam and water is separated in the steam field at 5.5 BarG and piped ~1km to the station. The IP separated water is flashed through segmented ball control valves and orifice plates at 0.3 BarG to provide LP steam. The LP steam is then piped 100 metres to scrubber vessels, and from there, 100 metres to the turbines.

Scaling was found to be a problem for the LP turbines, even though installed equipment was meeting design performance criteria for steam quality. In 2014, after less than 1 year of operation ~1 MW output loss could be measured and up to 5 millimeters of scale was found on the turbine inlet nozzles. The scale and mineral content had begun to cause corrosion pitting on the fixed and moving blading, as well as reducing output.

From 2014 to 2016, several changes were made to improve moisture and mineral removal. In some locations, catch rings were added to guide condensate on the wall of the pipelines to condensate drainpots. In other locations, additional condensate drainpots of good design (Morris, Mroczek and Misa, 2019) were added. Tests were conducted to evaluate the effect of the improvements made, and to determine the benefit of running a wash water system. These identified a small improvement from the modifications, and little to no improvement from running a wash water system. The wash water was largely removed by the drainpots and scrubbers, but the mineral content in the steam and drainpots downstream did not change.

5. TE MIHI LP FLASH PROCESS ANALYSIS

Analysis of plant data and inspection of the plant during outages found some interesting patterns. Directly above the orifice plates and flash valves a wear and erosion pattern could be observed (Figure 1). It appeared the normal opening of the segmented ball flash valves was intersecting the inner diameter of the orifice flow path (Figure 2). This caused the wear pattern on the manifold above to have a half moon shape to it, rather than being concentric to the orifice plate below.

Figure 1: During internal inspections biased wear and erosion pattern was found where flow from the orifice plates impacted the downstream separator inlet manifold

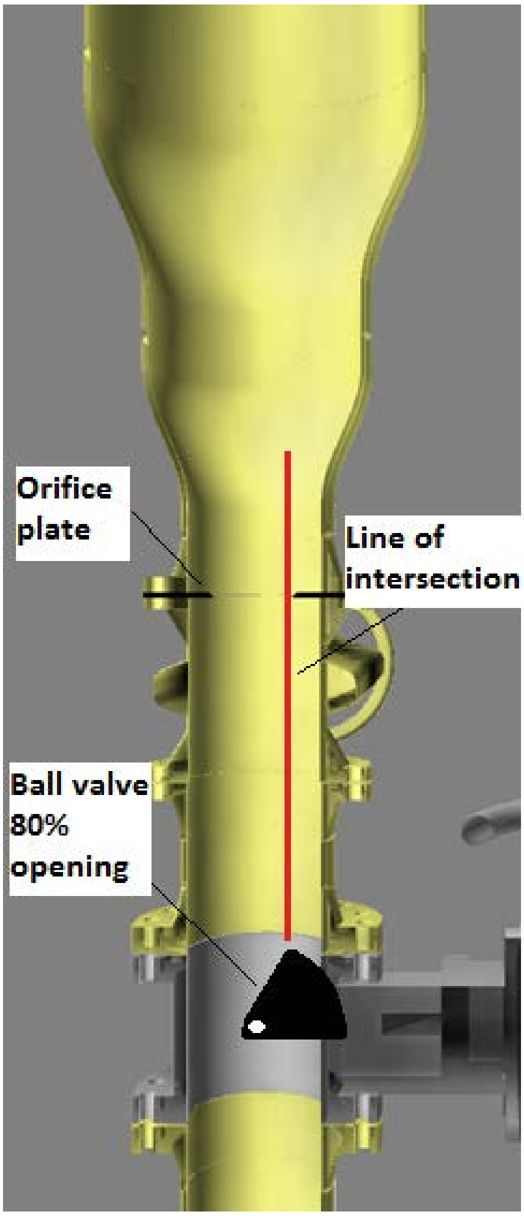

Figure 2: around 80% valve opening the segmented ball begins to cross the line of flow through the ID of the orifice plate. The throttling action of the valve was changing the spray pattern and droplet creation characteristics

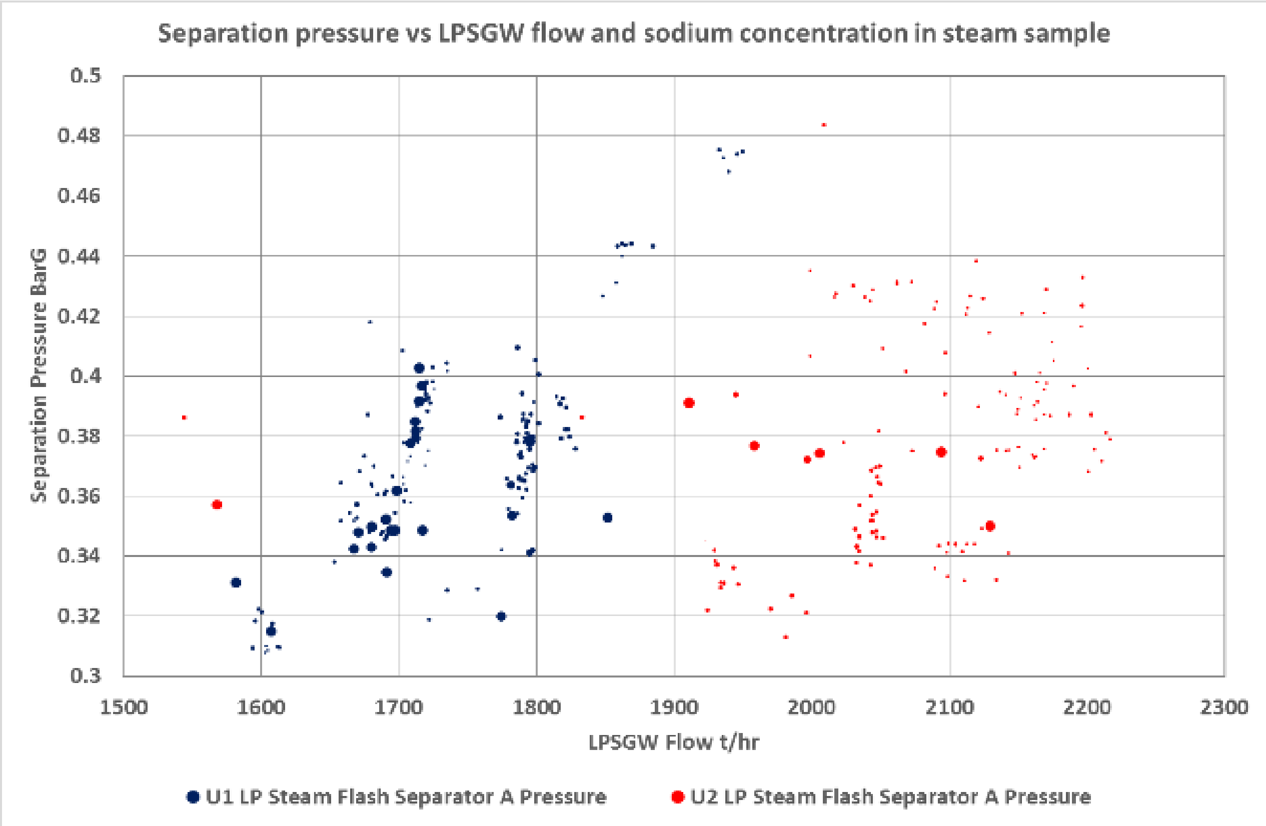

Figure 3: Bubble size represents LP steam sample sodium concentration – generally higher flowrates and higher pressures resulted in lower sodium concentrations in the bulk steam flow

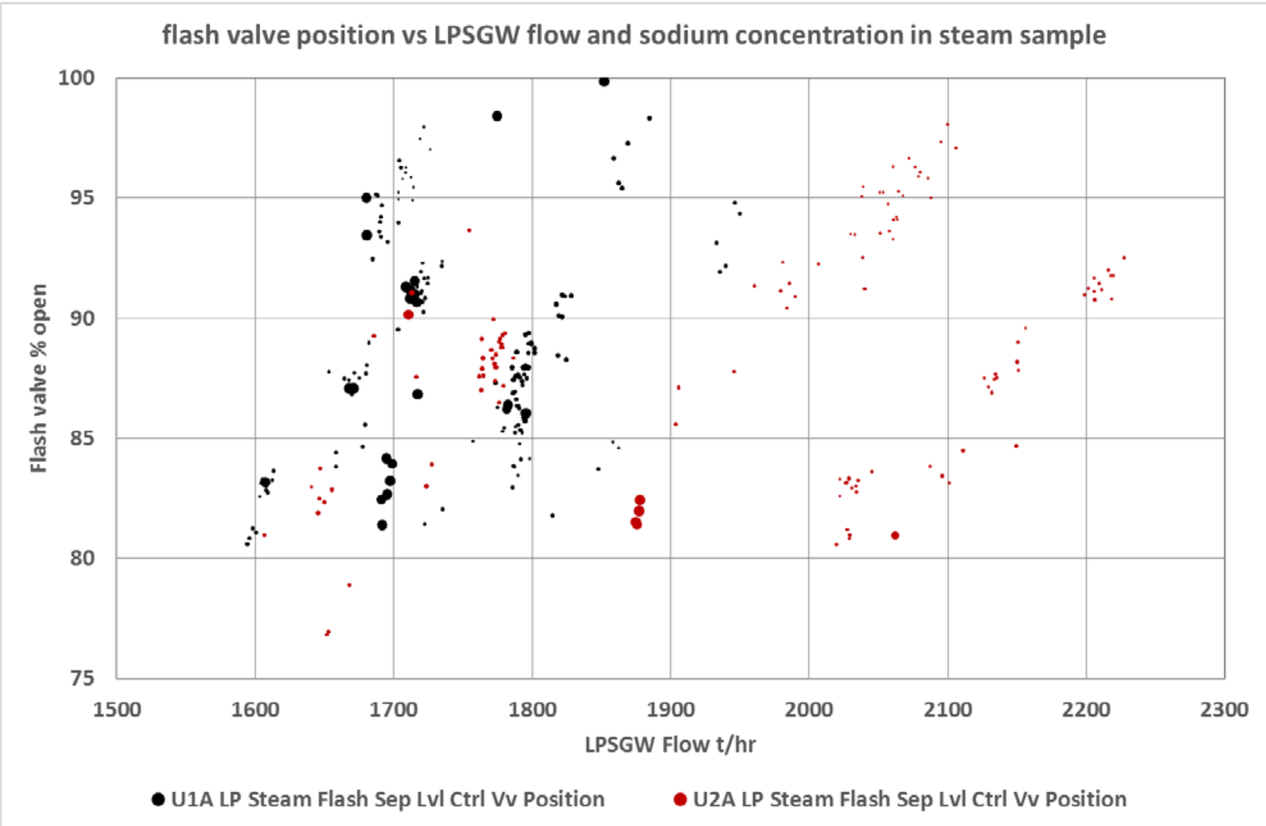

Figure 4: Bubble size represents LP steam sample sodium concentration – generally high flowrates and larger flash valve openings resulted in lower sodium concentrations in the bulk steam flow

Reviewing data from the plants online sodium analysers, with respect to valve opening and separation pressure, showed some trends. Generally larger valve openings, higher flowrates, and higher pressures resulted in lower sodium analyser readings (Figure 3, Figure 4). The best explanation found was that the segmented ball control valves were affecting the spray pattern and more small droplets were being produced – similar to holding your thumb over the end of a garden hose to create a spray rather than a solid stream of liquid.

A literature review was undertaken to understand what affects the droplet sizes produced in a flashing nozzle. This required looking outside the geothermal industry for information on sprays and nozzles. The majority of the information regarding sprays and nozzles is for single phase liquids (Schick 2008), but some information could be found on flashing or evaporating spray droplet sizing from process facility loss of containment modelling and other sources (Witlox Et. Al. 2009, Vu and Aguilar 2009). Information from the literature review provided a better understanding of the flashing and atomization process.

6. FLASHING AND ATOMIZATION PROCESS

The fluid starts as a subcooled liquid, upstream of the control valve and orifice plate. As it passes through the control valve and into the orifice, the pressure drops – vapour bubbles begin to form when the pressure drops below the saturation pressure for that temperature.

The bubbles expand rapidly, as the volume ratio of steam to liquid is very large. This rapidly increases the velocity, dropping the pressure further, and flashing off more steam. The two phase flow regime changes from primarily liquid to primarily steam as it flows toward the critical choke point. Downstream of the critical choke point, the fluid instantly drops below the critical choke pressure to the downstream pressure – this is the most rapid expansion of the flashing process and an inherent property of orifice plates.

The distribution of droplet sizes is produced by the breakup of the liquid portion through the entire phase change. Turbulence early on, including upstream of the flash location, creates more numerous, smaller liquid portions. These explode and flash off liquid mass to vapour, producing increasingly smaller droplets as the pressure drops.

In existing geothermal facilities, the fluid properties are fixed, and there are only limited changes that can be made to the process conditions for a given geothermal field. Minimising turbulence and slowing the expansion of flash steam downstream of the choke point, are the only means to increase to the size of droplets being produced. This is one of the few ways separation may be improved on existing flash plants, without the need for significant capital expenditure.

7. ENGINEERING OPTION FEASIBILITY REVIEW

TRIZ (Theory of Inventive Problem Solving) was used to help identify and consider 34 engineering options to reduce mineral transport to the Te Mihi steam turbines. This is a systematic problem solving and innovation method originating in Russia. There are now many practitioners using the methodology around the world, and a multitude of resources are available online.

The options were ranked upon consideration of cost, the time required to implement during an upcoming outage, risk of benefit failure. The most viable options were considered further. This was a qualitative review, as it was not possible to exactly define the improvement any option would give. Ratings had to be based on a combination of experience with each option, plant data from testing, and literature searches.

Option 1: Replace flash orifices plates with nozzles

These could bolt into the plant during a short outage, requiring no piping or other modifications. The nozzles would reduce the quantity of small droplets by minimizing turbulence and slowing the expansion downstream of the choking diameter. Literature review and analysis of testing at varying plant loads indicated significant improvement was possible, but no information regarding similar implementations on geothermal flash plants could be found. The implementation cost was low, but had significant level of uncertainty to the benefits

Option 2: Increase LP separation pressure

This would be achieved by restricting flow between the turbine and the scrubber vessel, to increase LP separation pressure. This option would require piping modification and result in a reduction in steam flow. Raising pressure by additional downstream restriction slows system velocity, improving separation and scrubbing. This would reduce total mineral quantity in the steam flow but reduce also generation capacity. This option has some certainty of providing improvement but would have a high cost in lost generation.

Option 3: Scrubber wash injection

Previous testing showed that to have a significant improvement, wash water would have to be injected at very high rates – reducing steam available and therefore generation. The volumes required would likely create erosion damage to pipelines and vessels, requiring expensive future repairs. Testing of the system resulted in 90% of the injected water begin removed in the drainpot prior to the scrubber with little additional mineral content. The installed system would have to be modified to perform better, this had a significant uncertainty to its outcome.

Option 4: Scrubber modification

The plant would need to be out of service for a significant period to complete any modifications. Outage time has a large cost, and there was significant uncertainty in improvement from this modification path because of the small droplet sizes.

Option 5: Separator modification

Similarly, the plant would need to be out of service for a significant period to complete any modifications. There was a reasonable level of confidence in making some improvements, but the outage time and cost of the work would be very high.

Option 1, changing from orifice plates to nozzles, was determined to have the largest potential for improvement and the lowest cost to implement. This was sufficient to outweigh the uncertainty in using an unproven method and justify the modification.

8. IMPLEMENTATION

8.1 Criticality of sizing and design features

Sizing of the nozzle throat was critical – too small and the flowrate would be insufficient to meet the required capacity; Too large and the upstream control valves would close in too far to control the system, adding unwanted turbulence, breaking up the liquid portion of the flow, and causing more small droplets to be produced.

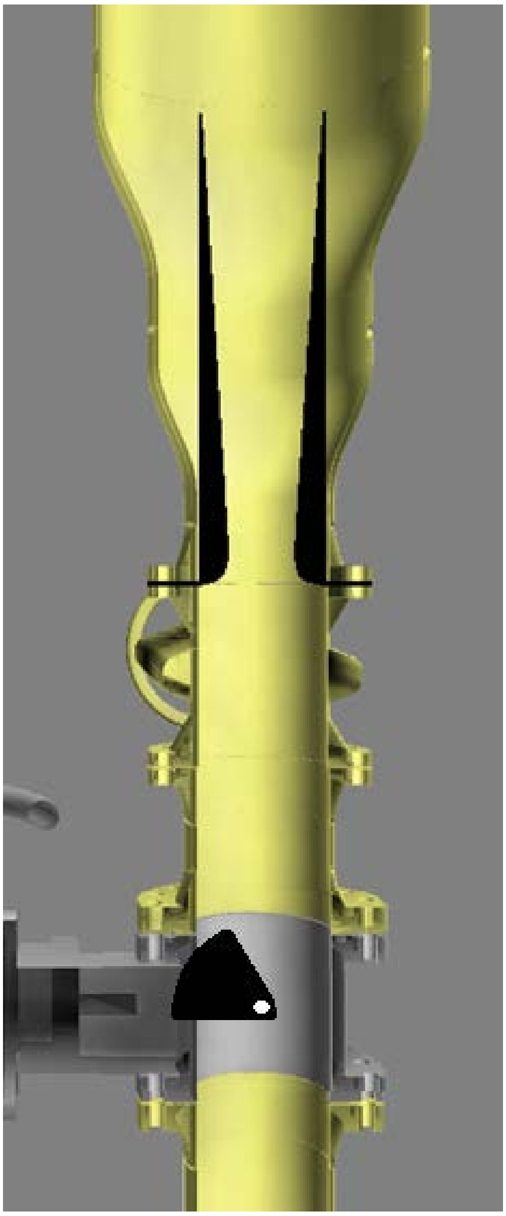

Figure 5: Sharp edged orifice plate replaced with "top hat" profiled nozzle designed to bolt into orifice plate location without piping modification

8.2 Two phase sizing methods

Sizing was carried out using two methods for calculation of two phase flow rates through nozzles. Cranes method outlined in Flow of Fluids Through Valves, Fittings and Pipes (Crane 1988), and the Omega method outlined in Guidelines for Pressure Relief and Effluent Handling Systems (AIChE 2017). These are proven methods for sizing of nozzles for safety valves, both gave very similar results.

8.3 Design features and considerations

One of the main factors in choosing this option was that the orifice plates could be removed and replaced with nozzles during a short three day outage. Due to the design of the plant, a spool piece and the control valve could be removed giving a maximum length for the nozzle of 900 millimeters. Ideally, to slow the expansion process, there would be a shallow taper less than 7 degrees from the choke point to the downstream piping diameter.

Upstream, a toroidal shape was chosen to minimise turbulence, without unduly affecting the length available for the downstream expansion section. The "top hat" design (Figure 5) could then be placed inside of the riser pipework, and the control valve and spool piece installed. The downstream diverging section of the nozzle was given as shallow an angle as possible with the space available. By extending the diverging nozzle the expansion of the vapour portion is slowed down and turbulence is reduced.

9. TESTING AND PERFORMANCE ANALYSIS

Before and after installation, steam flow was measured on plant instrumentation, and mineral analysis for sodium was completed on numerous samples. Samples were taken from the following locations – the upstream supply of brine before flashing, direct steam samples from fixed isokinetic probes, condensate drains before and after scrubber vessels, and flashed brine leaving the separators. Condensate drain flows were measured from each drainpot to allow a mineral flux in grams per hour of sodium to be calculated.

Following flash nozzle installation, the steam flows were found to be within 5% of the design values. A good result given the bespoke geometry. The results of the sodium analysis showed significantly less minerals were making it from the separators through the steam lines and scrubber vessels (Table 1). Both steam samples and condensate drain samples showed similar trends. Previously, drain samples were found to be lower at the drain immediately upstream of the scrubber, than the drains after the scrubber. Those results suggested droplets of carryover were making it through the scrubber, and were being collected further downstream. Following the nozzle installation, this reversed, suggesting

Table 1: Results of plant testing for steam mass flow rate, sodium concentration, and flux

	After plant commissioning	Overload condition with additional drainpots	After nozzle installation	Comparison with IAPWS steam purity standard
Separation pressure BarG	0.33	0.4	0.3	0.3
Steam Flow kg/s	51.4	55.7	51.3	51.3
Steam to turbine				
sodium concentration mg/kg	0.029	0.031	0.01	0.002
sodium flux g/hr	5.36	6.22	1.85	0.37
Last drainpot before station				
flow L/hr	63	41	49	N/A
sodium concentration mg/hr	3.47	6.3	2.6	N/A
sodium flux g/hr	0.22	0.18	0.13	N/A

more of the carryover was being caught on the walls of the piping upstream, and inside the scrubber vessels.

9.1 Vibration and noise

An unplanned improvement was a significant vibration and noise reduction. Previously, sound levels on the work platform adjacent to the orifice plates were over 90 db. There was also a periodic churn or slugging flow which would shake the piping, vessels, surrounding platforms, and equipment. Following the nozzle installation the sound level was reduced nearly 10 db, the slugging flow stopped, and the overall vibration level reduced by two thirds. This vibration reduction is a valuable improvement to equipment life in the long term.

10. CONCLUSION

A thorough review of a wide range of engineering solutions provided the necessary confidence to apply a novel solution to a difficult problem. Replacing sharp edged orifice plates with flashing flow nozzles resulted in a significant improvement in steam purity at Te Mihi Power Station. Reducing turbulence and rapid pressure drop in two phase and saturated steam systems, decreases the amount of droplets smaller than 10 micrometers that are difficult or practically impossible to remove. Replacing the orifice plates with nozzles also reduced sound and vibration levels significantly. Relatively minor changes in geothermal piping design and process control have the potential for significant improvement, or detriment to steam purity.

ACKNOWLEDGEMENTS

The authors would like to thank Contact Energy Ltd. for permission to publish this paper and the Contact staff involved in the works conducting testing, development and implementation of the project.

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