LIQUID CARRYOVER IN GEOTHERMAL STEAM-WATER SEPARATORS

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ABSTRACT

Geothermal steam power plant uses saturated steam to run the turbines. Therefore, it is important to ensure that the steam is high in quality and purity to keep turbines and other equipment working properly. Mineral deposition and moisture damage have been reported in many geothermal turbines around the world, affecting the turbine efficiency and leading to generation losses.

Current design models for calculating the separator efficiency reports about 99.995% separation efficiency, though it is often found that scaling and moisture damage continue to take place in newly constructed steam power plants. Recent studies have noted the potential for volatile silica to mainly contribute to this damage for cases of high separation pressures. However, this is not the view of the authors.

This work investigates water entrainment due to the formation of a liquid film on the walls of the cyclone separator, resulting in significant amount of entrained liquid droplets in the steam. A new model was proposed for addressing the liquid film entrainment. The model shows that the actual efficiency of separator is expected to be lower than the theoretical/calculated efficiency.

Liquid carryover analysis was presented to give better idea on the factors controlling liquid film carryover in vertical-cyclone separators. Liquid film entrainment modeling using field data from the Wairakei geothermal field was reported. The results show that the rate of entrainment increase as the liquid loading fraction increases. It also reveals the impact of liquid film thickness to the rate of entrainment since higher liquid loading leads to thicker liquid film. In addition, inlet velocity is important in determining the rate of liquid entrainment. As the inlet velocity rises, the entrainment rate increase causing more water carryover.

1. INTRODUCTION

The dryness and purity of the steam entering the turbine are important parameters in the long term operation of geothermal power plants. It is crucial to ensure that the inlet steam quality is higher than 99.5% in order to keep the turbines, pipelines and other equipment operating properly. The steam quality affects not only the turbine efficiency but also its reliability and lifespan. Ideally, the steam fed into the turbine should have wetness of less than 1%, but in practice many steam fields cannot meet this crucial requirement and this leads to turbine damage (Morris and Robinson, 2015).

Wet steam from the separator can lead to the problem of scaling in the turbine as liquid becomes superheated and leaves mineral deposits. In addition, water droplets in the steam will impact and erode the blades and rotor causing further damage in the turbine. Adiprana (2010) reported de-rating and below-optimal turbine behavior in the Gunung Salak power station, Indonesia was caused by solid particle and ferrous iron deposition in the turbine, scrubber and demister. The analysis and physical inspection concluded that those materials were brought by wet steam. Kubiak et al. (2005) presented an investigation of the failure of 110 MWe geothermal steam turbine blades in Mexico due to liquid carryover. Mubarok and Zarrouk (2016) reported similar moisture and mineral damage to the turbines in the Ulubelu geothermal power development.

Figure 1 shows the typical mineral deposition on a turbine rotor.

Figure 1: Mineral Deposition on a Turbine Diaphragm at Wairakei Power Plant (from Morris and Robinson, 2015).

The turbine is the most expensive piece of equipment in a power plant. Its maintenance obviously comes at high cost and causes lost generation, hence lost profit due to the unit needing to be shutdown. Thus it would be more efficient to prevent potential damage and keep the turbine in a top operating condition by supplying dry and clean steam.

The main steam-water separation equipment in wet geothermal fields is the separator, which can be a vertical cyclone separator or a horizontal separator. However, separators are not 100% efficient (Zarrouk and Purnanto, 2014). There is always liquid carryover from the separator and condensation in the steam pipeline that needs to be removed before the steam enters the turbine. The efficiency of separators is typically reported to be about 99.995% by design. Even when efficiency is that high, liquid carried in the steam line is a substantial factor in steam field operation. Morris and Robinson (2015) showed that for 100 t/h steam flow at 99.995% separator efficiency, there is 5 kg/h carryover.

The estimation of new separators efficiency is often based on sizing and design calculations (Zarrouk and Purnanto, 2014). The actual efficiency can be calculated after the construction and installation through field trials, which usually involve steam condensate or mass flow sampling. The actual efficiency of separators has been shown to be lower than that produced by calculation due to mineral deposition and turbine damage as the result of liquid droplet carryover.

2. STEAM-WATER SEPARATOR

The separator is the main equipment to separate water from steam in wet geothermal fields. In dry steam geothermal fields separators are not required, though a moisture removal system (MRS) is required near the power plant to ensure the dryness and the cleanliness of the steam entering the turbine. Most conventional geothermal fields worldwide are liquid-dominated reservoirs producing a mixture of steam and water and therefore separators are required (Zarrouk and Moon, 2014). Currently, there are two general types of separators used in the geothermal industry: horizontal and vertical.

2.1 Horizontal Gravity Separator

A horizontal separator relies on gravitational force to separate water from steam. Water, which has higher density, will fall to the bottom of separator and will be separated from the steam flow. A horizontal separator is commonly used for high gas-liquid ratio fluid whereas a vertical separator is used for low gas-liquid ratio fluid (Arnold and Stewart, 2008). Worldwide, horizontal separators are used less frequently in geothermal steam fields. Iceland, Japan and Russia are the main countries that use horizontal separators when designing the steam field (Zarrouk and Purnanto, 2014). Horizontal separators are often equipped with a mist eliminator at the steam outlet to improve the separation process (Figures 2-3). In general, for the same flow rate a horizontal separator requires a larger vessel than a vertical separator (Zarrouk and Purnanto, 2014) and gravity separation alone has lower efficiency than cyclone separation (Perry et al., 1997). On the other hand, horizontal separators are simpler to construct and operate compared with a vertical separator. It also has higher flow rate range. Horizontal separators do not require a water vessel at the brine outlet and less complex seismic design. The typical arrangement of horizontal separator is shown in Figures 2 and 3 below:

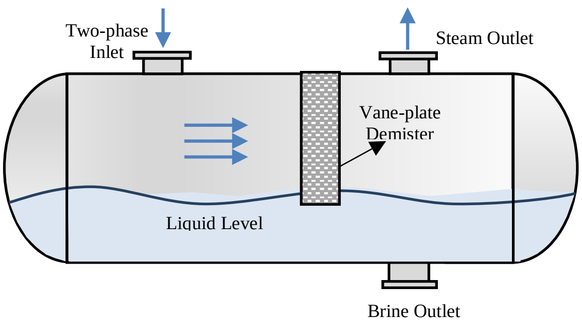

Figure 2: Typical Configuration of a Horizontal Separator (after Swanborn, 1988).

The design of horizontal separators has been improved in order to achieve higher efficiency. Many designs claim to have better separation efficiency than vertical separators. Improvement can be seen in the inlet of recent designs of separator which has used an inflow distributor to break the two-phase flow and effectively separate steam and water before the outlet chamber through the vane-plate demister. The steam outlet points towards the end cap in order to reduce the suction effect. The outlet chamber covers the steam outlet to prevent any liquid re-entrainment while the vane-plate demister eliminates small size mists/droplets that could not be separated in vertical separators. Two inlets with symmetrical design are used to improve efficiency in the case of higher flow rates. The larger liquid surface area in horizontal separators reduces the effect of brine surges. Schematics of the designs are shown in Figure 3 below.

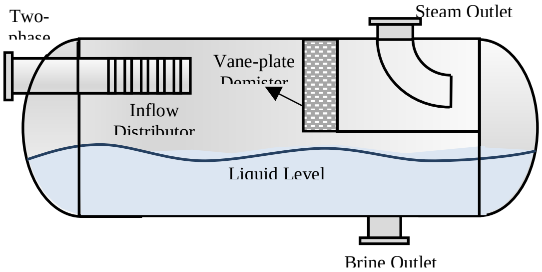

Figure 3: Design Development of a One-Inlet Horizontal Separator (after Josefsson, 2016).

2.2 Vertical Cyclone Separator

This design also known as the Webre separator (Figure 4), the design dates back to early 1950s and was first used in the Wairakei field, New Zealand. Since then, it has been used in many parts of the world to separate steam from brine in liquid dominated geothermal fields. The vertical bottom outlet cyclone (BOC) separator uses centrifugal force to separate steam and water. Steam, which has lower density than water, tends to flow in the middle area of the vessel whereas liquid flows on the separator wall, causing the liquid to lose its momentum and fall to the bottom of separator under gravity.

The efficiency of a vertical BOC separator is claimed to be higher than 99.9% (Lazalde-Crabtree, 1984) when simulated using computational fluid dynamics (CFD) (Purnanto et al., 2013). A vertical BOC separator offers the advantages of high efficiency and smaller size but the efficiency of separation is only achieved in a narrow flow rate range (Zarrouk and Purnanto, 2015), and it also involves some pressure drop. Large-sized vertical BOC separators are also difficult to construct and operate.

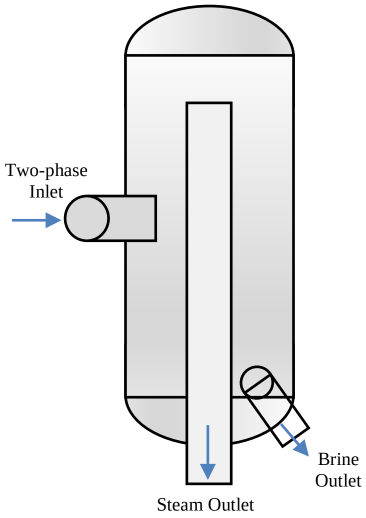

Figure 4: Vertical Bottom Outlet Cyclone Separator.

Most steam field system design nowadays involves the use of larger-size centralized BOC separators. This seems preferable because it involves relatively low capital and maintenance costs. The main reason for choosing a vertical BOC separator is its simplicity, since it is preferable for steam to be removed at the bottom near ground for simpler pipe support (Bangma, 1961). It also does away with interior baffles and funnels, which could corrode or be damaged by the deposition of minerals.

2.3 Steam-Water Separation Efficiency

Separator performance is a measure of the proportion of brine that is carried over with the steam:

$$\eta_s = \frac{\dot{m}_s}{\dot{m}_s + \dot{m}_b} \times 100\% \qquad (1)$$

where η_s is the separator efficiency and $\dot{m}_s$ and $\dot{m}_b$ are the flow rate of steam and brine carryover, respectively.

The efficiency of a cyclone separator depends on several design parameters, such as the dimensions of the separator, particle density and operating temperature. The physical properties of the fluid, namely the density and viscosity, and operating parameters such as the inlet velocity of the fluid into the cyclone and the outlet condition also affect the separation efficiency (Gimbun et al., 2004).

Combining these factors, Leith and Licht (1972) suggested that the efficiency of a BOC separator depends on three dimensionless parameters: a cyclone design number depending upon the physical shape (not size); a modified type of impaction parameter depends upon operating condition; and the exponent in the modified form of the vortex law for tangential velocity distribution. Leith and Licht's (1972) approach was based on the concept of continual radial back-mixing of the uncollected particles, coupled with the calculation of an average residence time for the gas in a cyclone separator having a tangential inlet. This was developed and modified by Lazalde and Crabtree (1984) for the geothermal vertical BOC separator. Lazalde and Crabtree (1984) defined the separator efficiency as a product of mechanical or centrifugal efficiency and annular efficiency:

$$\eta_s = \eta_m \times \eta_A \qquad (2)$$

where η_s is the separator efficiency, η_m is the centrifugal efficiency, and η_A is the annular efficiency.

The separator efficiency determined above is considered the theoretical separator efficiency. It does not really represent the actual efficiency since other mechanisms such as liquid re-entrainment is not adequately addressed in that correlation. Once steam and water is separated in a vertical BOC separator, most of the water drops down and goes out into the brine line ($\dot{m}_l$), though some water droplets stays with the steam and falls down the bottom of the pipelines ($\dot{m}_b$) as given in equation (1). However, a layer of liquid (brine), referred to as 'thin liquid film' form on the wall of separator. As the lighter steam moves upwards in a spiral, it contacts the surface of the film and causes the droplets to enter the steam flow as carryover ($\dot{m}_{carryover}$). The simplified flow mechanism inside the separator can be seen in Figure 5.

This re-entrainment mechanism was proposed by Foong (2005), which is based on similar liquid film behaviour. Foong (2005) noted that the water creeps along the separator wall and reaches the top before coalescing and falling into the steam outlet pipe. This mechanism will necessarily reduce the effective efficiency of the separator. It should be noted that while $\dot{m}_b$ can be quantified as will be described next. The $\dot{m}_{carryover}$ is not measured or quantified. There are two different opinions as to the nature of the mineral carryover (Arifin and Zarrouk 2015) suggested that $\dot{m}_{carryover}$ takes place through micro scale liquid partials/droplets while (Addison et al, 2016) related that to volatile silica in the separated steam.

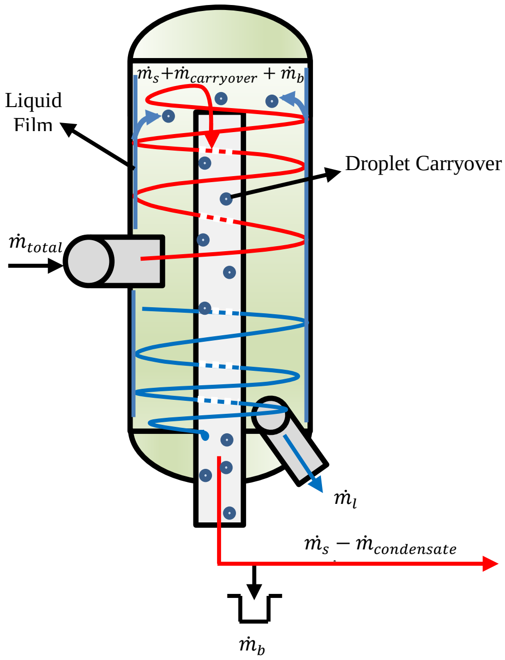

Figure 5: Simplified Flow Mechanism inside a Vertical BOC Separator.

The separation efficiency achieved by the cyclone separator is quite sufficient for most applications. However, in geothermal power plants, the cumulative effects of small brine carryover with associated dissolved chemicals can be quite large (Foong, 2005).

The current method used to determine the actual efficiency of a separator (1) requires the accurate measurement of the brine in steam ($\dot{m}_b$). Unfortunately, it is not possible to directly measure this since it is a small component of the total flow in the steam line. Moreover, the brine carryover is already diluted by steam condensate along the pipeline. However, the chemical signatures of geothermal brine can be used to indirectly measure the brine carryover.

Bangma (1961) and White (1983) included Sodium (*Na*) and Chloride (*Cl*) as the chemical signatures to measure carryover and separator efficiency. Sodium is preferable since it has a higher concentration limit which is detectable (> 1ppm) in the steam. The equation below calculates the brine carryover ($\dot{m}_b$):

$$\dot{m}_b = \frac{\dot{C_S}^{Na}}{C_{sb}^{Na}} \quad (3)$$

Where $\dot{C_S}^{Na}$ is the mass flow rate of Sodium in separated steam in mg/s and C_{sb}^{Na} is the Sodium in separated brine (Zarrouk & Purnanto, 2015). In many geothermal fields, Sodium analysis of samples in the first drain pot right after separator is used to compute the efficiency of separation through brine carryover.

$$\eta_s = \left[1 - \frac{\dot{C_S}^{Na}}{C_{sb}^{Na}}\right] \times 100\% \quad (4)$$

Nevertheless, the Sodium analysis in the drain pot outlet does not perfectly reflect the actual efficiency of separator because not all of the water carryover can be separated by the drain pot. As suggested in Figure 5, brine carryover ($\dot{m}_{carryover}$) as droplets in the steam. Their size varies from very small to larger ones that can possibly hit the inner wall or settle down at the bottom of the pipe. Those that are very small have little chance of settling down and will continue to flow along with the steam. The efficiency of the drain pot is also an important factor to determine how it can effectively remove the water. The same observation given above also applies if the ($\dot{m}_{carryover}$) takes place as volatile silica. However, while volatile silica may be plausible for high separation pressures, Morris & Mroczek (2015) show it isn't viable at lower pressures. If there is sodium present in the carryover, then it is fairly certain that volatile silica isn't a significant mechanism.

3. LIQUID CARRYOVER ANALYSIS

The liquid carryover ($\dot{m}_{carryover}$) is a common problem in geothermal power plants. Even though geothermal steam fields have moisture removal systems (MRS), it is often found that the steam flow entering the turbine contains high amounts of liquid. High concentrations of measured Sodium and Chloride in steam condensate indicate that there is significant liquid carryover. In several cases, turbine damage due to liquid carryover still occurs even though sampling results show that the steam which entered the turbine was clean (Morris and Robinson, 2015).

A set of field experiments from the Wairakei geothermal field, New Zealand shows that the Sodium concentration at the demister increases with steam washing. The simplified diagram of the steam field setup is shown in Figure 6. Sodium concentrations taken from samples at the outlet of drain pots are shown in Figures 7 and 8, respectively. Sodium measurements were made at various wash water rates upstream of the demister, downstream of the demister, and before the turbine inlet. The increase of Sodium concentration is caused by a larger amount of brine carryover passing over the drain pot as it flow with the steam.

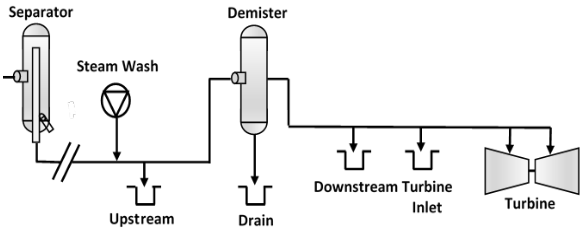

Figure 6: Simplified flow diagram of the steam field setup

Sodium brought by the brine from separator is diluted by wash water and accumulates in the demister. This shows that the performance of the separator is not always within design. Significant concentrations of Sodium are also found downstream of the drain pot after the demister and the turbine inlet drain pots.

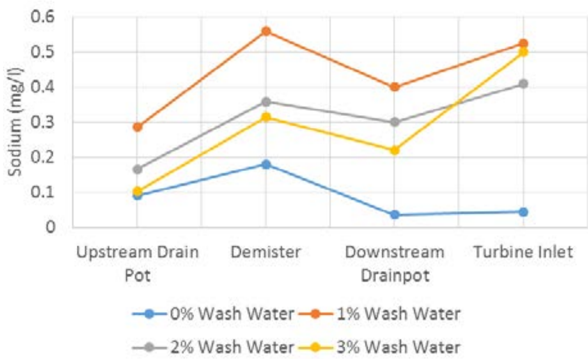

Figure 7: Sodium Concentration Taken from Drain Pots.

Generally, separator efficiency decreases as Sodium concentration increases (equations 1-3) in the samples taken from the drain pots. Any increase in separator loading means an increase in the inlet velocity and this will escalate the Sodium concentration downstream of the separator and vice versa.

Total dissolved solid (TDS) concentrations from the samples reveal similar information about the brine carryover (Figure 8).

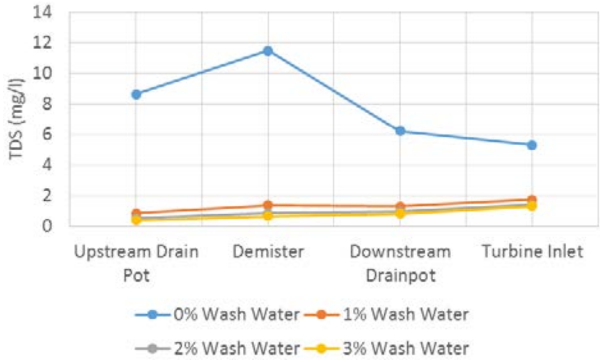

Figure 8: TDS of Samples Taken from Drain Pots, before and after washing.

Figure 8 shows a significant increase in TDS concentration at the outlet of the demister which is about three times the concentration at the upstream drain pot. Figure 8 also shows that water washing dilutes the TDS measured at the drain pots, higher water washing rate results in more dilution.

3.1. Liquid Entrainment Modeling

Entrainment is an important factor in liquid carryover analysis. In geothermal steam field operations, entrainment can take place in the separator or in the steam line. Based on the droplet-forming mechanism in two-phase annular flow, entrainment is caused by the thin liquid film formed at the separator vessel or pipe wall. High steam velocity creates high interfacial shear stress and instability on the film surface. At some points, it may create a wave effect causing continuous entrainment of droplets into the steam flow.

There are two relevant mechanisms of droplet re-entrainment at the separator or pipe wall: roll wave re-entrainment and undercut re-entrainment (Ishii and Grolmes, 1975). They are determined by the liquid film Reynolds number which is affected by the steam velocity:

$$Re_l = \frac{\rho_l \times u_l \times \delta}{\mu_l} \tag{5}$$

where Re_l is the liquid film Reynolds number, δ is the thickness of the film (mm), u_l is its mean velocity (m/s), ρ_l is the density (kg/m^3) and μ_l is the viscosity of the liquid (kg/m.s).

Figure 9 shows the droplet re-entrainment mechanism at the separator inner wall. The droplet entrainment mechanism is difficult to predict. No analytical solution exists due to the complexity of the flow and interfacial structure of entrainment. Yet, modelling attempts in the past have shown that it can be done with varying degrees of accuracy and complexity (Al-Sarkhi et al., 2011a). Many authors have proposed models for droplet entrainment in annular two-phase flow but no general entrainment rate correlation satisfies all the experimental information that has been developed.

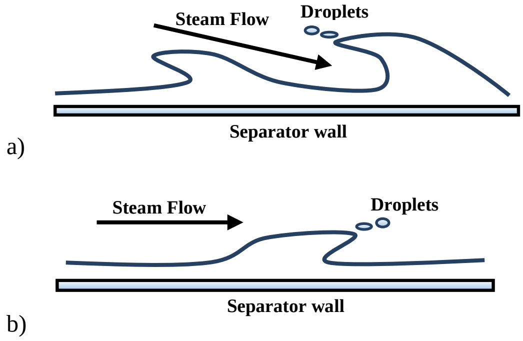

Figure 9. Droplet Breakage Mechanism (a. Undercut Re-Entrainment – Low Film Reynolds Number; b) Roll Wave Re-Entrainment – Higher Film Reynolds Number) (after Ishii and Grolmes, 1975).

It is important to know the rate of liquid entrainment since it affects the quality of steam sent to the power station. The term ‘entrainment fraction’ (Fe) is used to describe a quantification of the rate of liquid entrainment to the steam flow. It is defined as the fraction of the total liquid flow in the form of droplets in the steam core. By definition, the value of the entrainment fraction between 0.0 and 1.0. The entrainment fraction results from the dynamic equilibrium between the rate of deposition of drops from the steam core to the liquid film and the rate of droplet formation (also called atomization) at the vapour-liquid interface caused by waves occurring on the film surface (Pan and Hanratty, 2002a,b; Mantilla et al., 2009; Al-Sarkhi et al., 2011a).

Authors have used different correlations in their models, all of which vary in their prediction of the entrainment fraction and are often limited to certain conditions. Ishii and Mishima (1989) proposed an entrainment fraction correlation that is limited to a certain Reynolds number. Wallis’s (1969) correlation is very simple and straightforward but results in higher error for entrainment fractions greater than 0.5. Moreover, some correlations have narrow coverage (e.g. only air-water systems). Pan and Hanratty (2002 a, b) presented an entrainment fraction correlation in annular flow for vertical and horizontal pipes. These correlations are considered to be accurate but the model is very complex. Furthermore, Sawan et al. (2008) and Liu et al. (2001) have been actively involved in vertical two-phase annular flow simulation using computational fluid dynamics (CFD) which takes droplet entrainment and droplet behaviour into consideration. Their model has been adopted by fluid dynamic analysis software.

Sawant et al. (2008) divided the process of entrainment into three parts as shown in Figure 10. The first part of entrainment is dependent only on the Weber number. The second part is dependent on both the Reynolds number and Weber Number, while the last part depends only on the Reynolds number only.

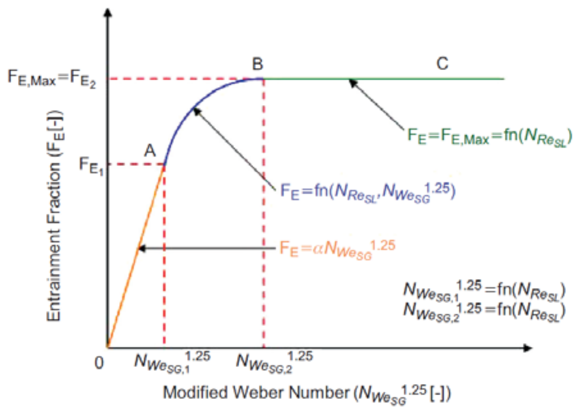

Figure 10: Sawant et al. (2008) Correlation Methodology.

Departing from the above methodology, Al-Sarkhi and Sarica (2011a) developed an entrainment model that is simple yet accurate and covers a wider range of applications. The model is equated to the fouling growth model for a conventional heat exchanger which has similar asymptotic trend characteristics (Figure 10). By analogy, the entrainment fraction equation leads to the following model:

$$F_e = F_{e,max}\left[1-\exp\left(\frac{We_{SG}}{We'_{SG}}\right)\right] \tag{6}$$

$$We_{SG} = \frac{\rho_G v_{SG}{}^2 D}{\sigma}\left(\frac{\rho_l-\rho_G}{\rho_G}\right)^{1/4} \tag{7}$$

where F_e is the entrainment fraction, We_{SG} is the superficial gas Weber number, $F_{e,max}$ is the asymptotic value of the entrainment fraction, v_{SG} is the superficial gas velocity, D is pipe diameter, ρ is density, and We'_{SG} is the analogous time constant.

The time constant in this case is dimensionless and is the Weber Number when the entrainment fraction reaches 63.2% of its asymptotic value (Al-Sarkhi and Sarica, 2011a). Since all the thermodynamic properties remain constant, the Weber Number ratio can be represented by the ratio of superficial gas velocities. The maximum entrainment fraction can be calculated using the equation (8) below:

$$F_{e,max} = F_{e,max,lim}\left[1-\exp\left(-\left(\frac{Re_{Sl}}{Re'_{Sl}}\right)^{0.6}\right)\right] \tag{8}$$

where Re_{Sl} is the superficial liquid Reynolds number, $F_{e,max,lim}$ is the asymptotic or limiting value of the maximum entrainment fraction (0.98 – 1.0) and Re'_{Sl} is the analogous time constant in the form of a Reynolds number.

This model was assessed and compared with other entrainment models. Several experimental data sets from previous authors are used to check whether the model can predict entrainment curve in general. The result shows that the model proposed can satisfy all the models with reasonable average error (Al-Sarkhi and Sarica, 2011a). For this reason, this model will be used to predict the liquid entrainment fraction in geothermal separator.

The first task is to determine Re_l, the liquid film Reynolds number. Under the influence of the upward centrifugal steam flow, the film moves upward along the cyclone wall at an angle (α) to the horizontal (Figure 11). We can therefore take the wetted perimeter as equation below:

$$P_w = \frac{y}{sin\,\alpha} \tag{9}$$

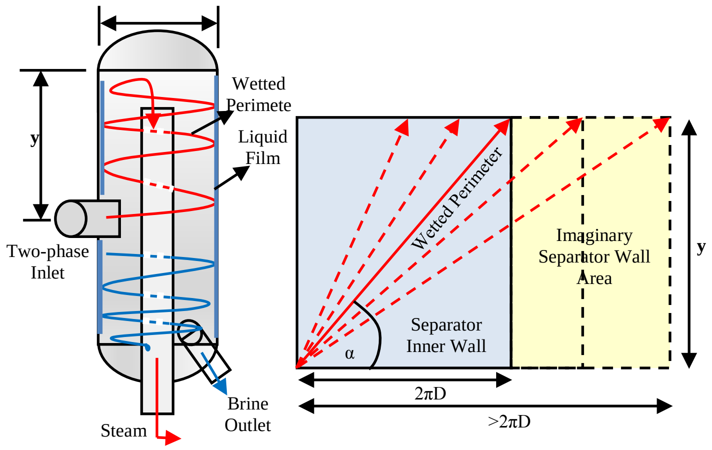

Figure 11: Wetted perimeter and inflow exit angle.

We define the wetted perimeter (P_w) as the width of the film measured normal to the direction of flow. In fact, the steam moves at certain angle from the horizontal, where α is the exit angle from the separator inlet. As an approximation, we assume that the steam moves at the same angle with liquid film (α). The wetted perimeter and inflow exit angle are described in Figure 11.

If it is assumed that the liquid loading fraction on the separator wall (ƒ) moves in the liquid film, we can get Re_l.

$$Re_l = \frac{Q_l \times f \times \rho_l}{P_w \times \mu_l} \tag{10}$$

where Q_l is the total liquid flow to the cyclone, f is the captured fraction, and P_w is the wetted perimeter (equation 9).

Theoretically, the entrainment rate ($Q_{e,s}$) in the separator can be calculated after the maximum entrainment fraction ($F_{e,max}$) and entrainment fraction (F_e) are known (equation 11). The $F_{e,max}$ has a value of little less than one (Assad et al., 1998; Sawant et al., 2008). However, it is also acceptable to use the value of 1. Since the $F_{e,max}$ is the ultimate amount of entrainment, the value of F_e is either lower than or approaching the value of $F_{e,max}$.

$$Q_{e,s} = F_e \times Q_l \times f \tag{11}$$

The entrainment becomes liquid carryover once it enters the steam line. Some will be deposited at the pipe wall because of turbulence, while those droplets of very small size stay in the core of the steam flow. The same entrainment mechanism also occurs in the steam line. The relative velocity difference between steam and liquid films will potentially create droplets and re-entrain them back to the steam flow as shown in Figure 9. Thus the entrainment rate in the pipe line can be predicted using the same model.

$$Q_{e,p} = F_e \times Q_{e,s} \times f \quad (12)$$

where $Q_{e,p}$ is the entrainment rate in the pipeline and F_e is the entrainment fraction in the pipeline.

It is important to note that it is difficult to exactly measure how much of the liquid fraction forms a film layer on the pipe wall. In this case, all the carryover is assumed to be deposited in the liquid film. Thus the value of f=1 is considered for simplicity. A more accurate prediction of the liquid carryover in the separator and scrubbing line might be obtained if the critical parameters (such as separator inlet flow angle, liquid film thickness, and steam-liquid relative velocity) are provided through CFD modelling.

A set of field data from a geothermal steam field in New Zealand was used to test the model. The entrainment rate in a vertical cyclone separator and steam line was simulated and compared with the actual data. The dimensions of the separator are shown in Table 1.

Table 1: Separator parameters used in the entrainment test.

μ_l	0.000168	kg/m.s
ρ_l	905.50	kg/m^3
A	1.13	m^2
$D_{separator}$	3.60	m
D_{inlet}	1.20	m
D_{outlet}	1.05	m

Figures 12 and 13 show the entrainment fraction and the amount of liquid carryover in the separator based on several liquid fractions loaded on the wall of separator. The inlet angle of the separator is represented as α=30°. It is clear that the rate of entrainment gets higher as the liquid loading fraction increases. This result also show the impact of liquid film thickness on the rate of entrainment as higher liquid loading will lead to thicker liquid film. In addition, the result also shows that inlet velocity is important in determining the rate of liquid entrainment. As the inlet velocity rises, the entrainment gets worse.

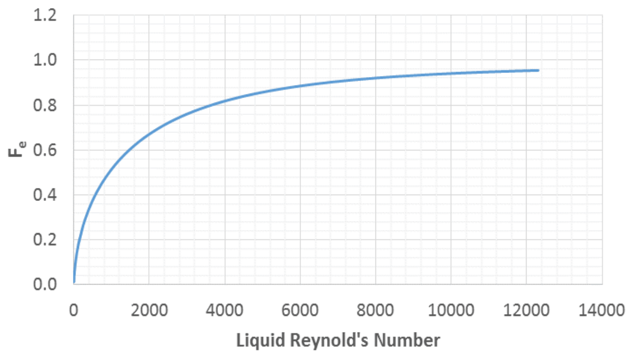

Figure 12: Entrainment Fraction in the Separator

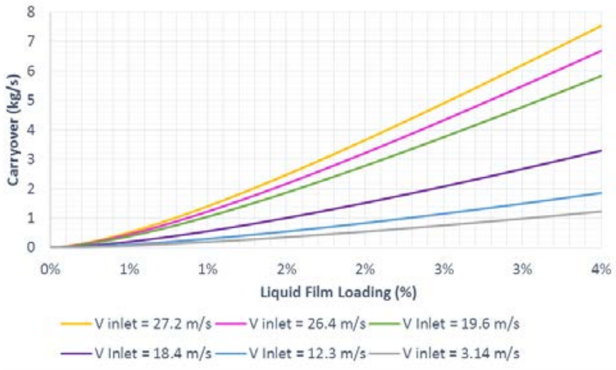

Figure 13: Liquid Entrainment in Separator at Different Inlet Velocity.

The amount of liquid carryover will necessarily reduce separator efficiency. For this reason, the actual efficiency of the separator can be expressed by the equation below:

$$\eta_{actual} = \eta_{effective} - \phi \quad (13)$$

$$\phi = \frac{F_e \times f \times \dot{m}_l}{\dot{m}_l} \times 100\% \quad (14)$$

where η_{actual} is the actual efficiency of separator, $\eta_{effective}$ is the theoretical efficiency of separator (using equations 1-3), ϕ is the deficiency of separator due to the liquid entrainment from liquid film inside the separator, F_e is the entrainment fraction, f is the captured fraction, and $\dot{m}_l$ is the separated water flow rate (Figure 5).

More entrainment from the separator will increase the amount of liquid carryover, which increases the deficiency and reduces the separator efficiency. The model simulation also predicts the effect of inlet flow angle in the separator. As shown in Figure 14, as the angle increase it will result in less deficiency compared to a smaller angle. This proves that a bigger angle will lead to a longer width of steam flow path in the separator which enhances contact between steam and liquid film to form more droplets.

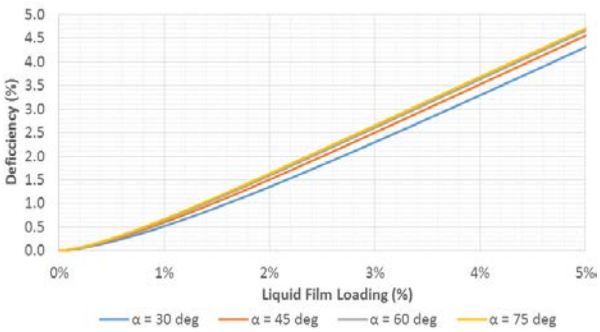

Figure 14: The Effect of Inlet Angle on Separator Deficiency.

To make sure that the model is applicable, the next stage will be to match the results from the model with the actual data taken from the field. In this case, the liquid carryover prediction should be compared with the actual brine flow analysis taken from the first drain pot after the separator. Unfortunately, the actual brine flow data needed is not currently available for comparison. Nevertheless, the model simulation result seems to be a satisfactory representation of the liquid entrainment in geothermal separator and steam pipeline.

CONCLUSIONS

Several geothermal power developments have reported moisture and mineral scaling damage in their turbines as a result of the separator breakdown (carryover).

The BOC vertical separator has potential problems in some of the cases presented that results in a reduction of the overall efficiency of geothermal steam field operation. The horizontal separator, on the other hand, has the potential to avoid some of these problems and thus it is reasonable to give consideration to the testing and utilization of a horizontal separator in new geothermal developments.

There are two different arguments as to the cause of the minerals carryover. The first due to small brine droplets carried with the steam, which cannot be quantified using existing separator efficiency models. The second is due to volatile silica carried with the steam. While both arguments are plausible for high separation pressures, we feel that droplets carryover is likely to be the main cause. This is supported by recent field testing data from the Wairakei. A new separator efficiency model is presented that account for this carryover.

The new separator efficiency model considered liquid field entrainment on the walls of the BOC separator through a deficiency correction parameter. However, this model requires more testing and field validation.

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