Testing of cyclone separators and steam pipelines for separation and scrubbing performance

Tom Misa[1], Ed Mroczek[1]

[1]Contact Energy, Wairakei Power Station, Private Bag 2001, Taupo 3352, New Zealand

[2] Wairakei Research Centre, GNS Science, Private Bag 2000, Taupo 3352, New Zealand

tom.misa@contactenergy.co.nz, e.mroczek@gns.cri.nz

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ABSTRACT

Testing for separation and scrubbing performance was undertaken on Intermediate Pressure (IP) and Low Pressure (LP) steam systems of a geothermal steamfield and power station. Testing was completed at a number of process conditions to determine what operating conditions caused changes in separation and scrubbing performance.

A suite of steam and separated water flow measurements were used in conjunction with changes in natural sodium and injected fluorescein carryover to observe the effect on plant performance. Results showed an unexpected significant holdup time of the added tracer, separator performance below design and the effects of flow regimes and geometries on system performance. Difficulties and benefits of completing this type of testing on operational industrial plant are discussed.

1. TESTING ARRANGEMENTS

All three plants tested consisted of large dual cyclone separators of greater than 3m diameter. The arrangement of each plant is different and required differing tracer injection arrangements.

1.1 IP System tests

Both IP separation plants are supplied by two sources of 2 phase fluids from a number of wet and dry steam wells. The inlet arrangements and available pipeline connections meant tracer injection into a common point was not possible. Testing was conducted with injection to one supply or the other during the testing but it was not practical to complete a full suite of tests with injection at each location. Injecting rhodamine as a second tracer into the other supply was considered but was not able to be arranged for this test program.

Similarly the arrangement and available pipeline connections on the steam and IP separated geothermal water (IPSGW) pipework for sampling dictated that each pair of separator vessels must be treated as a common unit in terms of separation performance. Some differences in vessel flows or performance can be inferred but to carry out any calculations it was necessary to assume the similarity of mixing and fluid supply to each vessel.

Steam flows were changed for testing by throttling in wells supplying each separation plant. Differences in steam piping and drainpot configurations between the two flash plants mean not all performance measures could be calculated in every case.

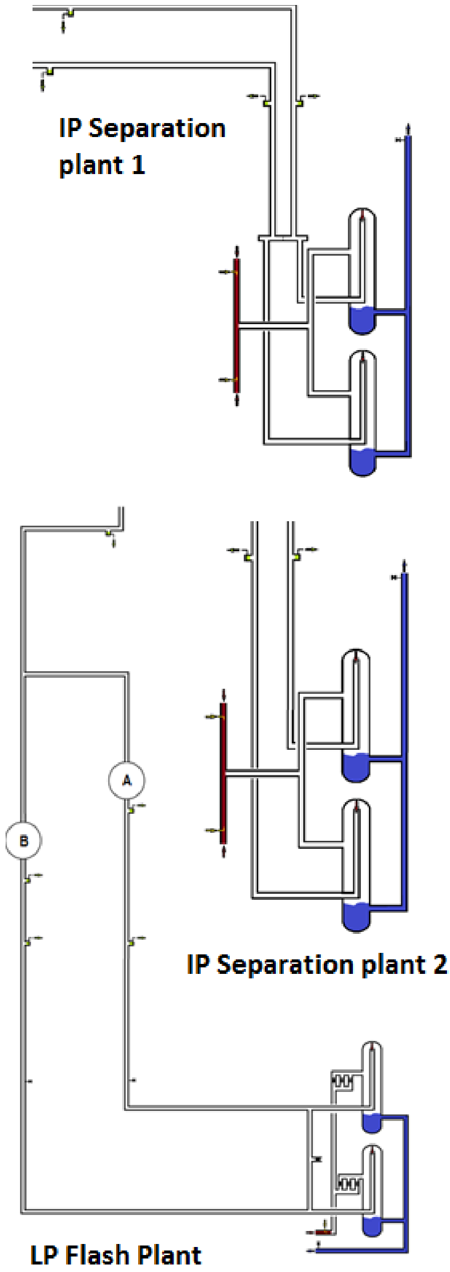

Figure 1 – All three separation plants tested had differences in process flow paths and piping geometry in addition to pressure and flow conditions.

1.2 LP System tests

The LP flash plant is supplied with the separated water from the two IP separation plants. The temperature and pressure are measured, so the enthalpy of the supplied fluid is known. Fluoroscein was injected into the IPSGW flow prior to being flashed through a pair of control valves and orifice plates for each vessel.

2. PROCESS AND OPERATIONAL CONSIDERATIONS

Conducting testing in a commercial facility presents a number of challenges. Effects of test conditions on plant output, the work and time required to set plant to each test condition and return to normal operation at the conclusion of testing have to be accounted for and planned well in advance. In addition, complying with electricity trading rules means there is no room to postpone or extend testing windows due to delays or unforeseen consequences, without making reductions in output for greatly extended periods. Doing so would add very significant costs to the testing in lost generation.

How flow changes are made affects flow regimes and plant performance. i.e. in the case of separation plants fed by two phase and dry steam wells, the flow regimes in the supply pipework can change dramatically. The ratio of steam to water, and pipeline velocities change depending on whether wetter or drier wells are throttled to make changes. Similarly with flash plants, changes in flow supplied alters the velocity in downstream piping and depending on the control methodology, the pressure and flash fraction downstream of the flash valve or orifice will also be affected.

3. BENEFITS TO CONDUCTING TESTING ON OPERATIONAL PLANT

By completing tests on the system as installed, response of the actual system can be measured rather than using an assumed, modelled or theoretical response to predict or explain the effects resulting from operational changes.

By recording these tests, further understanding of what can be tested or understood from measurements during normal operation is gained. Actual response time of the real system to changes can be monitored which allows future testing or testing of similar systems to be better planned.

Benchmarking plant performance enables better use of permanently installed online measurements to control the process, or understand the effects of off design running.

Understanding plant through such tests ultimately results in efficient generation through minimisation of the serious deleterious effects of poor separation and inadequate steam scrubbing.

4. MEASUREMENT CONSIDERATIONS

In addition to the test measurements, a number of installed plant instruments were used to analyse the system performance and enable calculation flow rates and flash fractions. Additional scrutiny of these measurement points was undertaken as the accuracy requirements of instruments for plant monitoring is lower than test instruments. Furthermore, most instruments in continuous geothermal service are subject to scaling, corrosion and other potential causes of error. Therefore the validity of all measurements in plant monitoring use must checked through a thorough knowledge of instrumentation, plant and processes.

4.1 Pressure transmitters

Pressure transmitters were cross checked against others in the same system at times when the system was out of service. This was necessary to check their zero calibration, enabling corrections to be applied to the recorded numbers or identify any clearly incorrect values. Transmitter data sheets were consulted to understand accuracy limits of the installed instruments. This was especially important in the LP steam system where small changes such as 0.05Bar are a significant percentage of the total pressure available in the system.

4.1 Flow measurements

Permanently installed vortex steam flow meters, ultrasonic separated water flow meters as well as correlations for steam flow for given turbine inlet pressure were compared to determine the most reliable measurement for the analysis. Pressure and temperature measurements were used to determine flash fractions and compare the measured flows directly or by summation. Flows were also calculated from the tracer injection but it appeared that in most cases unsteady separator inlet flows affected the accuracy and validity of those results when considered over an entire testing period. This highlights a significant issue in understanding the results of any testing on systems with potentially unsteady two phase flow regimes.

5. EVALUATION OF SEPARATOR EFFICIENCIES

5.1 Fluorescein and natural sodium tracer

The high concentration of sodium (Na) in geothermal fluid means that this natural tracer can be used to evaluate separator efficiencies. This is achieved by measuring the Na flux in the condensate discharged from steam-line drain pots at different separator mass loads. Na in LP steam upstream of the drain pots was sampled using fixed isokinetic probes. However, isokinetic sampling of wet steam does not give a reliable estimate of the total Na carryover. This is because the mineralised water and scrubbing is often close to, or on the walls of the pipelines as a microns thick layer. This is not where the isokinetic probes sample from (Morris and Mroczek, 2015; 2016). The Na was analysed by ICP-OES (APHA, 2012A) to detection limit of 0.02 mg/L and at low levels to 0.005 mg/L by Atomic Absorption Spectrometry (APHA, 2012B).

To complement the natural tracer fluorescein (disodium salt; FL) was injected upstream of the separator plant. This dye was selected as the tracer for the following reasons: it would not interfere with the on-going naphthalene sulfonate (NDS) tracer tests; it is strongly fluorescent, making detection possible even under highly dispersive conditions expected from the small SGW carry over into steam; it is stable and not easily affected by geochemical changes or temperature; it readily disperses and is not adsorbed by scale and other materials; it has low environmental toxicity (non-toxic) and is readily available at relatively low cost (Smart and Laidlaw, 1977; Adams and Davis, 1991; Hirtz et al., 2001; Turner Designs Fluorescein Application Note). In this application, it was considered to behave conservatively.

The two disadvantages of FL are that it is rapidly destroyed by sunlight and the fluorescence is pH dependent. All samples were stored in buckets and only removed from storage for analysis. The pH of all samples and standards was adjusted to be in the range pH 6 to 10 by addition of 0.1M sodium hydroxide. No attempt was made to adjust the solutions to a specific pH as long it was in the correct range. Practically as the steam condensate samples were all at similar pH, the same amount of hydroxide was added to all, achieving a final pH typically between pH 6.5 to 7.5. No background correction is required for FL analysis in the geothermal water.

All FL samples were reliably analysed using a hand-held Turner Designs AquaFluor fluormeter, minimum detection limit 0.4 ppb and dynamic range 0 to 400 ppb. The intention was to analyse samples in the field. However, this proved impractical, except for determining tracer breakthrough, due to the large number of rapidly accumulating samples collected from multiple drain pots.

5.2 Injection and sampling

The injection of tracer was undertaken with a precision Milton mRoy series hydraulic motor driven diaphragm metering pump. The rate of tracer injected was determined by weight loss using a precision industrial bench scale (A&D GP-12K; 12 kg capacity 0.1 g resolution). Injection rates varied between 3 and 4 kg/hr.

Once the power station/ flash plant mass flow had stabilised, samples for Na were collected from incoming 2-phase fluid at the tracer injection port and in the separated water (SGW) downstream of the separator and from all the drain pots. The injection of tracer then commenced and the drain pot flows were measured (bucket and stopwatch). After about 30 to 45 minutes (after tracer was shown to be present in the condensate), drain pot sampling for tracer commenced and continued at approx. 15 minute intervals and the SGW was also periodically sampled for tracer.

The tracer was injected via a quill inserted either inserted vertically into the top of the 2-phase line or in the bottom of the pipe at 45° down from the horizontal.

5.3 Results

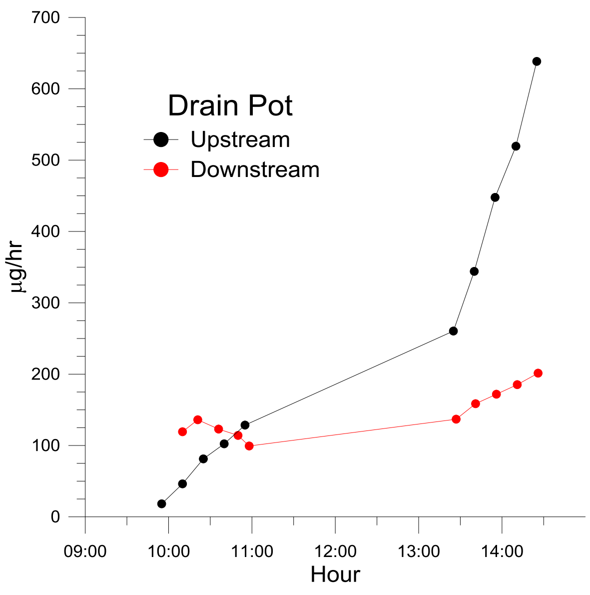

Figure 2 - FL tracer flux in an upstream and downstream drain pot of one steamline

The result of the Na tracer are summarized in figures 3 to 14 below. However, in these series of test the FL results could not be used to calculate the separator efficiency. For a particular mass loading the FL tracer results were consistent for a particular drainpot as well as when compared with the trends observed further upstream and/or downstream in the steam line. They also matched the changes in the Na tracer e.g. where Na increased so did the FL. This gives confidence in their reliability however typically the FL carryover were up to ~100x less than the Na. This was most likely due to the tracer concentrations not reaching steady state in time available for each test or being otherwise held up in the system which if correct is of interest in itself. Drainpot FL tracer flux in the afternoon tests was significantly higher than in the morning. Figure 2 shows a typical result, with apparently no correlation with mass flow to the separator. The increase in tracer recovered in the afternoon tests is thought to be more likely due to tracer hold-up in the circuit rather than a reflection of the operating condition of the plant as FL readily disperses and is not adsorbed by scales or other materials.

The injection of the tracer was undertaken into ports which were not ideally or consistently placed for this purpose, with some vertical and others angled. The large mass flows immediately before the separator into which the Fl tracer was injected were phase segregated. But the segregation zone shifted depending on the mass flow. So at times the Fl injection was into steam, into a mixture with varying fractions of water through to almost separated water (depending also on quill depth and angle). How the fluids enter the separator affects the carryover efficiency but also how the tracer mixes and disperses. Tracer injected into the segregated steam may be carried over into steam line in a different rate and concentration than when injected into the segregated water or into a well mixed 2-phase mixture. Na tracer appears less affected as the fluids are close to steady state concentrations at all times.

Future tests are intended and will be programmed over a longer time period so that the tracer carryover is not confounded by fresh tracer injection mixing with “held up” tracer.

6. MEASURED PERFORMANCE

6.1 Total Na flux

Total mass flux of Na measured was calculated from the samples taken. Multiplying the flowrate at each drainpot by the measured concentration giving an amount of sodium collected for the given time period.

Where taken, the measured Na concentration in the steam from isokinetic probes was multiplied by the steam flow rate. An assumption was made that the measured concentration in the steam changes little as it travels down the line over the lengths being considered (<500m) (Arifen, Zarrouk and Kuriawan 2015, Stacey, Bacon and Empson 1981). In the LP testing, isokinetic measurements were taken at upstream locations but unfortunately the downstream online sodium analyser was not operational at the time of testing. Comparing the results from the upstream measurements to downstream measurements from the online analyser at similar process conditions at later dates showed this to be a reasonable assumption.

6.2 Separation efficiency by measured total Na flux

Summing the total grams per hour of Na measured in drainpot and grams per hour of Na in the steam flow, then dividing by the concentration measured in the separated water gives the flow rate of carried over brine. Summing the flow of brine carryover with measured steam mass flow gives the total flow in the steam line. Dividing the steam flow by the total flow in the steam line gives the separation efficiency. Note this number is a maximum. Actual Separator performance must be worse than this figure, as it is known that the drainpots and scrubbers are not 100% efficient.

6.3 Condensation collection rates

The rate of condensate and brine mixture measured in the drainpot flows and scrubber vessel collection largely reflects heat loss. Approximately the same amount of condensation will be produced for a given steam temperature regardless of the flowrate in the line, provided the pressure drop is minimal.

Increases in steam flow will result in a proportional percentage increase in additional brine carryover if separation efficiency is assumed to be static.

Changes in condensation collection rates are directly proportional to efficiency of total moisture removal for a given steam temperature and ambient condition. For the testing carried out, only the one of the LP tests had a significantly different temperature to the others on that system.

6.4 Condensate Na concentration

The concentration of Na in condensate samples directly measures the ratio of carryover to condensation collected by the drainpot. If all condensation formed and carryover in the pipeline were a homogeneous mixture at each sample location, the concentration measured would increase proportional to steam flow (for a given temperature). This would be because a larger amount of carryover would be mixing with the same amount condensation.

The reverse of this implies a decrease in measured concentration at a given sample location means less mixture of carryover with condensation is occurring, meaning poorer scrubbing performance. This is a primarily the case for the first drain following a separator, the concentration at subsequent drainpots will be greatly affected by changes in removal efficiency of those upstream under different flowrates.

6.5 Steam sample Na concentration

The Geothermal fluids are flashed below or above ground, piped as combined two phase fluid and then separated. Each of these processes can potentially create small droplets or conglomerate them. These very small droplets are not greatly affected by gravity or changes in direction and take long periods of time to scrub out (Arifen, Zarrouk and Kuriawan 2015, Stacey, Bacon and Empson 1981, Morris and Mroczek, 2015; 2016). The very low concentration of Na in isokinetic steam samples (< 0.04 mg/L) reflects the small number of these very small droplets remaining in the steam following those processes. However, all the dissolved minerals measured in the droplets are going to flow all the way to the steam turbine inlet. Any other brine carryover travelling near or on pipe walls will be in addition to this. This boundary layer or pipe wall portion is difficult to measure with any certainty, especially as velocities increase.

6.5 IP Separation plant 1 results

Velocities for drainpot flows at IP Separation plant 1 are shown based on individual steam line flowrates, total or general values shown at average velocity of the two steam lines. Na concentration in steam was not measured at IP separation plant 1 so efficiency was determined only from measured drainpot Na fluxes.

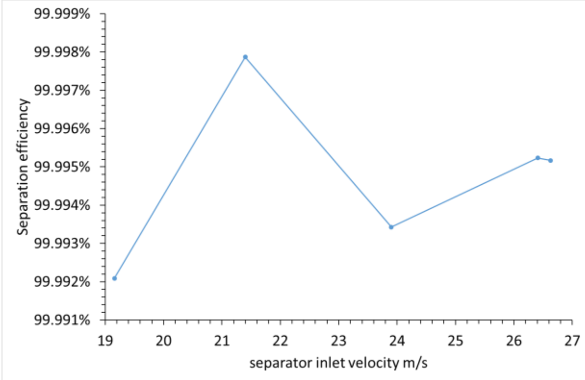

Figure 3 – IP Separation plant 1 efficiency. Note that change in efficiency from 99.992% to 99.998% reflects a 75% reduction in carryover per ton of steam

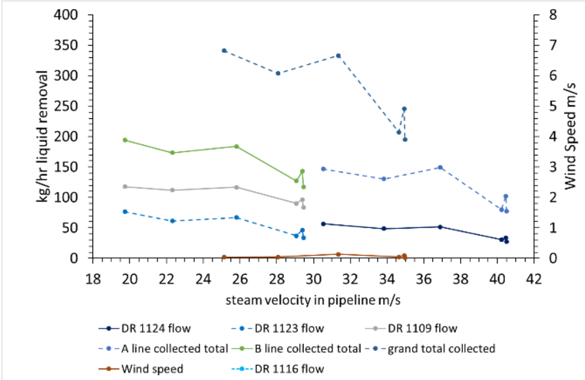

Figure 4 - IP Separation plant 1 liquid removal. Collection volumes can be seen to change with steam line velocity and pipeline heat loss due to ambient conditions.

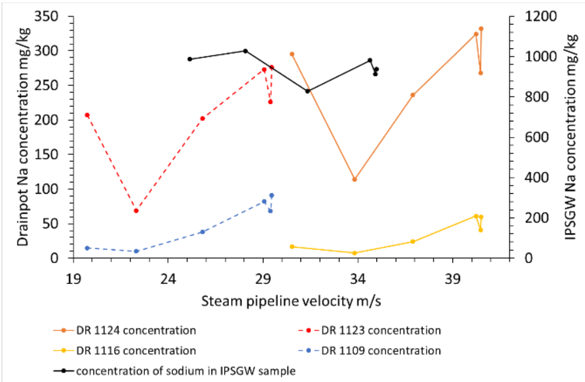

Figure 5 - IP Separation plant 1 Na concentrations. The general trend of increasing drainpot concentrations at a higher rate steam flow increase suggests separation performance is deteriorating with increasing flowrate.

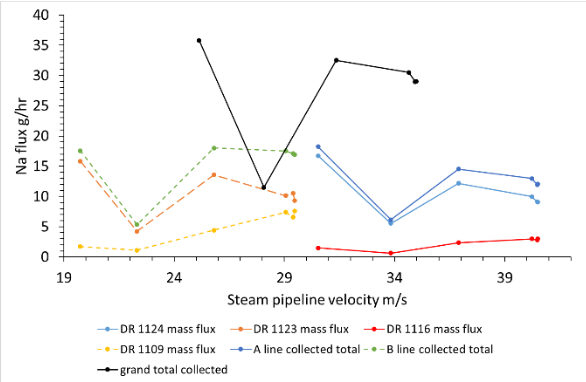

Figure 6 - IP Separation plant 1 Na mass flux results. It can be seen that under one of the tests the carryover measured was half that measured under the other test conditions and was reflected in all four drainpots to a greater or lesser extent.

6.6 IP Separation plant 2 results

Velocities for drainpot flows at IP Separation plant 2 are shown based on individual steam line flowrates, total or general values shown at average velocity of the two steam lines. Na concentration in steam was not measured so efficiency was determined only from measured drainpot Na fluxes. Steam flows for the two lines and separators were almost the same so the average figure has been used for all tests here.

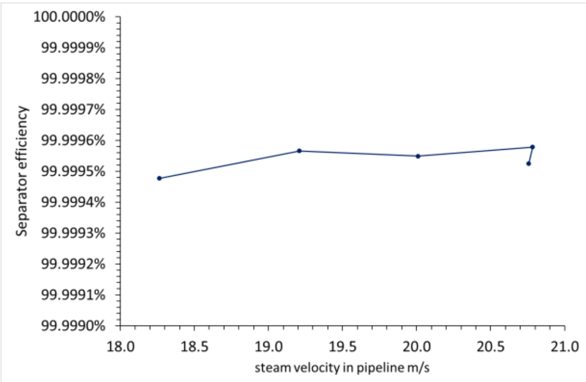

Figure 7 – IP Separation plant 2 efficiency. Only two drainpots could be measured for these tests and as they are situated close to bends so their efficiency is much lower than those in the IP Separation plant 1 tests. This is likely why the measured efficiency is markedly higher – much of the carryover is travelling past these drains.

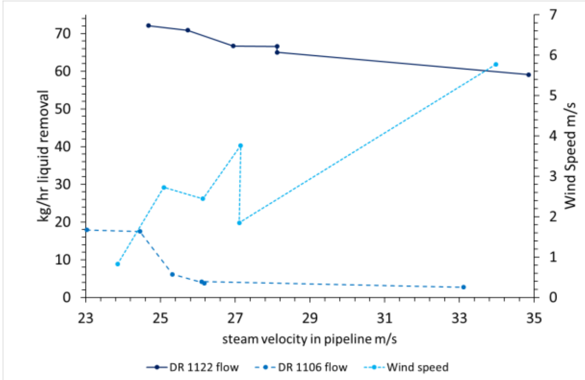

Figure 8 – It can be seen Drainpot DR1106 is ineffective at collecting condensate and carried over brine. Both drainpots are reducing in performance as velocity increases.

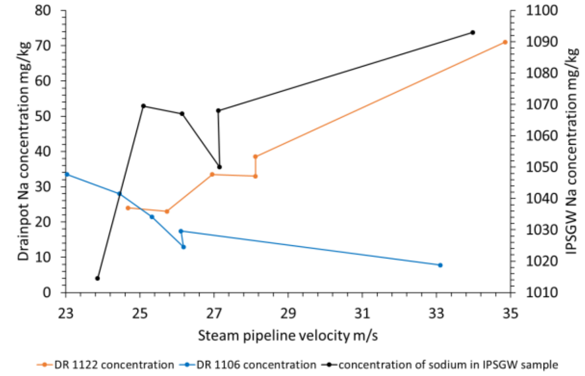

Figure 9 – IP Separation plant 2 Na concentrations. DR1122 values show separator carryover is increasing with steam flow rate as concentration triples for a 50% increase in flow. DR1106 is reducing markedly in performance with increasing flow. Most of the measured flow is steam condensed in the drainpot itself rather than collected from flow in the line.

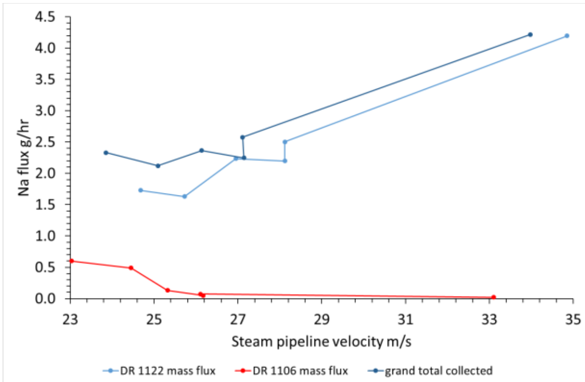

Figure 10 – IP Separation plant 2 Na mass flux. Highlights the marked difference pipeline geometry can make on sampling results. Both separators and steamlines have similar steam flow and conditions, while the difference of 5 fold at lower flows might be plausible, 200x at 30% higher flow is highly improbable, and indicates carryover is bypassing this location under those conditions.

6.7 LP Flash plant results

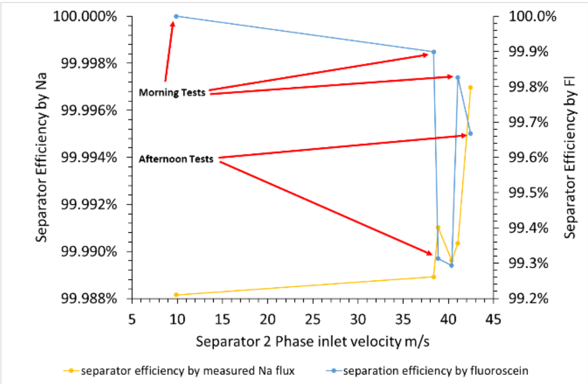

Figure 11 – LP Flash plant Separation performance. Inconsistencies in results from fluorescein tracer can be seen. Increase in efficiency show at the highest flow is likely false, and due to reduction in scrubbing performance markedly affecting measurements.

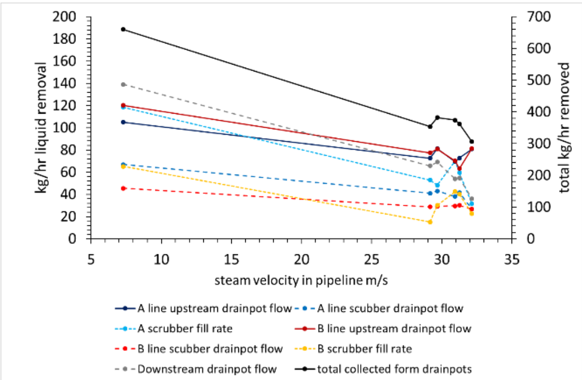

Figure 12 – LP Flash plant liquid removal results. Results at lowest flowrate are for the 2.0BarG test which has half the steam flow and a much higher steam temperature. At the highest flow rate all except the upstream drains markedly reduce in collection performance.

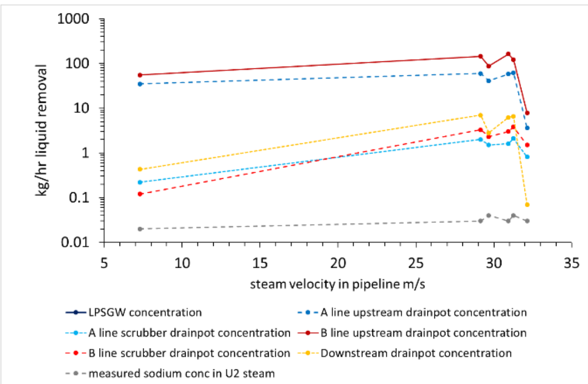

Figure 13 – LP Flash plant Na concentration results. At the highest flowrate concentrations markedly drop, implying mixture of carryover and pipewall condensation has reduced significantly.

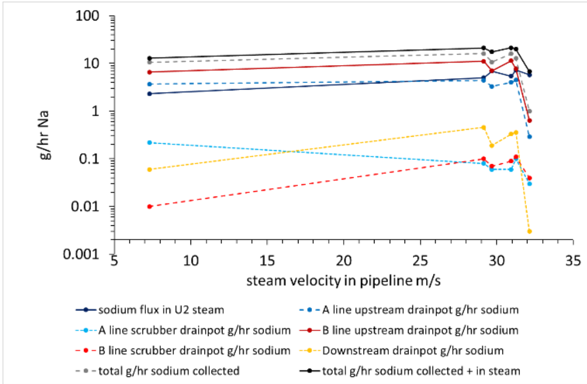

Figure 14 – LP Flash plant Na mass flux results. Large reduction in Na mass flux measured in drains further highlights the reduction in scrubbing performance. Na mass flux measured in steam decreases slightly at the highest flowrate, suggesting there may be an improvement in some aspects of separation efficiency.

7. DISCUSSION/FINDINGS

7.1 Stabilisation/holdup time

Steam is travelling in these lines at velocities of 10-40m/s giving travel times from the tracer injection points to the drainpots in the range of 20-60s. Time to exchange 100% volume of fluid in the separator and associated piping is in the range of 30-120s.

Given the finding of tracer being present at the drainpots two hours after ceasing of injection implies some amount of carryover is travelling very slowly. In the given testing, this would be in the order of 1m per minute. Alternatively, the carryover is remaining somewhere in steam lines and drainpots, not mixing with condensate for several hours. In either case, this means carryover is not fully mixing with steam condensation in the system tested.

7.2 Process and operational factors

Two phase separator inlet, and outlet steam line velocity are functions of the volume flow rate and system geometry. Both go up and down together, but have opposite effects on overall performance.

Steam samples in the LP system do show a reduction in Na concentration with increasing steam flow rates. This could either be due to an improvement in separation of smaller droplets at higher cyclone velocities or effects of changes in two phase flashing and flow regimes at higher flows creating fewer small droplets.

It is difficult to determine what the impact of the individual factors are in this situation. The combined effects of pressure, flash fraction, volume flow, condensation rates, geometry (for both separator inlet and steam line scrubbing) are all tied together and usually change concurrently; e.g. higher separation pressure will result in higher temperatures, more condensate production, and lower velocities for the same mass flow into the separator as well as a lower flash fraction so less steam flow out of the separator.

7.3 Other factors

In the specific case of the very low separation pressures in this LP flash plant, two other factors may also have important effects on separation and scrubbing performance

At very low pressures the rate of change of densities of fluid and gas diverges markedly (Figure 15). The implication of this is that for the same mass flash fraction the volume fraction of each fluid is markedly different. This will have a large impact on flow regimes and puts the flows in such lower pressure systems on the edges of most flow regime maps.

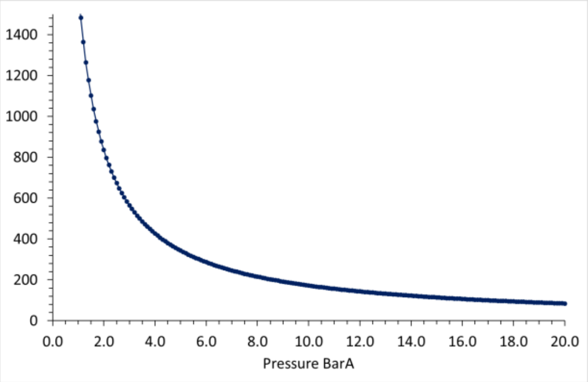

Figure 15 – Water density to Steam density ratio at saturation pressures from 0bar to 20Bar

Traditionally in geothermal systems, steam is usually flashed in two ways. Gradually as pressure drops with flow up the wellbore and two phase pipework feeding a separation plant, or at a single point through a fixed orifice plate or modulating control valve. The flashing process itself is very good at creating small droplets and is used in other industries for that and other purposes (Vu & Aguilar, Witlox et. al., Waxman et. al.) A sudden flash and expansion at a single restriction may be more likely to create these small and difficult to remove droplets than the more gradual boiling from pressure drop along a length of wellbore or piping. This is an area for further consideration in future steam field designs.

CONCLUSIONS

Accurate testing of separator and scrubbing performance on running geothermal facilities is difficult to achieve, due to the miniscule volume fraction of the liquid carryover and condensation present. Careful interpretation of separator and scrubbing test results is useful in directing the operation and design of geothermal steamfields. This is important, to minimise mineral and moisture carryover to steam turbines, so performance and longevity of the equipment can be maintained (Morris & Mroczek).

While separation efficiency could not be determined via the fluorescein tracer in this testing, the holdup time found may be a useful measurement tool in future. Using the delay time and quantity found in isokinetic steam samples vs. drain flows could to help quantify droplet sizes, mixing of carryover with condensation or distribution of carryover inside the steam pipeline.

Steam line and drainpot design has a very large effect on scrubbing performance. Increasing steamline velocity always reduces scrubbing performance and increases mineral loading on turbines for a given level of separator performance. Well designed and located scrubbing and drainage equipment suffers dramatically less performance deterioration under increased velocities than less than ideal designs and locations.

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