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Review of Steam-Water Separator Performance Testing

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ABSTRACT

A review of theoretical calculations and test results for geothermal steam-water separator performance is presented. An overview of different test methodologies is given, including a discussion of their limitations, potential parameters that might influence their results and relevance to plant process conditions. The implications of separation performance test for equipment suppliers and plant owners are discussed.

1. INTRODUCTION

Vertical Bottom Outlet Cyclone (BOC) steam-water separators used in many geothermal fields follow the design notes published by Bangma in 1963 and Lazalde-Crabtree in 1984 (Rivas-Cruz et al., 2015). Bangma provided field measurements and Lazalde-Crabtree described an empirical approach to calculate the dimensions and efficiency of a BOC Separator based on calculated two-phase flow conditions in the inlet piping. The success of this type of separator is its simplicity and high separation efficiency (Rizaldy et al., 2016), commonly reporting steam-water separators efficiencies of 99.95% or higher (Watson, 2013).

A separator is the first stage of two-phase geothermal fluid separation, and its performance is widely recognized to be vital to ensure only steam with low mineral contamination enters to the steam turbine to avoid scaling and corrosion on turbine blades and auxiliary equipment. Separator efficiency is measured by the amount of brine carryover in the separated steam (Sihombing, et al., 2018) by means of particular methodologies adopted by the steamfield owner. However, little is discussed about the accuracy and relevance of results from these tests to the overall geothermal plant process. For example, often omitted in the analysis of steam quality, carryover droplet size can determine the distribution of water flowing through the steam line, thus playing an important part in the level of steam sampling accuracy.

This paper reviews the separation performance tests in Vertical BOC Separators based on published information, relevant experiences and collected field test results focusing on the three important elements:

1. The accuracy of the results when measuring brine carryover in separated steam,
2. The elements and/or variables that are not controlled by the separator designer/manufacturer that might impact the performance of the separator, hence the separator test results, and
3. The relevance of separation performance to the power plant equipment downstream of the separator.

2. SEPARATOR TEST METHODOLOGIES

Separator performance testing relies on the correct quantification of brine carryover in separated steam at the separator's outlet. The selected test methodology and procedure will impact in the overall separator's steam quality assessment result. Morris and Robinson (2015) explain that in some cases, turbine damage due to deposition and carryover is still present even when sampling results show that the inlet turbine steam has low mineral contamination.

Accurate monitoring of carryover is complex, whereby a robust quality control system for sampling and sample analysis is paramount to avoid significant errors in the results. In literature, there are few documented methodologies to measure steam quality and to calculate separator efficiency. Recognized methodologies include:

- Natural Tracer Test from the Brine Phase (e.g. Chloride or Sodium Concentration)
- Injected Tracer Flow Test
- Throttling Calorimeter

2.1 Chloride and Sodium Concentration

Chloride (Cl) and Sodium (Na) are present in the water phase upstream of the separator and are natural signature elements in separated steam that allows measuring the brine carryover present (Sihombing, et al., 2018). High concentration of sodium and chloride in steam condensate indicate that there is significant liquid carryover (Rizaldy et al. 2018).

Cl and Na Concentration is the most common test used to determine steam quality. It has higher accuracy than any other method for steam quality determination. Jung (2000) explains that Cl and Na concentration in steam samples can also provide a ratio of Total Dissolved Solids (TDS) in the steam i.e. steam purity in the system. This information is beneficial because these elements are indicators of scaling and corrosion.

This method relies highly on the accuracy in representing the flow conditions/regime in the steam pipe. Samples are taken by means of probes inserted into the line or by condensate collection in drain pots located downstream of separation plant. Description of these sample collection methods is presented in sections 2.1.1 and 2.1.2. Once the samples are taken from the steam line, laboratory analysis can determine the concentration of the tracer and then by given formulae brine carryover can be computed (Sihombing, et al., 2018).

The drawback of this method is the complexity of the overall process to measure concentrations of natural tracers. This means that it requires a strict control of multiple variables to avoid erroneous results (described in subsequent sections). Additionally, sampling is performed in a discrete fashion, which could potentially unevenly distribute concentration results during the test, or even collect comparative brine/water samples at well flow conditions that are not a true representation of the operating conditions.

2.1.1 Tracer Collection – Isokinetic Probes

Isokinetic sampling probes are a common method to collect steam samples for carryover analysis. Isokinetic probes are designed to maintain the velocity of the sample identical to the velocity in the steam line in order to maintain equilibrium between particles deposition and particle re-entrainment. Multiport steam samples are commonly used in geothermal pipeline due to their large size, and each port diameter shall be sized correctly to achieve the correct sampling rate to match the steam velocity.

Isokinetic probes details and accurate sampling guidelines are addressed in two standards:

- ASTM D1066 – 2018e1- Standard Practice for Sampling Steam
- ASME PTC 19.11 – 2008 – Steam and Water Sampling, Conditioning, and Analysis in the Power Cycle.

Following the guidelines from these standards ensures that the sampling will have a high level of accuracy to represent the characteristics of the sampled steam. However, strict adherence to these standards might be a limitation when a plant is not designed to comply with all the requirements. For example, ASTM D1066 describes that steam sampling nozzles shall be located in long vertical pipes to ensure water droplets are carried out uniformly in the flow stream, a condition that would be difficult to achieve in geothermal steam piping.

Another limitation of isokinetic probes in geothermal steam pipes is the carryover droplet distribution across large diameter pipe. Experimental data has shown that the flux of droplets traveling through a horizontal pipe (a common pipe setup to take probe samples) does vary across the cross section area of the pipe, i.e. when a probe is used horizontally, it might be missing carryover flux from the bottom of the pipe, compared to the side of the pipe in a annular flow regime. Carryover flow regime becomes another factor that affects the probe efficacy when sampling. This is shown in section 5. Test Results vs. Separator Theory.

2.1.2 Tracer Collection – Drain Pots

The primary purpose of the condensate drain pots (CDP) is to collect the carry over and condensate from separated steam over the length of the pipe. The condensate is mixed with carryover of the separated steam, settling and collecting in the drain pots. The first drain pot after separation plant is utilized in many geothermal plants for collection of steam quality samples (Sihombing, et al., 2018). CDP are not 100% effective and measurements from only one CDP will under-measure the carryover.

Measuring the flow and tracer (natural or injected) concentration from all the CDP's and the scrubber can provide a tracer flux and therefore the total carryover. But after the last CDP or scrubber there will still be carryover droplets continuing to the turbine, eventually mixing with the cooling water system or collecting in the condenser. This last section of carryover has to be measured in another way, which can be challenging to achieve in an accurately fashion. In the case of binary plants using steam, accurate Cl or Na concentration measurement through CDP's is theoretically possible to accomplish since the condensate remains unmixed after the condensing process.

Samples from drain pots are easier and faster to collect than probe sampling since this is part of the steam quality management already in place. Drain pots need to be deep, large in diameter and baffled to be effective (Morris and Robinson, 2015) but even meeting these requirements, condensate samples depend in the carryover particle size to settle and represent the actual flow composition in the line.

2.2 Tracer Flow Test

Misa and Mroczek (2017) described the utilization of fluorescein (disodium salt) injection upstream of the separator to measure carryover. Fluorescein was selected because its strong fluorescent characteristics are comparatively easy to detect under highly disperse conditions after separation and its compatibility to on-going operations at the time of the test in the selected steamfield.

Reliability of this injected tracer to measure carryover can vary since it depends on mixing and reaching steady state before samples are taken, as opposed to natural tracers that are close to steady state concentration all the times. Furthermore, the tracer can be held-up in the system prior sampling, varying the results of the concentration, hence under- or over-estimating carryover flux (Misa and Mroczek, 2017).

2.3 Throttling Calorimeter

The Calorimeter uses a probe with a nozzle to expand steam adiabatically; the liquid fraction is then atomized and vaporized into super-heat. The moisture in the steam is determined by measuring the amount of super-heat within the Calorimeter. The relationship of super-heat conditions and carryover is determined by means of formulae or using the Mollier Diagram (Jung, 2000).

The advantages of this technique according to Jung (2000) are that it is a quick way to determine steam quality for carryover greater than 0.25% and the continuous monitoring capability. The main drawbacks of the technology are the reported erroneous measurements due to potential thermodynamic changes in the sampling process and the maximum reported accuracy measurement up to 99.95%. This method also relies on steam sampling with a probe so it has the same limitations with carryover droplet distribution as described in section 2.1.1 Tracer Collection – Isokinetic Probes.

McAuliffe (2017) has proposed a new throttling calorimeter to improve the efficacy of this technology but geothermal field test results have not been publically reported.

3. SEPARATOR EFFICIENCY AND STEAM QUALITY

Separator efficiency and steam quality are not the same calculation and shall not be confused. Steam quality is often called steam dryness.

Separator efficiency is the percentage of the water/brine removed from the two-phase inlet stream. 99.9% efficiency means that 99.9% of the liquid from the two-phase mix has been removed and 0.1% remains in the steam at the separator's outlet. This is not the same as stating that the steam is 99.9% dry. For example, if the fluid upstream of the separator were composed of a mix of 500 t/h of water and 100 t/h of steam, 99.9% separation efficiency would imply that 0.5 t/h of the liquid carryover is present in the separated steam flow, but the steam quality (or dryness) would be 99.5%. Steam dryness (from a separator) is the percentage of total fluid in the steam line that is steam, therefore, 0.5 t/h of water in 100 t/h of steam is 99.5% dryness (or 0.5% wetness).

Away from the separator outlet, the condensation of steam will add mass to the liquid carryover, especially if pipeline insulation is not effective. Under these circumstances, absolute steam dryness cannot be computed by measuring the concentration of the carried over minerals and ignoring the liquid contribution from condensation, which lowers the chemical concentration of the samples.

4. EXPERIENCES IN SEPARATOR TESTING

In 1960, Bangma recorded separator test results, affirming that it was almost impossible to compare separator performance among tests because of the difficulty to control the ratio of steam to water in the inlet mixture. Bangma (1960) explained that over a short period of time, the test wells gradually declined during the course of the test schedule. Bangma utilized isokinetic-sampling probes to collect steam samples and evaluate steam quality in separators.

Another variable in Bangma's tests was the location of the sampling points, which according to diagrams (Figure 1), these were located 10 meters downstream of the separator's steam outlet. Carryover flow regimes were not discussed in the investigation, which would have influenced in the reported values of separated steam quality.

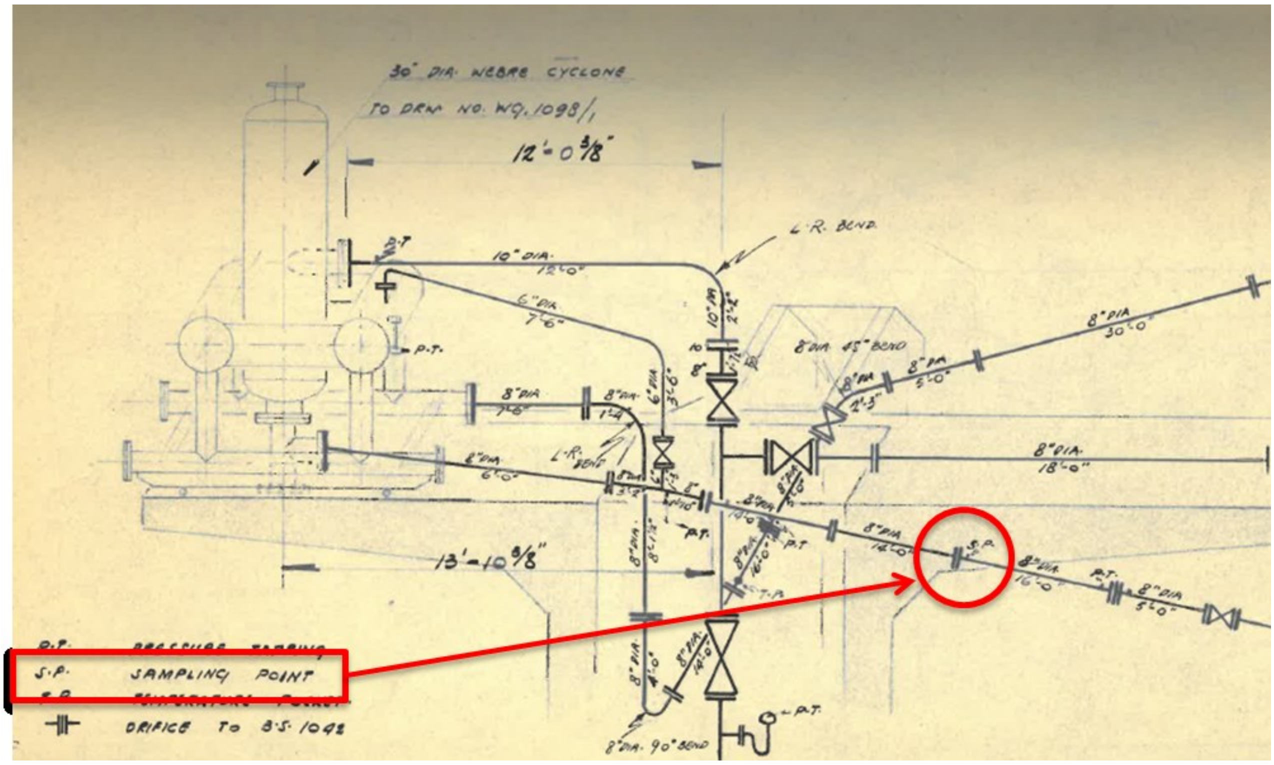

Figure 1: Bangma's separator test arrangement in 1960's. Steam sampling point circled in red (Bangma, 1960)

Lazalde-Crabtree (1984) also reported that separator efficiency depends on operating variables, one of them being the pressure-flow curves particular of each well, i.e. separator inlet steam-water ratio would be variable between wells at equal Well Head Pressure (WHP), or even within a period of time in the same well. The variability of this flow pattern impacts on the liquid-phase droplet size, which according to Lazalde-Crabtree, has a direct correlation with the separator efficiency.

Further on the outlined experiences from Bangma (1960) and Lazalde-Crabtree (1984),
Table 1 shows few publically available observations in separator testing, identifying that Chloride and Sodium concentrate are the common test methodology for steam quality and also that inlet separator flow conditions have an impact in the tests results.

Table 1: Documented experiences in separator testing

Reference	Location	Separator Type	Test Type	Separator Performance (%)	Results
Sihombing et al., 2018	Lahendong	BOC	Sampling Chloride concentration of steam and brine	99.70 – 99.86	The lower the WHP the lesser carryover in separator
Rizaldy et al., 2016	Wairakei	BOC	Carryover in steam by Sodium concentrations in drain pots downstream separator	Not defined	When assessing separator performance via drain pots, efficiency of these are important factor to determine brine carryover.
Bangma, 1960	Wairakei & Kawerau	BOC w/external water drum	Comparison between Sodium content in samples taken steam and water phase (using a perforated isokinetic probe)	99.70 – 100.0	A volumetric reduction of inlet wetness was inevitable during tests, thus controlling inlet steam-water ratio was unsuccessful. Separator performance and pressure drop results were quantified based on steam inlet velocities.

5. TEST RESULTS VS. SEPARATOR THEORY

As mentioned in the introduction, most BOC Separators designs are based in Bangma's measurements and Lazalde-Crabtree empirical approaches. Performance curves from Bangma's tests in 1960, and later published in 1963, have a close similarity to Lazalde-Crabtree's results in 1984 (Figure 2). Therefore, it is normally expected for any geothermal BOC Separator based on the aforementioned published guidelines to present a performance similar to these curves with the following main characteristics:

1. Steam quality is dependent of the inlet steam velocity
2. Steam quality increases as steam velocity increases to a point of breakdown when high level of liquid re-entrainment occurs
3. Poor separation at low steam velocities occurs mainly due to low centrifugal efficiency to separate the two phases
4. Steam velocity thresholds depends on the inlet mixture characteristics

Note that Bangma (1960) defined the liquid breakdown point in a separator, as the point where the separated steam mass becomes 0.5% wet, i.e. 99.5% steam quality, which was an arbitrary figure below the maximum steam wetness value nominated by a third party consultant. Nowadays, this limit is based on experience on preferred steam quality requirements.

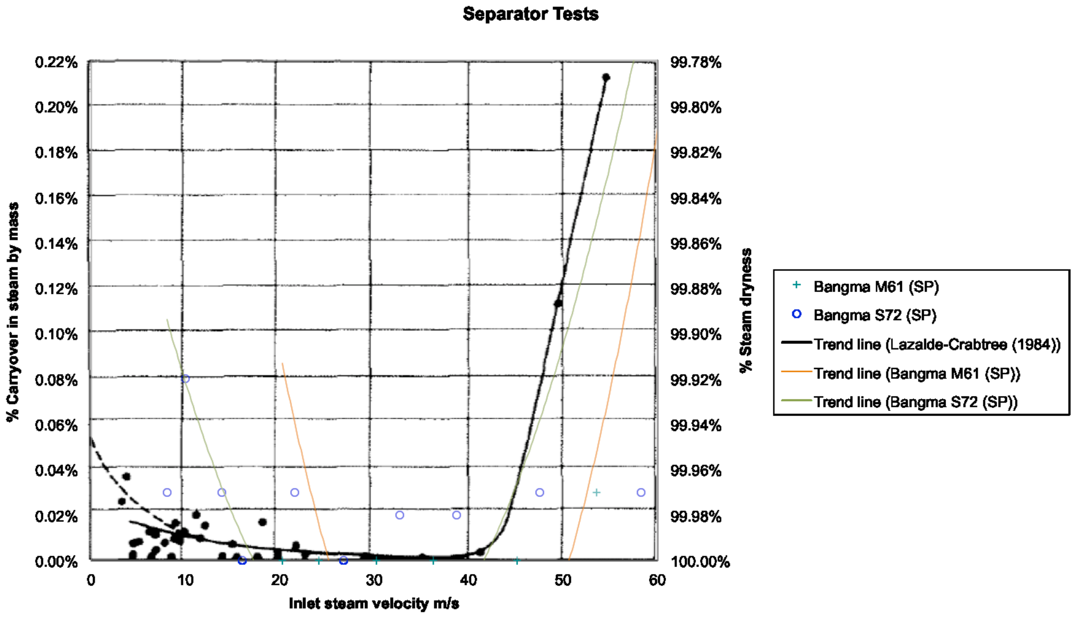

Figure 2: Comparison between Bangma's (1960) and Lazalde-Crabtree's (1984) empirical separation performance trend lines measured by outlet steam quality (%) and mass wetness of steam outlet (%) against steam velocity (m/s)

Comparison between the accepted theories in separator and actual steam quality test results may exhibit different patterns. Steam quality data from 8 different separator settings were collected from different sources and compared to each other in order to understand the relevance of test results to the expected behavior in geothermal separator theory.

5.1 Field Data

Figure 3 shows separator outlet steam quality and mass wetness of steam (or liquid carryover) against steam inlet velocity from 8 different separators compared to Bangma's trend lines of separator performance from 1960. Some of the data points are from well conditions and separator sizes different from Bangma's tests conditions, but according to the theory, their performance curves should be comparable and displaying the 4 main characteristics outlined in previous section. Nevertheless, Figure 3 reveals that separator sample data can be scattered without a clear match to the early findings by Bangma and Lazalde-Crabtree.

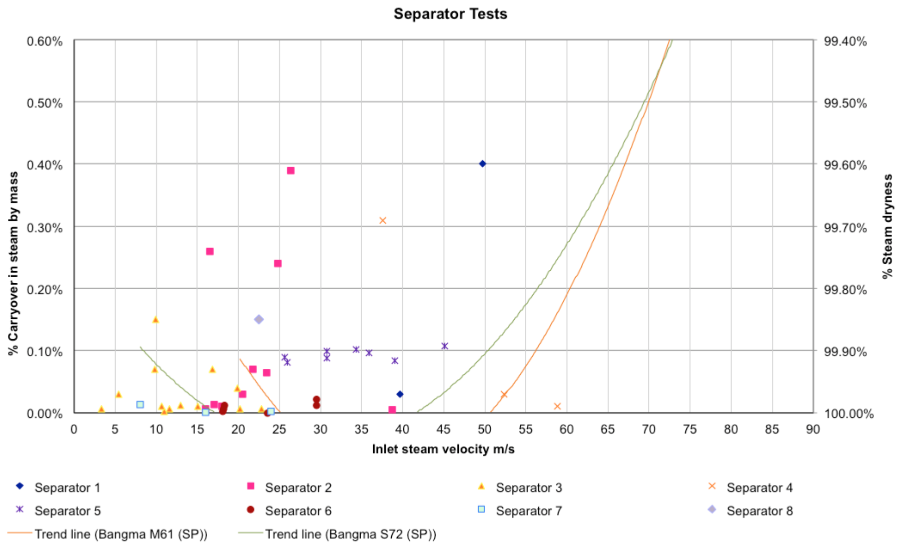

Figure 3: Outlet steam quality (%) and mass wetness of steam outlet (%) against steam velocity (m/s) from 8 different separator settings compared to Bangma's (1960) separator performance curves

Most data points shown in Figure 3 differ from Bangma's separator performance trend lines within the design range. These results might imply that separation performance in various settings is not adequate; however, the reality is that plant performance is acceptable.

Based on this collected field data and experiences around separation plants, potential impact to the results from identified variables is described below

5.1.1 Sample Location

In Figure 3, results from Separators 1 and 5 are interesting. These data points are from the same separator design and size with similar operating conditions. Separator 1 carryover was measured with an isokinetic probe at a considerable distance from the separator, while Separator 5 had a probe located close to the separator outlet and next to a tee. Results for Separator 1 show very low carryover on the design range, compared to Separator 5 results, which show a higher content of carryover at a similar design range.

Flow conditions within the steam line are difficult to determine. Deviation from the recommended vertical long run to sample with an isokinetic probe as per ASTM (2018) could be the case for inconsistency on sample data points.

5.1.2 Droplet Size

Droplet size in the carryover can be another factor that contributed to the difference in data results distribution in Figure 3. Rizaldy et al. (2016) explains that larger droplets could settle over a length of steam main pipe downstream of the separator or hit pipe walls and coalesce, whilst smaller droplets have less chance to settle thus continuing their path to the steam turbine or heat exchanger. Therefore, droplet size have the potential to vary the results if the sample location is either immediately after the separator or downstream the long steam main line.

5.1.3 Discrete Sampling

Discrete sample data during unstable flow conditions can lead to erroneous representation of separator performance. Extrapolating experiences from well TFT's to steam quality test by natural tracers, Broaddus et al (2010) explain that test results from tracer sampling can over-estimate well flow by almost 25% due to uneven distribution of the discrete sample points in the overall flow pattern.

5.1.4 Separator Inlet Flow

Enthalpy, mass flow rate and pressure at the separator inlet are parameters that could affect the results in the steam quality measurement. In section 4. Experiences in Separator Testing, it was mentioned that different authors recognised that the control of separator inlet conditions are important when sampling separated steam. Power plant can monitor separated phases accurately, but two-phase flows are challenging. Water-steam ratio is variable between fields and even among wells and it is impossible to control.

Bangma (1960) documented separation breakdown at lower steam velocities when the inlet mix has a higher percentage of liquid phase as shown in Figure 2, where separation performance in Test S72 started to decrease at earlier steam velocity than in Test M61. Test S72 had 33% more inlet water flow than M61 (SP) under similar separation pressure and same separator design. From experience, it could be proposed that inlet water faction affects not only the point of breakdown but also separator performance below breakdown.

Droplet size at the separator inlet will also affect the separator performance. Upstream elements, such as a throttling valve, could recreate a two-phase distribution with many small droplets. These sorts of elements might be out of the scope of the separator designer, therefore, it is important to consider when designing the whole SGS of the plant.

Another factor found in the inlet mix is equipment or piping arrangement upstream of the separator. Data results from a separator with a change in elevation in the inlet pipe, in conjunction with the inlet flow regime, creates a cyclic surging or slug flow prior to entering the vessel. The surging effect could be linked to variation of carryover concentration results at similar steam velocity.

6. DISCUSSION

6.1 The Variables that Affect Separator Output Result

Based on the presented methodologies and experiences around separator testing, **Error! Reference source not found.** shows identified variables that affect separator performance tests and impact the separator steam quality output measurements.

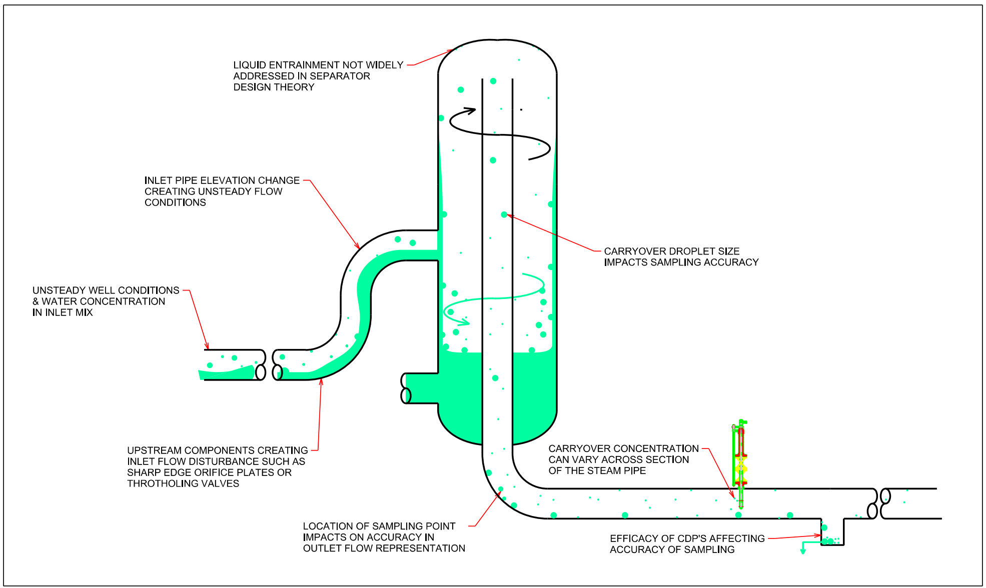

Figure 4: Identified variables affecting separator performance and steam quality test results

A further description of the impact of these variables in separator testing is listed:

- Well conditions, i.e. enthalpy/steam fraction, mass flow rates, pressure can impact the performance of the separator and alter the designed steam velocity boundaries of breakdown, i.e. lower enthalpy inlet mix can decrease the steam velocity breakdown point.
- Mixture inlet flow regime, which according to Lazalde-Crabtree (1984), a slugging inlet flow regime is best for the separator performance, but this statement was related to the liquid-phase droplet size, which impacts the separator performance. From experience, slugging flow at the inlet can create unsteady flow conditions and worsening liquid re-entrainment on the internal steam outlet pipe.
- Test equipment can give accurate results or misleading data analysis depending on its efficacy. Isokinetic probes are the common method for sampling in geothermal power plants but tracer flux sampling from CDP's could be more accurate if CDP's efficiency is high.
- Test procedure and quality management is important to get an accurate representation of the steam flow, e.g. isokinetic probe sampling rate to match the steam velocity. Additionally, correct laboratory and analytical procedures shall also be included in the quality assurance.
- Probe sampling location for the steam can affect steam quality results, since it has been proven that carryover concentration can vary across the section of the pipe and flow conditions are linked to water volume variation on the section.
- Discrete samplings can over- or under-estimate steam quality due to unsteady flow conditions.
- Droplet size of the steam carryover impacts the sampling accuracy in CDP's and isokinetic probes if not located adequately. Furthermore, droplet size can impact the efficacy of steam wetness removal downstream of the separator, i.e. CDP's and scrubbers.
- Carryover outlet flow regime can affect the results if isokinetic probes location is near an unsteady flow, e.g. bends, tee junctions, downstream restrictions.

5.2 Relevance of Separation Performance Test

For the power station owner, there is a high level of importance in separator performance since this equipment is one of the most expensive parts between the wellhead and the turbine (Jung and Wai, 2000); furthermore, low steam quality could cause scaling and erosion problems in turbine blades and heat exchangers, increasing maintenance expenditure and loss of revenue from unplanned plant outages. Nevertheless, micron-sized droplets of carryover from a very high efficiency separator, would be difficult to remove downstream of the separator and therefore continue to travel to the turbine and cause erosion and/or scaling problems.

Therefore, purchasers and suppliers of separators should be aware of the following statements on contractual separator performance tests and guarantees:

- There are no intentional standard for steam sampling method appropriate to geothermal steam lines.
- Expectations of separator performance are based on historic field measurements, which have shown to vary considerably.
- Expectations of separator performance are based on historic measurement methods; changing the method will change the result.
- Two-phase inlet conditions do affect separator performance and cannot be controlled to fixed test conditions.

Separator design parameters by Lazalde-Crabtree (1984) are an accepted baseline for new plants, but even the author recommends that the approach be taken as a starting point for separator design, since the method was not tested exhaustively. Moreover, water re-entrainment mechanics such as liquid creeping over the top dome to the steam outlet pipe is not adequately addressed in the correlation (Sihombing, et al., 2018).

Geothermal separator design relies on variables extrapolated from earlier work but this does not mean that current designs are not up to date; however, it would be advantageous to invest in standardizing this important part of the equipment using current methodologies and field experiences.

6. CONCLUSION

Vertical BOC Separator performance test results presented in this paper confirms that separator theory developed from Bangma (1960) and Lazalde-Crabtree (1984) is applicable to current separator equipment; however, it is important to consider variables that can impact the accuracy of the results. The review of the separator theory, the different test methodologies, and field data concluded that these variables are:

- Inlet two-phase flow regime
- Test equipment and procedure
- Sampling location
- Droplet size of the steam carryover

Some of these variables can be controlled to a certain extent (e.g. test equipment and quality management of sample procedure) and others have a high level of complexity that makes it almost impossible to control (e.g. well conditions and water-steam ratio of inlet mix). The recommendation is to maintain a strict control of output steam sampling test by a quality management system and consider in the analysis those variables that might impact the result.

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