SCRUBBING LINES IN GEOTHERMAL POWER GENERATION SYSTEMS

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ABSTRACT

Geothermal steam-water separators are not 100% efficient *(Zarrouk and Purnanto, 2015*), this result in liquid carry over into the geothermal steam turbines. In addition to the liquid carry over, there will be steam condensates forming inside the pipeline due to loss of heat (thermal power) through the insulated pipeline.

Since low and semi volatile contaminants dissolves in liquid, any water entrainment could cause severe damage to the turbine blades, casing and nozzles leading to reduction in turbine's performance. The combined carry over and the steam condensates is discharged from the steam pipeline using steam traps in the form of drain pot in a process known as scrubbing. If the scrubbing line has enough length, it will allow the carried over droplets to settle down at the bottom of the pipe. This will help achieve the desired high purity steam with a quality of ≥ 99% at the turbine inlet.

This paper reviews the main parameters that have an impact on the scrubbing line performance and drain pot design. A mathematical model was proposed for setting the pipeline geometry (diameter and length). The mathematical approach is based on the gravity settling theory.

Data from Wairakei field testing are presented in this work as comparison. It shows that at an average steam velocity scrubbing line performance decreases as pipeline diameter increases.

1. DRAIN POT

Drain pots are also known as catch pot, knock-out pot and condensing pot *(Jung, 1995; Lee, 1983).* This device is classified as pipeline component attached on the bottom of the pipe. The main function of the drain pot is to capture, collect and clear out liquid and solid debris from pipeline or piping system *(Jung, 1995; Lee and Jenks, 1989).* Drain pot acts as a separation device which prevents condensate build-up and consequently reduces possibility of overloading of the final polishing separator thereby improving the steam purity before entering the turbine *(Jung, 1995).* Geometry, design, location and steam condition are the main factors affecting performance and cost of drain pots.

1.1 Drain pot design

Published research on drain pot design shows that maximum efficiency can be attained if the drain pot depth is set at 3 times the diameter of the pipe it is connected to *(Freeston, 1982).* However, this ideal condition is hard to achieve when there is a construction in steam pipelines due to the fact that there is limited clearance between the pipe and ground. For an example, the Wairakei bore field, drain pots depths were varies between 0.5 and 0.7 pipe diameters *(Lee, 1983).*

Freeston and Rentzios (1980) used an air-water laboratory test to demonstrate that to achieve a high drain pot efficiency there are dimensional critical ratios of $h/d \geq 0.6$, $D/d=1.5$, (where h is the depth, d and D are pot and pipe diameters respectively). At these critical ratios, the drain pot collection efficiency is relatively stable at about 85 %. Even when there was a small change in water flow, the collection efficiency dropped with an increase of wetness from 1-4% and improved at around 7-10% when the dryness increases to about 10%. It was concluded from this experiment that the efficiency of a standard drain pot is a function of depth as shown in Figure 1.

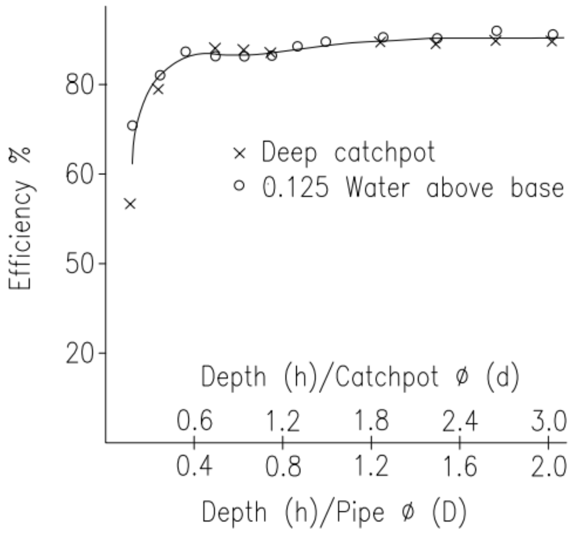

Figure 1: Drain pot efficiency for D/d = 1.5 *(from Freeston and Rentzios 1980).*

For D/d = 1 at 0.5d, the collection efficiency was only about 75 %. Such reduction in efficiency was inferred to be the effect of a very strong pair of vortices on either side of the drain pot. *Freeston and Rentzios (1980)* suggested a modification of the design which involves the insertion of a baffle transverse to the flow direction (Figure 2). This will stop the formation of vortex systems and improved the collection efficiency to 95%.

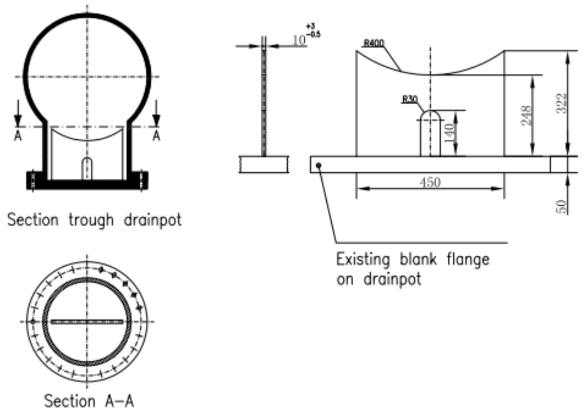

Figure 2: Baffle Plate Design *(after Freeston 1981)*.

1.2 Drain pot location

Drain pots have to be installed on all low points along the pipeline or piping system *(Jung, 1995)*. In order to obtain high removal efficiency, this device should be installed at a certain distance from any bend, sudden contraction, diverging and other devices that cause turbulence flow in the pipeline *(Jung, 1995)*. Under moderate line velocities the distance is about 25 pipe diameters but generally it could be up to 100 pipe diameters (see Figure 3) *(Jung, 1995)*. However, the application numerical modeling and under special design features, the straight pipe requirement for profile development could be reduced substantially from 100 pipe diameters) *(Jung, 1995)*.

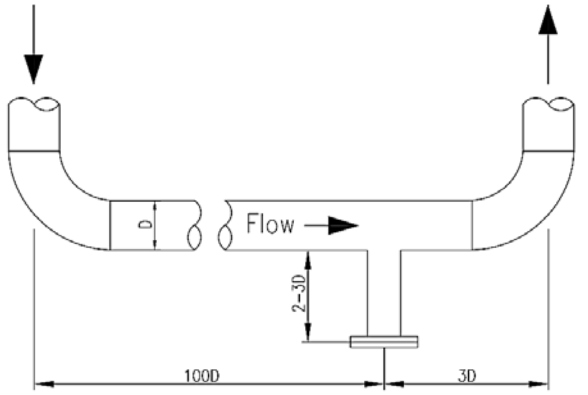

Figure 3: Ideal drain pot location *(after Jung 1995)*.

Spacing between drain pots should also be considered, especially for drain pots which are installed on the steam transmission line in the power station for condensates removal effectiveness. Total moisture that enters the turbine depends largely on the effectiveness of the last two or three drain pots *(Lee, 1983)*. The spacing between the last two adjacent drain pots should therefore be as short as possible to reduce the quantity of residual condensate passing the last drain pot but long enough to prevent interference between them. In Wairakei, 50 pipe diameters seem to be the optimum spacing for the last two drain pots *(Lee, 1983)*.

1.3 Flow regime

Drain pots can work effectively if gravity and time cause the liquid and solid fraction to flow along the bottom of the pipe (stratified flow regime) *(Jung, 1995)*. As the velocity increases, the flow regime could change to annular, mist or disperse (Figure 4). Under these flow profiles, drain pots are not really effective since the fluid tends to jump over the pots and other gas dynamic condition occur *(Jung, 1995)*. Figure 4 illustrates behavior of different flow profiles across drain pot.

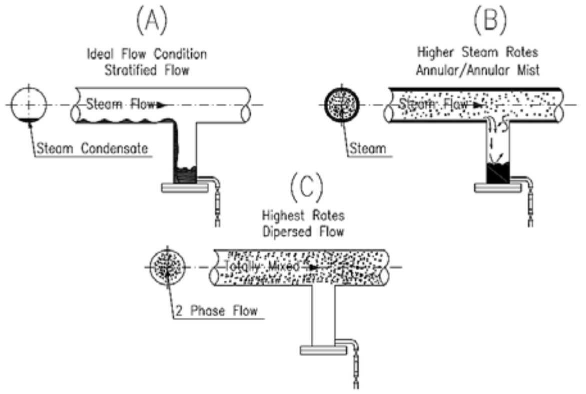

Figure 4: Different flow profiles across drain pot *(after Jung 1995)* showing (a) liquid flow on the bottom of the pipe, (b) liquid flow along pipeline wall, (c) liquid droplets mixed with steam flow.

1.4 Pressure drop

Generally, the pressure drop across the drain pot is low and is within a range 2% to 20% of the dynamic head. However, the pressure drop could increase to 50% if the pot is installed near down-stream of the elbow *(Jung, 1995)*. *Lee (1982)* reported that high pressure drop of 13% occurred at h/d=0.52 for drain pots with D/d =1 (large drain pots diameter). At nearly the same h/d, but D/d=1.5, 10% of pressure drop was observed while for a small drain pots 1-2 % of the pressure drop was observed.

2. SCRUBBING LINE SIZING

It is acknowledged that scrubbing is one of the effective methods to improve steam quality before entering turbine *(Morris and Robinson, 2015; Thorhallsson, 2005; Zarrouk and Purnanto, 2015)*. *Morris and Robinson (2015)* highlighted that in the ideal geothermal plant, the right combination between separator and scrubbing line meet the nominal design conditions for steam turbines which is just below the saturation point with a steam quality ≥ 99%. This steam quality can only be reached if the scrubbing line has enough length which allows droplets to settle down at the bottom of the pipe. The scrubbing line should be designed to give optimum steam quality at acceptable construction cost. *Zarrouk and Purnanto (2015)* suggested that separator should be roughly 400 m away from power plant to allow enough distance for scrubbing. One of the potential methods for determining the optimum length of the scrubbing line is based on gravity settling theory by modeling the pipeline as a long horizontal separator.

2.1 Single droplet model

A single droplet model is developed to analyze the behavior of a single liquid droplet moving with the steam using gravity settling theory *(Wiencke, 2011)*. The gravity settling theory shows that there are three forces affects the flow of spherical object (single droplet) flowing with the vapor/steam. The combination of those three forces will allow the object to fall freely in a vapor/gas phase (Figure 5).

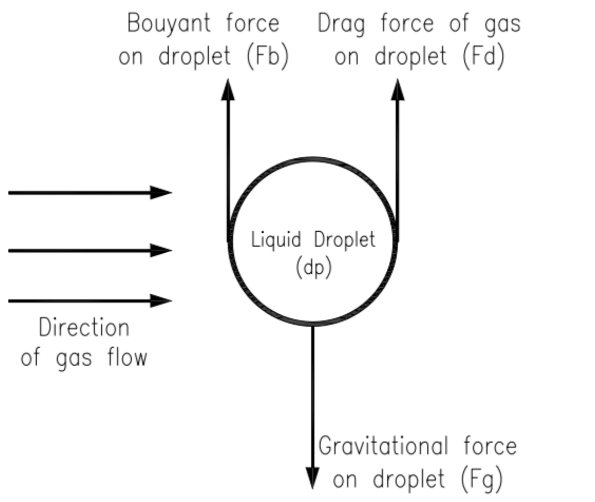

Figure 5: Schematic of force balance acting on a water droplet in horizontal steam line flowing under gravity settling.

Buoyant force and drag force are two forces acting in vertical upward direction and defined as

$$F_b = \frac{\pi}{6} {d_p}^3 \rho_g . g \qquad (1)$$

where :

F_b Buoyant force (N),
d_p Droplet diameter (m),
ρ_g Density of the continuous gas phase (kg/m^3),
g Gravitational acceleration (m/s^2).

$$F_d = C_d A_d \rho_g \frac{V^2}{2} \qquad (2)$$

where :

F_d Drag force (N),
C_d Drag coefficient (dimensionless),
A_d Cross-sectional area of the droplet (m^2),
V Relative velocity (m/s).

While the gravity force acts against two previous forces (normal to the motion) and defined as:

$$F_g = \frac{\pi}{6} {d_p}^3 \rho_l . g \qquad (3)$$

where :

F_g Drag force (N),
ρ_l Liquid density (kg/m^3).

In horizontal flow (scrubbing line), liquid droplets have higher density than gas. Therefore a liquid droplet will travel in vertical downward direction. In other word, force of gravity is higher than the buoyancy force resulting in droplet acceleration in a vertical direction towards the bottom of the pipeline. When the liquid droplet starts to accelerate under the force of gravity, an opposing drag force slows the liquid droplet rate of fall. The drag force continues to reduce the liquid droplet falling rate until a certain point when the resultant forces applied to the liquid droplet reach zero and the liquid droplet falls with a steady velocity. This is called the terminal condition where droplet velocity is the terminal velocity (resulting velocity).

Using the definition above, the terminal velocity can be calculated by equating three acting forces.

$$F_g = F_d + F_b \qquad (4)$$

Substituting V with V_t in Equation (2), when substituting Equations (1-3) into Equation (4), the terminal velocity can be defined as:

$$\frac{\pi}{6} {d_p}^3 \rho_l . g = C_d \frac{\pi}{4} {d_p}^2 \rho_g \frac{{V_t}^2}{2} + \frac{\pi}{6} {d_p}^3 \rho_g . g \qquad (5)$$

$$V_t = \sqrt{\frac{4 g d_p (\rho_l - \rho_g)}{3 C_d \rho_g}} \qquad (6)$$

If $d_p$unit is in μm (10^{-6} m) and gravity acceleration is 9.81 m/s^2 then:

$$V_t = 0.0036 \sqrt{\frac{d_p (\rho_l - \rho_g)}{C_d \rho_g}} \qquad (7)$$

where

V_t Droplet terminal velocity (m/s).
C_d Drag force coefficient.

Arnold and Stewart (2008) proposed the following equations for estimating the drag force coefficient.

$$V_t = 0.0036 \sqrt{\frac{d_p (\rho_l - \rho_g)}{C_d \rho_g}} C_d = \frac{24}{Re} + \frac{3}{Re^{0.5}} + 0.34 \qquad (8)$$

$$Re = 0.001 \frac{\rho_g d_p V t}{\mu} \qquad (9)$$

where

Re Reynolds Number (dimensionless),
μ Viscosity of gas (cP).

Equation (7) is implicit due to the fact that there are two unknown parameters (V_t and C_d), therefore it can only be solved iteratively. The iteration is started by assuming C_d = 0.34 because this is the limiting value for large Reynolds numbers *(Arnold and Stewart, 2008)* until calculated C_d is the same as that assumed C_d. When the previous constrain is achieved, the solution will be reach *(Arnold and Stewart, 2008)*. *Bothamley and Campbell (2013)* summarized other approaches to compute terminal velocity without iteration as given in Table 1.

Table 1 Terminal velocity equations for different regions of Reynolds number.

Settling Law	Reynolds Number (Re_p)	Terminal Velocity Equation
Stoke's Law	< 2	$V_t = \frac{g {d_p}^2 (\rho_l - \rho_g)}{18 \mu_g}$
Intermediate Law	2-500	$V_t = \frac{0.1529 g^{0.714} {d_p}^{1.142} (\rho_l - \rho_g)^{0.714}}{{\rho_g}^{0.286} {\mu_g}^{0.428}}$
Newton Law	500-200,000	$V_{max} = K_s \sqrt{\frac{\rho_l - \rho_g}{\rho_g}}$

Figure 6 illustrates the separation process of a liquid droplet in horizontal flow (scrubbing line). The liquid droplet will traverse a certain horizontal length (horizontal separation distance) before finally settling down at the bottom of the pipe. The horizontal separation distance of each droplet is highly dependent on terminal velocity while the terminal velocity is greatly affected by the droplet size. Larger size droplets will fall in higher terminal velocity, consequently they require a short scrubbing line length and vice versa.

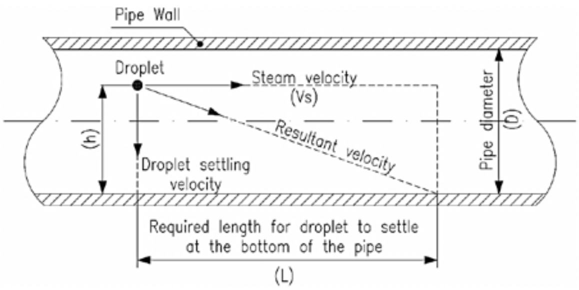

Figure 6: Schematic of Separation in Scrubbing Line *(After Arnold and Stewart, 2008)*.

Figure 6 shows that the maximum vertical distance for the liquid droplet to fall down is equal to pipe diameter, thus the resident time can be computed by the following equation

$$t_s = \frac{h}{V_t} = \frac{L}{V_s} \quad (10)$$

Length of pipe required for a droplet to reach bottom of pipe therefore is:

$$L = t_s V_s \quad (11)$$

$$V_s = \frac{4\dot{m}_s}{\rho_g \pi D^2} \quad (12)$$

where

- t_s Time required by droplet to fall from the top to the bottom of the pipe (second),
- L Horizontal length required for gravity settling (m),
- h Distance of droplet from bottom of the pipe (m),
- V_s Steam velocity (m/s),
- D Pipe diameter, (m),
- $\dot{m}_s$ Steam flow rate (kg/s).

2.2 Calculation of separation in a scrubbing line

The aim is to predict the length of a straight pipe required for various droplet sizes to settle under gravitational effect on the scrubbing line.

Figure 7 and Figure 8 give a comparison between the iterative process, Stoke's Law and Intermediate laws of Table 1 in calculating terminal velocity (*Vt*) and Reynold number of the particle (Rep) as a function of droplet sizes (d_p). Stokes law works best and nearly matches with the iterative process in the region Rep < 2 and droplet sizes 3-50 µm. *Perry and Green (1997)* explained that stokes law is still acceptable to calculate terminal velocity for droplet size up to 100 µm in diameter. Although the result seems to underestimate, the intermediate law seems more reliable than stokes law to calculate terminal velocity of the particles where 2 > Rep < 500 and droplet sizes > 100 µm with relatively small margin of error when compare to iterative process.

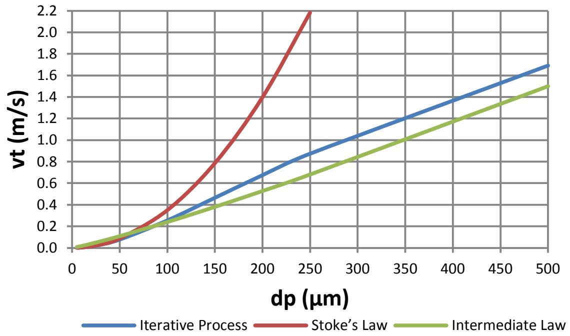

Figure 7: Terminal velocities as a function of droplet sizes for the three different methods of Table 1.

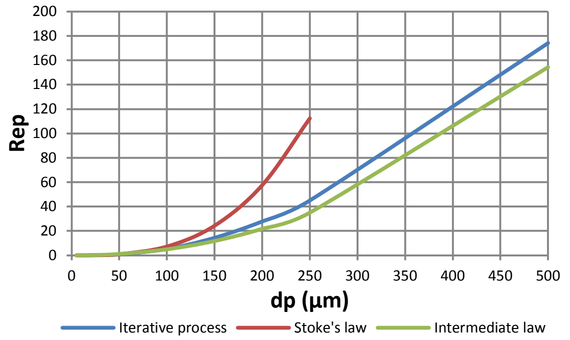

Figure 8: Reynolds number as a function of droplet sizes for three different methods of Table 1.

A droplets distribution inside the pipe is required to examine the effect of droplet size. Assuming that all droplet particles distribute uniformly in the pipe as is shown in Figure 9. The fraction of droplets which exist within a known distance from the bottom of pipe can be evaluated.

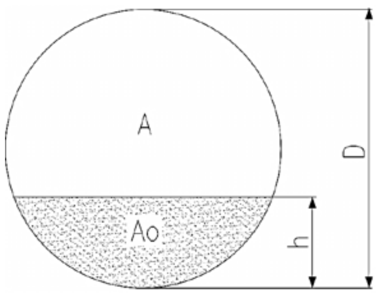

Figure 9: Partial and full cross sectional area of pipe.

- h Distance from the bottom of pipe (m),
- *D* Pipe diameter (m),
- Ao Partial cross sectional area of pipe at distance of h from bottom of pipe (m^2),
- A Cross sectional area of pipe (m^2).

Using circle geometry the relation between h/D with Ao/A can be presented as shown in Figure 10 below.

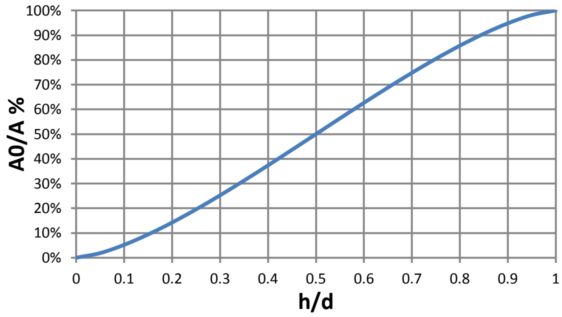

Figure 10: The relation between Ao/A and h/d.

Figure 10 is used to show that for 25% separation of droplet particles at a certain size, the particle within height of ≈ 0.3 pipe diameter should be removed. For 75% separation of droplet particles, all the particles within ≈ 0.7 pipe diameter should be removed. Using parameters from Figure 10, the length of pipe which is required for separation of droplet at certain sizes can be calculated. The results are shown in Table 2.

Table 2: Scrubbing line calculated parameters

Droplet Diameter (μm)	Calculated Steam Velocity (m/s)	Calculated Terminal Velocity (m/s)	Length Required for Gravity settling ,(m) Ao/A 25%	Ao/A 50%	Ao/A 75%	Ao/A 100%
500	36.4	1.6915	6.8	11.3	15.8	22.6
250	36.4	0.8739	13.1	21.9	30.6	43.8
200	36.4	0.6746	17.0	28.4	39.7	56.7
150	36.4	0.4645	24.7	41.2	57.6	82.4
100	36.4	0.2545	45.1	75.2	105.2	150.3
50	36.4	0.0771	148.9	248.1	347.4	496.3
25	36.4	0.0208	553.0	921.6	1290.3	1843.2
10	36.4	0.0034	3350.8	5584.6	7818.4	11169.2
5	36.4	0.0009	13312.1	22186.8	31061.5	44373.6

As shown in Table 2, the scrubbing is more suitable to separate liquid droplets which are larger than 50 μm. Below this droplet size, scrubbing may not be a viable option due to the very long straight pipe that will be required.

2.3 Scrubbing line effectiveness based on separator efficiency

Scrubbing lines are expected to remove liquid carry over from the main separator, as shown in the previous section. Scrubbing line design depends on liquid carry over particle sizes which will be removed if the droplet sizes are larger than 50 μm. Thus, knowing centrifugal separator efficiency as a function of droplet size is required in order to design scrubbing line sizing. *Lazalde-Crabtree (1984)* proposed an equation which determined centrifugal separation efficiency from a centrifugal separator as a function of droplet size.

$$\eta_m = 1 - EXP\left[-2(\psi' C)^{\frac{1}{2n+2}}\right] \qquad (13)$$

$$\psi' = \frac{\rho_w \; d_w^2 \; (n+1)\; U}{18 \; \mu_v \; D_s} \qquad (14)$$

where

η_m Centrifugal separation efficiency (%),
ψ' Centrifugal inertia impaction,
C Cyclone design number,
n Free vortex law coefficient,
ρ_w Water density (kg/m^3),
d_w Droplet diameter (m),
μ_v Steam viscosity (kg/m.s)
U Inlet steam velocity (m/s),
D_s Separator diameter (m).

Using equation (13) above, the calculated result is presented in Table 3

Table 3 Theoretical centrifugal separation efficiency as function of droplet sizes.

Droplet size, μm	100	50	25	10	5	1
Centrifugal separation efficiency	99.99%	99.80%	98.26%	89.91%	77.51%	42.28%

Table 3 shows that liquid droplets larger than 50 μm can be removed by centrifugal separator. *Perry and Green (1997)* stated that the centrifugal separator is still effective in removing liquid droplets down to 10 μm. Considering *Perry and Green (1997)* statement, it seems having larger amounts of liquid carry over is less likely. In fact, liquid carry over from centrifugal separator is likely to have larger droplet sizes because turbulence in a centrifugal separator tends to agglomerate fine particles and forms secondary larger droplets *(Foong, 2005; Machemer and Jonas, 2004)*. *Foong (2005)* argued that small droplets will coalesce on the roof vessel forming bigger droplets which will fall from the roof vessel into the steam outlet pipe. *Machemer and Jonas (2004)* measured the droplets profile distribution from an outlet of atmospheric cyclone separator. The result indicated that liquid carry over was dominated by droplet sizes in range of 50-200 μm. Nevertheless the test was carried out in a atmospheric cyclone separator in which the steam outlet is directed to atmosphere. These conditions however can be different from the main centrifugal geothermal separator resulting in a different droplet profile distribution.

Another point to be noted is that scrubbing seems to be less effective removing moisture which is formed by condensation. This is because the droplet sizes formed by condensation are typically in the range of 0.1 – 30 μm *(Fabian, Cusack, et al., 1993)*. Turbulence in the pipeline might cause the finer droplets to coalesce and enhance the separation process. However, the coalescing mechanism is difficult to quantify.

Pilot plant experiments at Wairakei power station showed that at an average steam velocity scrubbing performance decreases as pipeline diameter increases *(Brown and Bacon, 2009)*. Figure 11 demonstrates measurement result of silica concentration in the steam line in Wairakei power station for three different pipeline diameters (520 mm, 760 mm, and 1220 mm). Figure 11 shows that for the same level of silica concentration, smaller diameter pipeline requires a shorter length compare to larger diameter pipelines.

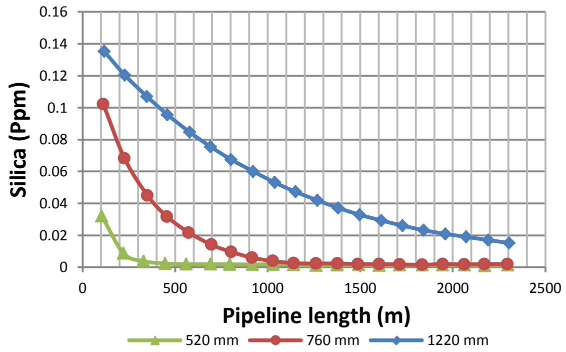

Figure 11: Silica concentrations as a function of pipeline length *(after Brown and Bacon, 2009)*

The results reported by *Brown and Bacon (2009)* are effectively similar to the result of single droplet model for a scrubbing line. Large pipeline diameters require longer distance for a liquid droplet to travel from its initial position to the bottom of the pipe. Figure 12 provides a comparison of liquid droplet size in three pipelines of different diameters (720 mm, 1050 mm, and 1220 mm) at moderate steam velocity (36 m/s). Figure 12 shows that for the same droplet size the bigger the pipeline diameter the longer distance is required for the droplet to settle compared to a small pipe diameter.

As an example: a 500 µm liquid droplet in a 720-mm diameter pipeline requires a pipeline length of approximately 16 m to reach the bottom of the pipeline, whereas the same droplet size in a 1050-mm pipeline requires about 23 m.

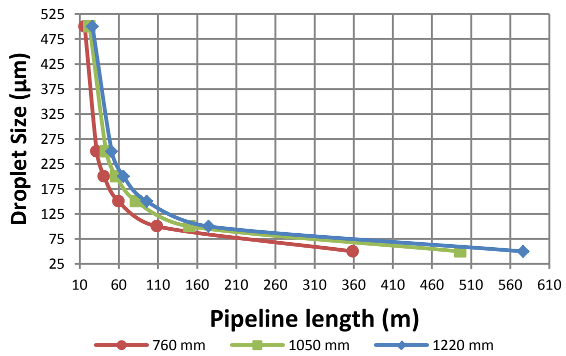

Figure 12: Droplet Sizes as a function of pipeline length.

3. DISCUSSION AND RECOMMENDATIONS

It can be concluded that it will be more effective if scrubbing lines are designed in two or more parallel smaller diameter pipeline instead of single large diameter pipeline. However this comes at a higher investment cost and causes an increase in pressure drop.

Past research showed that water injection has increases separation efficiency of wet scrubbers *(Hibara et al., 1990)*. The same approach may also be applied to scrubbing lines. The reason for this is because single phase hydraulic spray nozzles commonly generate liquid droplets larger than 50-200 µm *(Fabian, Cusack, et al., 1993)* these drops will agglomerate with finer (carry-over) liquid droplets to form larger droplets. However, further study is required to identify whether the approach will improve the scrubbing line efficiency.

Scrubbing line efficiency could also be increased by installing a flow guide on the walls of the scrubbing line to take advantage of the impingement mechanism. This method is almost similar to what is applied in horizontal separators. The installation of an inlet diverter and baffles as an internal part in the horizontal separator aims to improve the separation process *(Arnold and Stewart, 2008)*.

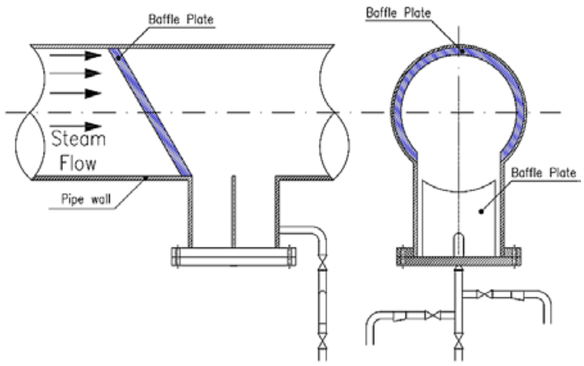

Figure 12: Schematic of the proposed baffle installation to improve scrub line.

Theoretically any "natural flow obstruction" in pipe such as bend: reducers and elbows will assist in steam water separation. However, these obstructers need to be examined further as they may initiate re-entrainment of droplets into the steam flow.

Further study is required to determine appropriate design of flow obstruction devices and analyse the effectiveness of installing those devices to improve scrubbing line efficiency against pressure drop and installation cost.

4. CONCLUSION

Droplet size and drain pot efficiency are two major factors that affect scrubbing line performance.

A drain pot with diameter of approximately two to three pipe diameter, depth of 0.6 drain pot diameter and baffled is more likely to have efficiency of up to 95% and is more efficient under stratified flow regime. However, these criteria were obtained when testing smaller pipelines and there applicability in larger diameter steam pipelines need to be re-examined.

Drain pots have to be installed on all low points along a pipeline or piping system, 100 pipe diameters away from any elements that cause turbulence.

A scrubbing line is effective in removing liquid droplet in steam flow when the droplet size is larger than 50 µm and it may be less effective to remove smaller liquid droplets formed by steam condensation.

Separation in a scrubbing line can be improved by installing a baffle or other internal devices and spraying water into the system.

Scrubbing lines will be more efficient if they are designed using smaller pipe diameters instead of big diameter pipeline. However the smaller pipeline cause higher pressure drop and increase in cost.

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