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Improvement of Well Test Equipment in Olkaria Geothermal Field, Kenya

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ABSTRACT

Geothermal wells are discharge tested after drilling to capture important parameters such as steam and brine output, enthalpy, discharge wellhead pressure and characteristic fluid chemistry at different throttle conditions. These parameters are useful in estimating the power capacity of a well, and for the design of the geothermal power plants and associated steam field infrastructure. The geothermal field in Olkaria is liquid dominated at reservoir pressure with steam overlying liquid, producing both steam and liquid at the wellhead on expansion, which must be separated during a well discharge test. The silencer/separator is used to separate these two phases where the liquid phase is known as brine because it contains mineral salts and other dissolved solids. Noise is generated by conversion of kinetic energy into noise by sonic expansion of steam in the silencer/separator causing turbulence as a result of mixing high velocity mass flow with quiescent air.

Wellhead silencers/separators have been undergoing improvements on both separation efficiency and noise reduction since the start of geothermal development in Olkaria. The current silencers/separators used for well testing cause noise generation of more than 107 decibels which is way beyond allowable noise limits for industrial and commercial areas in Kenya. This has predisposed KenGen to conflicts with local community and Kenya Wildlife Service (KWS) who are our main stakeholders in Olkaria. Furthermore, these conflicts have resulted in delays in discharge testing of drilled wells and hence affecting the field development plans.

The separator/silencer must be designed to achieve two requirements; efficient separation of the two-phase flow and to attenuate the noise generated to acceptable limits. The design approach in this study is to handle the two challenges separately, by using a lower separation unit and an upper silencing unit. Based on the cyclone and the gravity separation principle, two prototypes were designed and tested. Both separators/silencers achieved permissible noise levels for industrial and commercial areas at the well pads with better brine separation efficiencies.

1. INTRODUCTION

Production test is one of the crucial activities in the development of a geothermal field. Confirmation of availability of exploitable geothermal resources is based on these well tests data which also guide the field development plans. Geothermal power plants are designed based on the chemistry and discharge characteristics of wells obtained by carrying out well production tests after drilling. These parameters are important in estimating the power capacity of a geothermal well and are useful for design of associated steamfield infrastructure and later in the management of these systems. Production test also cleans the well bore of drill cuttings and drilling mud enhancing well permeability. Several accurate methods are available for carrying out these measurements, which are complex and require use of heavy equipment and instrumentation. These well test equipment may be uneconomical for carrying out well tests for a short period of time.

Russel James developed a fairly accurate, easy and economical method in 1965, for carrying out flow measurements called the James lip pressure method. When a large flow of compressible fluid such as steam-water mixture flows along a pipe towards a region of low pressure (atmosphere), the flow velocity is sonic on exit. The pressure along the pipe falls to a value above atmospheric at the discharge point. This discharge pressure is directly proportional to the flow rate and stagnation enthalpy of the flowing liquid. The method involves use of water separator to separate the liquid phase from the steam phase and a weir box to measure brine flow.

The Olkaria geothermal reservoir is liquid dominated at depth and Russel James lip pressure method is suitable for well testing. The sonic expansion of water-steam mixture at the lip of a pipe causes aerodynamically induced noise, which need to be reduced to conform to environmental regulations.

Impacts Associated with Noise

The Olkaria geothermal field is located in a national park where there are stringent noise regulations. It is also located in proximity to the local community and noise from well testing has been a source of conflict between KenGen and the local community. These conflicts have caused delays in the past in testing wells and hence affecting the field development plans. The current silencers/separators used for well test are inefficient in suppressing the noise and therefore there is need to improve on noise attenuation. The impacts associated with noise in the Olkaria geothermal field fall into three categories namely, socio-economic effects, health effects and the effect on wildlife.

<u>Socio-economic effects</u>

- Depreciation of property value

- Penalties for violating laws & regulations, i,e EMCA Cap 387 for Kenya
- Work/project stop orders by industry regulators and associated loss of revenue
- Community agitations
- Human resettlements, migration/immigration and associated disturbance costs
- Accidents at the workplace
- Litigation costs on disputes relating to noise emissions

Health effects

- headaches and stress
- poor concentration
- productivity losses in the workplace
- communication difficulties
- fatigue from lack of sleep
- cardiovascular implications
- cognitive impairment
- tinnitus
- hearing loss

Effects on Wildlife

- Animal agitation and human attacks
- Migration/immigration of wildlife
- Loss of wildlife habitats
- Change of animal behavior e.g eating habits, aggressiveness

Applicable Laws, Regulations in Kenya on noise Pollution

Environmental Management and Coordination Act (EMCA), Cap 387

EMCA is an Act of Parliament that establishes legal and institutional framework for the overall environmental management in Kenya. Key subsidiary regulation of EMCA in regard to noise emission is the Environmental Management and Coordination (Noise and Excessive Vibration Pollution Control) Regulations, 2009. These regulations provide measures to control excessive noise emission and vibration associated with various activities be it temporary or long lasting. The aim is to prevent annoyance, disturbance, adverse psychological or physiological effects on persons, or damages to property in the neighborhood. Noise emission limits as provided in EMCA-Cap 387 are indicated in table 1 below while table 2 shows noise emission limits by the World Health Organization (WHO).

Table 1: Noise emission limits as provided by EMCA

Receptor/ zone	Max. Permissible Sound level limits in dB(A)	
	Day (6:01am to 8:00 pm)	Night (8:01pm to 6:00am)
Residential indoor	45	35
Residential outdoor	50	35
Mixed residential (with some commercial & places of entertainment	55	35
Industrial & Commercial	60	35

Table 2: Noise emission limits as provided by WHO

Receptor/ zone	Max. Permissible Sound level limits in dB(A)	
	Daytime (0700-2200hrs)	Night time (2200-0700hrs)
Residential, institutional & educational	50	45
Industrial & commercial	85	85

SEPARATOR/ SILENCER DESIGN

The first separator/silencer design in Olkaria was made of concrete which had very low separation efficiency and risky to personnel and animals because the inlet was made of large culverts. This resulted in anything near the inlet being sucked into the silencer, which is a potential hazard to personnel working in the field as well as animals nearby. The next generation of separators/ silencers was a tangent inlet type which were both inefficient in separation and noise reduction. The present type of separators/silencers is the twin silencer that has been in use for a long time in Olkaria for well testing and they are sufficient in steam/brine separation. With the accelerated geothermal field development in Olkaria, wells located in noise sensitive areas have been drilled and these silencers are found to be inefficient in noise reduction.

The design procedures followed are as a result of review of literature sources and accepted industrial design guidelines. The design involves optimizing the length and diameter by minimizing the weight of the shell and height. The design approach is to treat the steam/brine separation and the noise reduction separately resulting in the design of a lower separator unit and an upper silencer unit. Fluid separation is achieved in two stages. Primary separation stage uses an inlet diverter so that the momentum of the fluid entrained in the vapor causes the largest droplets to impinge on the diverter and then drop by gravity. The second secondary stage is the separation of the smaller droplets by gravity as it moves along the disengagement area.

Separator Section Design

Three principles used to achieve physical separation of gas and liquids or solids are momentum, gravity settling, and coalescing. Two-phase separators are either on horizontal or vertical orientation on installation depending on the vapor liquid ratio of the mixture to be separated. Vertical separators are preferred for mixtures with high vapor to liquid ratios whereas horizontal separators are preferred for mixtures with lower ratios. Liquid separation is achieved in two stages with the first being primary separation where the flow impingement of the flow on a diverter causes larger droplets to fall by gravity, the second stage is secondary separation where smaller droplets fall by gravity as the flow advances on the impingement area.

Liquid droplets will settle out of a gas phase if the gravitational force acting on the droplet is greater than the drag force of the gas flowing around the droplet. The maximum allowable velocity for gravity separation must be calculated so that the liquid disengagement area can be adequately determined. The steam gravity separation can handle steam with a high liquid loads and has two main functions; that is reduction of entrained liquid load not removed by the inlet expansion and the smoothening of the steam velocity profile.

Separation Theory

Considering a brine droplet of diameter, D_P in the steam phase; two forces act on the droplet. First is the gravitational force F_G exerted by the weight of the droplet and drag force F_D exerted by the steam flow. The drag force acts to entrain (carry-over) the liquid droplet whereas the gravitational force pulls it down to separate the liquid droplet from the gas phase.

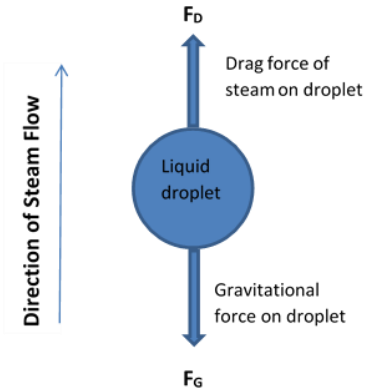

Figure 1: Forces acting on a liquid Droplet.

$$\text{Drag force; } F_D = \frac{C_D A_P \rho_L V^2}{2g_c} \qquad (1)$$

$$\text{Droplet projected area; } A_P = \frac{\pi {D_P}^2}{4} \qquad (2)$$

$$\text{Gravitational force; } F_G = \frac{(\rho_L - \rho_v)\, V_D g_c}{g} \qquad (3)$$

$$\text{Volume of spherical droplet; } V_D = \frac{(\pi)}{6}\ {D_P}^3 \qquad (4)$$

Where C_D Drag coefficient, A_P droplet projection area, v steam velocity, ρ_l liquid density, g_c correction factor, D_P droplet diameter, V_D droplet volume and ρ_v steam density.

Assuming the velocity of fluid to be constant across any cross section (plug flow); with no eddies or disturbances and ignoring end effects; the two forces are equal at equilibrium; $F_D = F_G$.

Substituting for F_D and F_G and solving for maximum allowable vapor velocity V_T which prevents liquid entrainment is given by:

$$D = \left(\frac{4gD_P}{3C_D} X \frac{\rho_L - \rho_V}{\rho_V}\right)^{1/2} \quad (5)$$

Substituting the first term with design (sizing) parameter $K = \left(\frac{4gD_P}{3C_D}\right)^{1/2}$;

$$V = K\left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{1/2} \quad (6)$$

This equation is referred to as the Souders-Brown equation. The terms ρ_V and ρ_L are the gas phase and liquid phase densities, respectively.

The design parameter, K, in the Souders-Brown equation is an empirical parameter and is a key factor for sizing of the vapour-liquid separator vessel diameter. Its value depends on several factors including:

- Pressure
- Fluid properties
- Separator geometry
- Steadiness of flow
- Inlet design and performance
- Relative amounts of steam and liquid

Vertical separator design

The first step in silencer design is the determination of the terminal velocity using Sauders-Brown equation to calculate the disengagement area. The K value is a function of pressure and there are several methods in literature that estimate the K values used for separator design. In this particular design, K values used are the ones specified in the Gas Processors Supplier Association (GPSA) Engineering Data book. The allowable vertical velocity for droplet settling to occur is equal to the terminal velocity. The allowable vertical velocity is 0.75 times the terminal velocity for a conservative design. The hold time is the time required to reduce the water from normal liquid level (N_{LL}) to low liquid level (L_{LL}) (empty) while maintaining normal outlet flow that is important during operation so that steam does not escape through the weir box during well test. The surge time (t_s) is the time required to increase the water level from normal liquid level (N_{LL}) to maximum liquid level (H_{LL}) while maintaining the normal feed without outlet flow. This is also important to avoid brine from rising above the fluid entry level, which adversely affects the separation efficiency. For vertical separators, the vapor disengagement area is the entire cross sectional area of the vessel and the diameter is determined from the equation $D=4Q_V/\pi U_v$, where Q_v is the vapor volumetric flow rate, D is the vessel diameter and U_v is the vertical velocity. Then the corresponding cross sectional area, A is determined. The next step is to determine the vapor disengagement height. The main design dimensions for the cyclone separator section are shown figure 2 below.

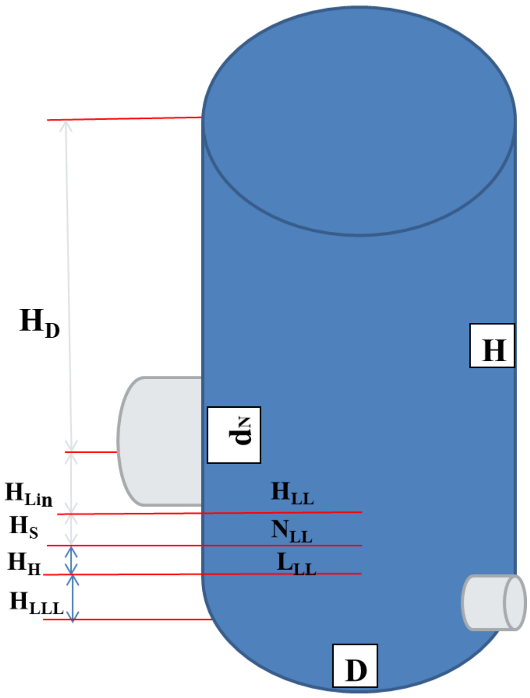

Figure 2: Cyclone separator section design

Horizontal separator design

The horizontal two-phase separators are occupied by both steam and liquid on the cross sectional area and for design purposes, the width and height are assumed and the normal liquid level (N_{LL}) is set by liquid hold up (V_H) volume while the high liquid level is set by liquid surge volume (V_S). The vapor disengagement height (H_V) is the height required for the liquid droplet to separate from the vapor and the vessel length (L) is calculated to accommodate liquid surge and hold up or vapor disengagement. The vapor volumetric (Q_V) flow rate and liquid volumetric flow rate (Q_W) are then calculated. Surge time (t_s) and hold up time (t_H) is taken as 10 and 5 minutes respectively and the hold-up volume (V_H) and surge (V_S) volumes are calculated. The main design dimensions for the cyclone separator section are shown figure 3 below.

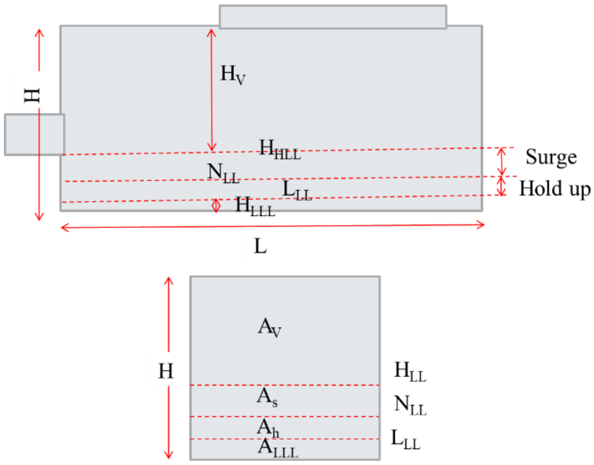

Figure 3: Gravity separator unit design

The design pressure is equal to operating pressure plus (15-30 psi) which whereas the design temperature is taken as the saturation temperature at +40 ^{0}F. Since corrosion is expected due to acidic gases, ASTME SA 516 Grade 7 material is selected. The allowable stress is 17500 psi and the shell thickness calculated.

Silencer section design

Silencers are devices designed to attenuate and absorb air-born sound waves propagated in a flowing medium. There are three types of silencers used for noise attenuation:

- Absorptive
- Reactive
- Dispersive

The main consideration in designing silencer units for geothermal application is to design a silencer that creates little backpressure as much as possible while meeting noise level requirements. The silencer section is designed to reduce noise emitted by two methods. The first is reactive silencing where noise is reduced by reflection while the second noise reduction mode is by use of noise absorbing materials.

Absorptive silencer design

This silencer type uses absorptive materials to attenuate the sound waves. The thickness of acoustic linings should be selected according to the most dominant frequency of the noise to be absorbed. The incident sound energy is partially transformed into heat as it moves along the absorptive material. In Absorptive silencer design, various types of fibrous packing materials effectively absorb noise energy; the resulting viscous friction dissipates the sound energy as small amounts of heat. The main applications of absorptive silencers are absorption of the high frequency noise. Different packing materials can be used in absorptive silencers and chosen for use based on varying absorptive performance, price, temperature and corrosion resistance characteristics. Absorptive silencers are made of perforated tubes lagged with noise abortive materials.

Lined elbow section

A lined bend improves sound attenuation by forcing sound energy through a corner. The walls are lined with sound absorbing materials, sound energy is forced to impinge on the sound absorbing surface as it reflects its way around the corner with each successive impingement taking sound energy from the travelling wave. A lined bend is acoustically effective when it extends at least three times the inlet diameter.

Expansion section

The separation unit acts as a plenum chamber for noise reduction. The expansion section is lined with sound absorbing materials that absorb most of the sound energy when it is reflected back at the walls of the chamber.

Reactive or Reflective Silencer Design

This consists of expansion chambers where the inlet opens into a large volume creating an abrupt change in cross sectional area at each end of the volume. The primary function of this type of design is to reflect sound wave back to the source. Energy is dissipated from extended flow path resulting from internal reflections and by absorption at the source. Reactive silencers are effective for high frequency attenuation. The length of the chamber is adjusted so that reflected wave cancels the incident wave.

Transmission loss through an expansion chamber is the difference in sound pressure level of the incident sound wave and the transmitted sound pressure level. The length of the chamber controls the frequency at which there is maximum attenuation and increasing the mean flow velocity through the muffler up to 30 m/s increases the transmission loss. Large chamber walls should be avoided because they vibrate and radiate noise.

Dispersive silencer part

The silencers reduce the fluid pressure, reduce the velocity, and straighten the flow reducing turbulence, which is the source of aerodynamically induced noise. The flow sound intensity is proportional to the eight power of the jet velocity and small reduction in velocity results in large reduction in noise.

RESULTS

Separator Design

Several wells were chosen across the entire Olkaria field based on the flow rates of both steam and brine to capture well discharge parameters simulating any discharge conditions that may be encountered during well discharge tests. Ten wells were therefore chosen for design including the biggest wells that have been drilled in Olkaria. The vessel diameter ranges from 2 to 6.1 m controlled by the steam volumetric flow rate whereas the total vessel diameter ranges between 1.9 and 6.4 m. The main challenge for separator design for well discharge test is to design a silencer that can economically handle wells with big variations in steam and brine volumetric flow rates. The diameter of the vessel is therefore chosen as 3.6 m based on vessel diameter values which can handle several wells and can be conveniently transported from one well to another as well as meeting the Kenyan road standard requirements. The resulting height requirement for each well at 3.6 m vessel diameter was calculated.

Table 3: Cyclone silencer/separator design results

Well	steam (W_v) kg/s	Brine (W_L) kg/s	Diameter (D_{VD}) m	Height (H_T) m	Diameter (D_{VD}) m	height (H_T) m
OW-733A	22	5.7	4.1	2.3	3.6	2
OW-802B	8	22	2.5	6.4	3.6	4
OW 50A	23	1	4.2	1.9	3.6	2
OW-916	31	3.4	4.9	2	3.6	2
OW-908	5	2.1	2	2.7	3.6	2
OW-35	20	0.2	3.9	1.9	3.6	2
OW-14	8	0.4	2.5	2.1	3.6	2
OW-40v	7	23.6	2.2	8.1	3.6	4
OW-40A	15	29.5	3.4	5.1	3.6	5
OW-915B	26	52.9	4.4	5.3	3.6	7
OW-921A	49	51.8	6.1	3.6	3.6	7

Vessel total height ranges from 2 to 7 m with most wells having 2 m. The design height of 3.6 m was settled upon constrained by installation stability during discharge tests. The silencer size handles most of the wells in Olkaria, whereas a well with total height greater than 4 m means use of more than one separator.

For gravity separators, height of vessel is calculated from the surge volume and hold up volumes and it varies between 0.5 and 3.3 m. The length L varies between 2.7 to 8.4 m while minimum length for liquid droplet separation L_{MIN} is between 2.1 and 26.6 m. If L< L_{MIN} then L is set at L_{MIN} meaning vapor/liquid separation is controlling and if L> L_{MIN}; the design is acceptable for liquid separation.

Table 4: Gravity silencer/separator design results

Well	Steam (W_v) kg/s	Brine (W_L) kg/s	Height (H) m	Lenth (L) m	Min Length (L_{MIN}) m	Height (H) m	Lenth (L) m	Min Length (L_{MIN}) m	Design Length (L_D)
OW-733A	22	5.7	1.5	3.1	11.6	2	1.8	9	9
OW-802B	8	22	2.5	4.3	3.3	2	7.4	3.5	8
OW 50A	23	1	0.9	2.9	18	2	0.3	9.5	10
OW-916	31	3.4	1.3	2.9	18.6	2	1.1	13	13
OW-908	5	2.1	1.1	2.7	3.5	2	0.7	2.2	3
OW-35	20	0.2	0.5	9.2	26.6	2	0.1	8.2	9
OW-14	8	0.4	0.6	4.5	8.6	2	0.1	3.4	4
OW-40v	7	23.6	2.5	4.9	2.1	2	7.6	2.7	8
OW-40A	15	29.5	2.7	5.5	4.3	2	9.5	6.2	10
OW-915B	26	52.9	3.3	8.4	5.3	2	17.1	10.5	18
ow-921A	49	51.8	3.2	8.2	10.3	2	16.7	20.3	17

Considering ease of transportation, L and L_{MIN}, the vessel height is set at 2 meters. Height varies between 0.1 and 17.1 m and L_{MIN} between 2.2 and 10.5 m. Comparing L and L_{MIN} results in design length for each well with lowest being 3 m and the highest is 10 m. To accommodate several wells in Olkaria, the vessel length is therefore set at 12 m.

Silencer Section

Silencer design section was done by reviewing the design of the current silencers that are not efficient enough in noise attenuation. It involved first identification of the sources of noise in the current silencers which was identified as follows:

- Inlet noise generation
- Noise emitted from the walls of the silencers
- Emission of noise at the silencer steam outlet

Inlet Spool

The inlet spool is made long enough to make flow as laminar as possible and diffuse noise by reducing turbulence that is a source of noise. The inlet was also covered to reduce air suction which causes noise as well as low fluid separation efficiency. It also provides for noise reduction by expansion from the lip pipe cross section to a bigger volume causing reactive noise cancellation. The dissipated noise was reduced by lagging the inlet with fiberglass material that absorbs the noise. Fiberglass was particularly chosen as a lagging material because of the following properties:-

Chemical resistance- Fiberglass textile fabrics will not rot, mildew or deteriorate. They resist most acids with the exceptions of hydrofluoric acid and phosphoric acid.

Dimensional stability- Fiberglass fabrics will not stretch or shrink. Nominal elongation break is 3-4 percent. The average linear thermal expansion coefficient of "E" glass is 5.4 by 10.6 cm/cm/°C.

Good thermal properties- Fiberglass fabrics have a low coefficient of thermal expansion and relatively high thermal conductivity. Glass fabrics will dissipate heat more rapidly than asbestos or organic fibers.

High tensile strength- Fiberglass yarn has a high strength-to-weight ratio. Fiberglass yarn is twice as strong as steel wire.

High thermal endurance- Fiberglass cannot burn and is unaffected by curing temperatures used industrial processing. Fiberglass will retain approximately 50 percent of its strength at 700°F and as much as 25 percent at 1000°F.

Low moisture absorption-Fiberglass yarn has extremely low moisture absorption.

Cost-effective- Fiberglass fabrics offer cost advantages compared to other synthetic and natural fiber fabrics.

Separator unit

The separator section acts as both reactive and dissipative silencer for noise attenuation. The separator section acts as a reactive noise reducer by providing an abrupt change in inlet cross section which is effective in the high frequency noise band attenuation. Double walls are also used where 200 mm thick fiber glass material is stuffed in between to absorb the noise and avoid wall emission.

Silencer unit

The silencer unit is designed as an absorptive silencer to reduce noises emitted at the outlet and increase noise transmission losses that are effective in low frequency noise attenuation. Stainless steel perforated tubes and panels are stuffed with fiberglass and rapped with fiberglass cloth to avoid erosion of fiberglass by steam. To improve the noise absorption efficiency, the silencer unit is made as long as possible where an effective length of 2.9 meter was used as well as minimum fiber thickness of 200 mm, perforations of over 40% open area and fill density greater than 100 kg/m^3.

Separator/Silencer Test results

After the design was completed, the silencers were fabricated taking into consideration the design details. All the silencers/separators were tested on well OW-49C so to obtain comparable results. Background noise levels was collected before the well was vertically discharged to obtain noise data both when the well is not discharging and while discharging with no silencer/separator installed.

Cyclone Separator/Silencer Prototype test results

The test results for the improved cyclone separator/silencer are shown in figure 4 to 7 below. Figure 4 below is a plot of noise measurement against distance from the silencer for the improved cyclone separator/silencer and the old cyclone type separator/ silencer. The background noise levels recorded was around 55 decibels at the well pad with a high of 62 decibels 300 m from the silencer location. The vertical discharge results indicate a high of 118 decibels at the cellar and a low of 55 decibels at around 650 m.

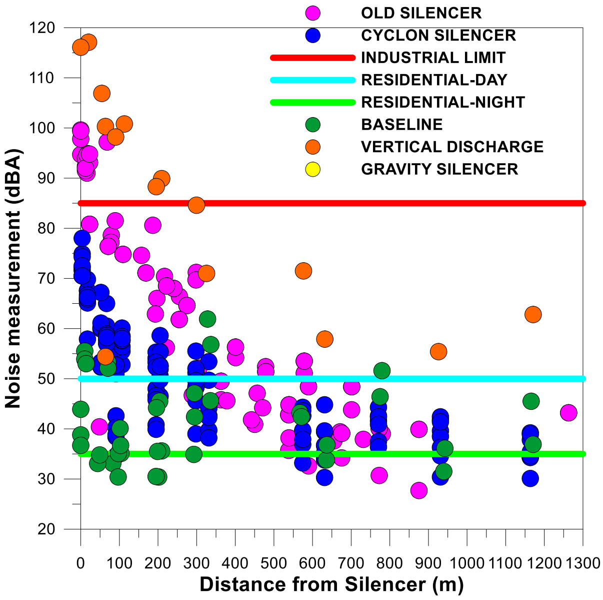

Figure 4: Plot of Noise Measurement against Distance from Silencer

The results show that the highest recorded noise for the improved cyclone separator/silencer is 75 decibels at the silencer whereas the highest recorded noise for the old cyclone separator at the same location is 99 decibels. Moving just 10 m from the silencer the highest recorded noise for the improved separator/silencer is around 61 decibels while the old silencer noise measurement at the same point was around 95 decibels. At 100 m from the silencer, 60 decibels was recorded for the improved cyclone separator/silencer as compared to 83 decibels for the old cyclone separator.

The results show decreasing noise levels as you move away from the silencer for both types of silencers. There was no change in noise measured after around 800 m for both silencers and no difference in noise measured for the two types of silencers. Figure 5 below shows a plot of the measured brine flow verses well head pressure at 8” and 6” lip pipe throttled conditions.

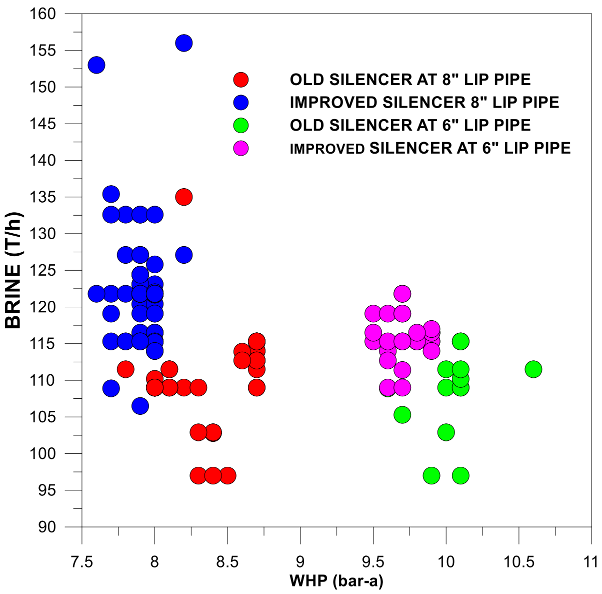

Figure 5: Brine Flow Verses Well Head Pressure.

Figure 6 is a plot of the total mass flow from the well against wellhead pressure while discharging at 8” and 6” lip pipes.

The results show that higher brine flow was measured for the improved cyclone separator/silencer as compared to the old silencer at the same throttling condition while discharging at both 8 and 6”. The old silencers recorded a generally higher wellhead pressures as compared to the newly improved silencer. Both silencers recorded a decrease in brine flow as you discharge the well at an increased throttle condition by changing the lip pipe from 8” to 6”. The total mass flow was slightly higher for the improved cyclone separator/silencer as compared to the old silencer for both 8 and 6” lip pipe. There was a reduced total mass flow for both separator/silencer as you change the lip pipe from 8 to 6”.

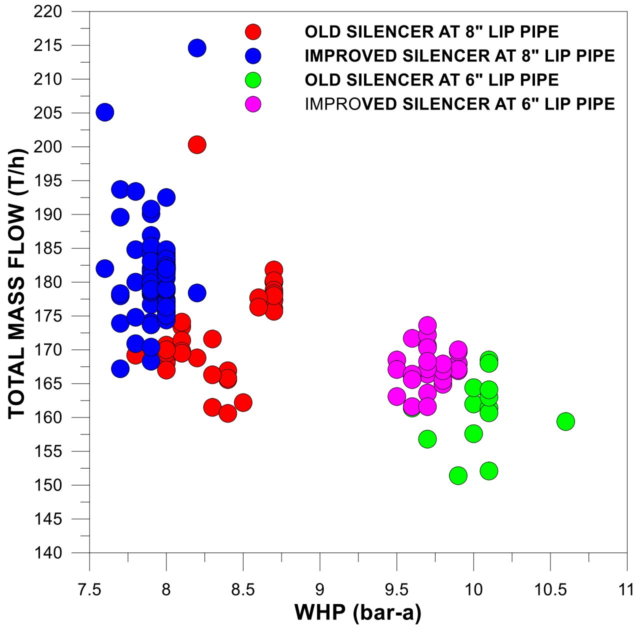

Figure 6: Total Mass Flow Verses Well Head Pressure

Figure 7 below shows a plot of steam flow verses wellhead pressure while discharging on both 8" and 6" lip pipes. The plots show increased steam supply for the old separator/silencer as compared to the new separator/silencer while discharging on both the 8 and 6" lip pipes for both the types of separator/silencers. There is a general decrease in steam flow rate for both types of silencer/separator as you change the pc from 8 to 6".

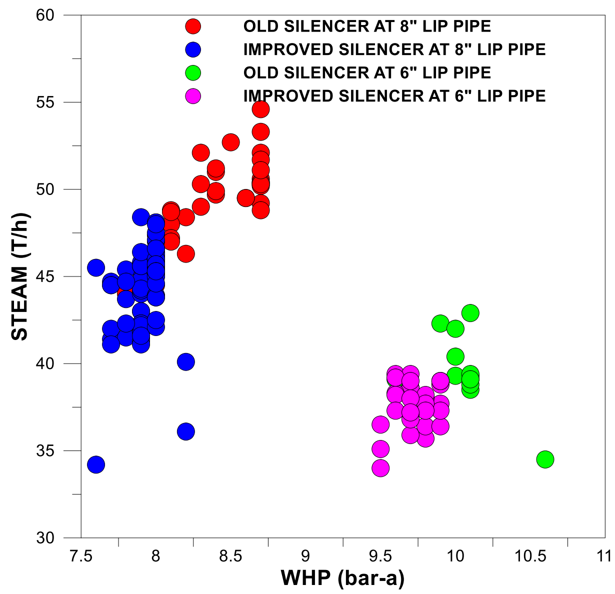

Figure 7: Steam Flow Verses Well Head.

Gravity Separator/Silencer Prototype

The test results for the improved gravity separator/silencer are shown from figure 8 to figure 11. Figure 8 below is a plot of noise measurement against distance from the silencer for the improved gravity separator and the old cyclone type silencer/separator. The results show that the highest recorded noise for the improved gravity separator/silencer is 81 decibels at the silencer, 74 decibels at 10 m from silencer and 65 decibels at 100 m from silencer. A measurement of 60 decibels is captured at around 200 m from the silencer and 57 decibels at 300 m. The results show decreasing noise levels as you move away from the silencer up to around 750 m from the silencer where 55 decibels is measured. There was no much change in noise measured beyond 900 m.

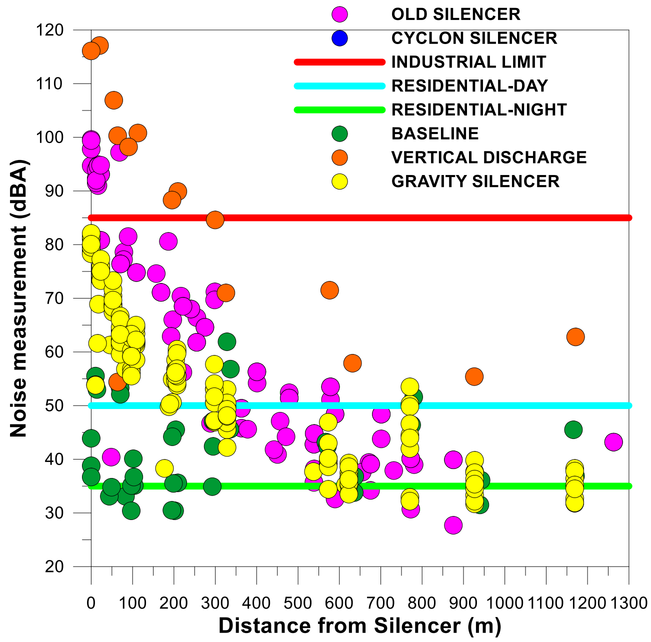

Figure 8: Plot of Noise Measurement against Distance from Silencer

Figure 9 below shows a plot of the measured brine flow verses wellhead pressure at 8" and 6" lip pipes throttled conditions. Figure 10 is a plot of the total mass flow from the well against well head pressure while discharging at 8" and 6" lip pipes. The results show a higher brine flow for the improved gravity separator/silencer as compared to the old silencer at the same throttled conditions while discharging at both 8" and 6" lip pipes. The old silencers recorded higher wellhead pressures as compared to the improved gravity silencers at the same throttled conditions. The old silencer recorded comparably same brine flow as you discharge the well at increased throttle conditions by changing the lip pipe from 8" to 6" whereas the improved gravity separator/silencer showed slightly decreased brine flow. The total mass flow was slightly higher for the improved cyclone separator/silencer as compared to the old silencer for both 8 and 6" lip pipe. There was a reduced total mass flow for both separator/silencers as you change the lip pipe from 8" to 6".

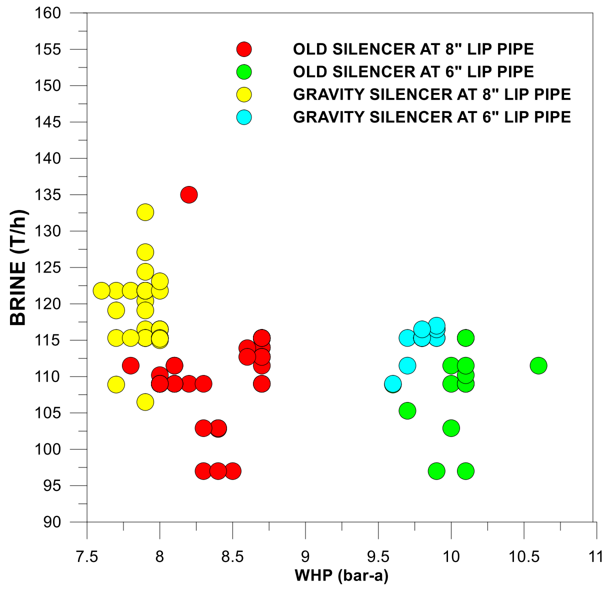

Figure 9: Brine Flow Verses Well Head Pressure

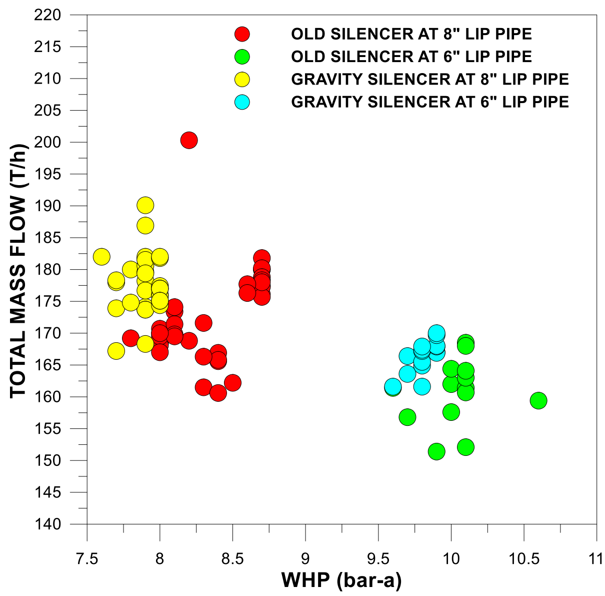

Figure 10: Total Mass Flow Verses Well Head Pressure

Figure 11 below shows a plot of steam flow verses wellhead pressure while discharging on both 8" and 6" lip pipes. The plots show higher amount of steam flow for both 8" and 6" throttled conditions for the old silencer as compared to the improved gravity separator/silencer. There is a general decrease in steam flow rate for both types of silencer/separators as you change the lip pipes from 8 to 6" with the old silencers recording higher wellhead pressures at the same conditions.

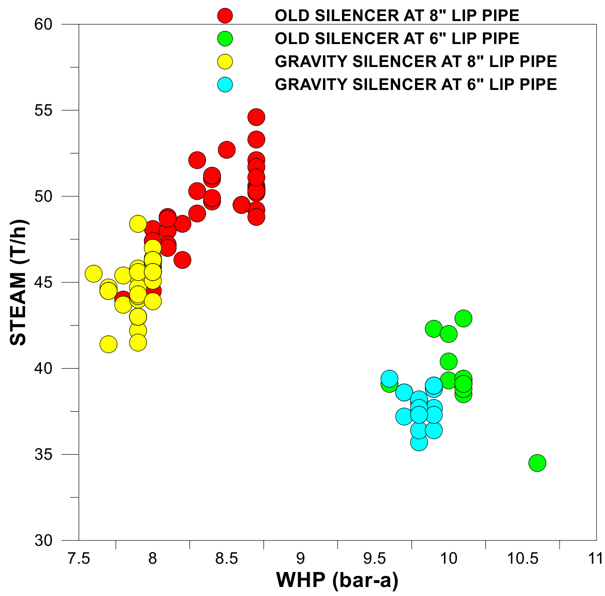

Figure 11: Steam Flow Verses Well Head Pressure

DISCUSSIONS

Cyclone and Gravity Separator/Silencer Prototypes

Figure 12 below shows the noise level comparisons measured for the different test scenarios.

Background noises of about 60 decibels control the noise levels in this area. The results also show that without any silencer installed, the expected noise levels is around 118 decibels which is way beyond the maximum allowable noise level of 85 decibels for an industrial set up. Comparison of noise levels after 300 m between the background data and the three types of silencers show no much difference which is an evidence of background noises being in control.

The improved cyclone separator/silencer design test results showed very good noise attenuation as compared to the old separator/silencer. The maximum-recorded noise level of 75 decibels at the silencer is much lower than 99 decibels for old separator/silencer and lower than the 85 decibels required in the workplace noise limits. At about 10 m from the silencer, the noise is 60 decibels, which means that the improved cyclone separator/silencer is within the limits of noise regulations in the workplace. Workers at the well pad are able to communicate audibly which is important in reducing accidents and incidents at the well pad. The daytime residential limit of 50 decibels compliance is possible at 300 m from the improved cyclone silencer/separator provided that the background noises is lower while for the old silencer this limit is achieved after 750 m from the silencer. This means that wells nearer to the local community can be safely discharge tested by using the improved separator/silencer without conflicts with the local community and environmental pollution regulators. There was no further reduction in noise after 650 m from the silencer meaning that noise measured beyond this point is controlled by background noises from other discharging wells as well as the power plants in close proximity.

Comparison of noise measurements from the cyclone separator/silencer with gravity separator/silencer shows that the cyclone separator has better noise attenuation capacity.

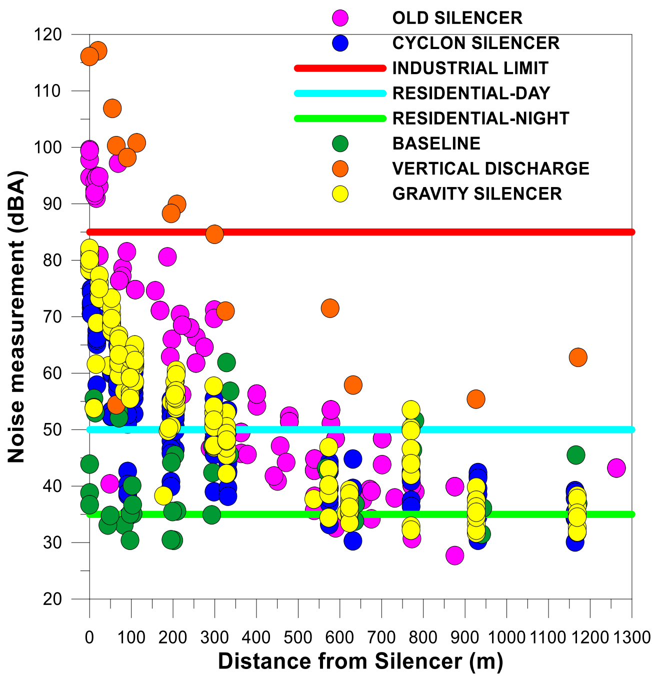

Figure 12: Noise level results

Comparison of brine discharge from the two separator/silencers as shown in figure 13 below indicates that the brine flow measured from the improved separator/silencers is higher than the brine flow measured with the old silencer. This means that the improved separator/silencer separated more brine from the flow than the old silencer which could be as a result of better separation efficiency. However, the old silencer recorded higher wellhead pressures as compared to the improved silencers. The higher wellhead pressures and consequently lower brine flow from the old separator/silencers than the improved separator/silencer could be because of sizing issues with these silencers. This could result in the conditions of the well changing causing the difference in steam and brine ratio for the different type of silencer/separators. To conclusively determine if the increased brine is as a result of improved separation efficiency or sizing issues; the well will be re-tested with two twin old silencers.

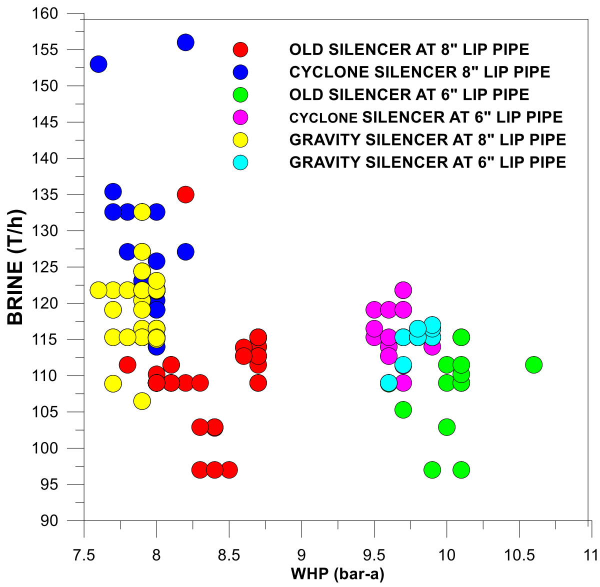

Figure 13: Comparison of brine

There is no observable change in well head pressure when the well is discharge tested using the cyclone type separator/silencer as compared to the gravity type separator/silencer which may show that both silencers are correctly sized for this well. Brine and total mass flow from the well as shown in figures 13 and 14 respectively shows that there is slightly higher flow when tested using the cyclone separator/silencer than flow from the gravity separator/silence.

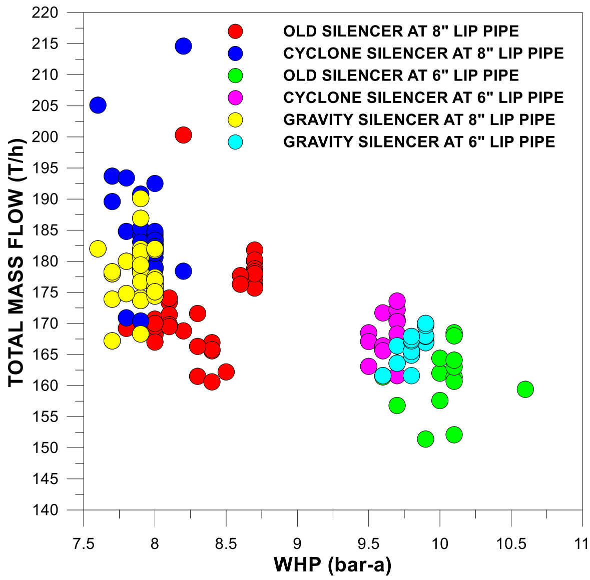

Figure 14: Comparisons of total mass

Since the two types have comparably same wellhead pressures at the same throttled conditions, the only explanation for this higher brine flow is better separation efficiency for the cyclone separator/silencer as compared to the gravity type separator/silencer.

The brine flow measured in the weirbox is calculated as follows (Hirowatari, 1986):

$$\mathrm{k} = \frac{0.24}{h} + 81.2 + \left(\frac{12}{P^{0.5}} + 8.4\right)\left(\frac{\mathrm{h}}{\mathrm{B}} - 0.9\right)^2 \qquad (7)$$

$$\mathrm{M}_{w.atm} = kx\ 81.2x\ h^{2.5}\ x\ 60\ x\ \rho_f \qquad (8)$$

where h is the water level height through v-notch (m), p is the height of weirbox excluding v-notch (m), B is the width of the weirbox (m), $m_{w(atm)}$ is the brine flow at atmospheric conditions (t/h) and ρ_f is the density of brine (kg/m^3).

$$H = \frac{2675+925\mathrm{Y}}{1+7.85\mathrm{Y}} \qquad (9)$$

$$Y = \frac{\mathrm{M}_{w.atm}}{\mathrm{A\ x}\ P_c^{\ 0.96}} \qquad (10)$$

$$\mathrm{M} = \mathrm{M}_{w.atm}\ \mathrm{x\ FCF} \qquad (11)$$

$$FCF = \frac{1}{\text{l-X}} = \frac{h_{fg.atm}}{h_{g.atm} - \mathrm{H}} \qquad (12)$$

$$X = \frac{H - h_{g.atm}}{h_{fg.atm}} + 1 \qquad (13)$$

where H is the total enthalpy, M is total mass flow, FCF is flash correction factor, X is the dryness fraction, $h_{fg.atm}$ and $h_{g.atm}$ are enthalpies of mixture and steam at atmospheric conditions.

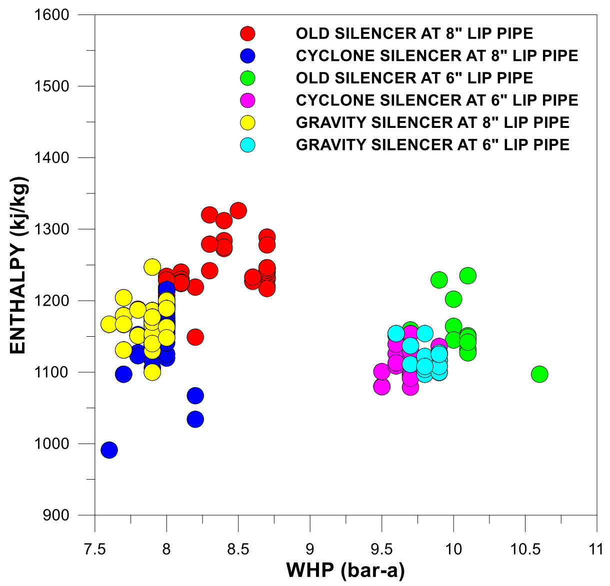

Figure15: Comparison of total enthalpy

From equation 10, if more brine flow is measured in the weir box; the value of Y increases and the total enthalpy in equation 9 is reduced. This explains the increased enthalpy as shown in figure 15 above for the old silencer as compared to the improved silencer.

Figure 16 below shows that the same amount of steam was measured at the same wellhead pressure for the gravity and cyclone separator/silencer whereas higher steam was captured for the old separator/silencer at the same throttled conditions. Increased total enthalpy results in increased dryness fraction X as shown in equation 13 above which explains the higher steam ratio for the old silencer than the improved silencers. This means that production testing the well with the old silencer overestimates the enthalpy and the steam flow.

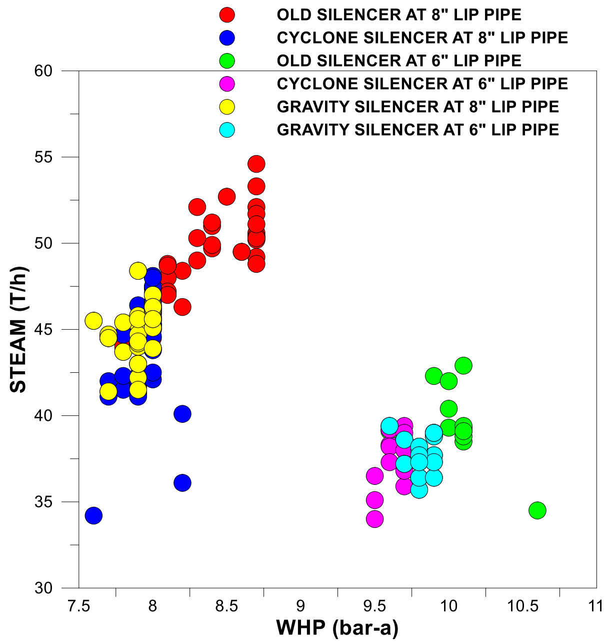

Figure 16: Comparison of steam flow

Consequently, good separation efficiency is very important so as to obtain accurate brine flow measurement at the weir-box which greatly determines the accuracy of well measurement parameters from the Russel James lip pressure method. This mean better accuracy for the improved separator/silencers as compared to the old separator/silencer. During well test, the cyclone separator/silencer proved to be more structurally rigid than its gravity counterpart as no leakages were observed during the tests.

The test proved the cyclone separator/silencer to be superior to the gravity separator/silencer prototype in terms of noise reduction, parameter accuracy, separation efficiency and structural integrity and therefore recommended for future well testing in the Olkaria geothermal field.

Cost Benefit Analysis

It is possible to enhance geothermal development plans and have additional generation capacity faster as a result of using the new improved separator/silencers. As an example, total of 18.4 MWe was confirmed after testing of wells OW-40V, OW-40A, OW-803 and OW-803A which may not have been tested without the improved silencers because of resistance from our stakeholders, specifically, KWS and the local community.

Table 5 shows the total cost of ownership for the improved silencers and the old silencers while table 6 below shows the cost benefits of using improved silencer as compared to the old silencer. The cost difference of kshs 680,000 for the ownership of the newly improved silencer as compared to the old silencers is negligible. However, the benefits of using the improved silencer far much outweighs the slight difference in price.

Figure 7 below shows an estimate of the total costs and revenues for well testing. It normally takes three months to discharge test a geothermal well in the Olkaria geothermal field. For two silencers, it is possible to test 8 wells per year. For a pessimistic result and assuming an average of 5 MWe per well, a total of 40 MWe resource potential can be confirmed per year with the two silencers. The gross revenue sales from electricity per year assuming 7 Kshs per kwh is 2.5 billion but assuming a lowest electricity tariff of 4 Kshs per kwh, gross revenue is Kshs 1.4 billion.

For a pessimistic approach, the other benefits are assumed zero as shown in table 7 below and only revenue from sale of electricity is used in calculation of the payback period. Assuming 5% of total revenue per year from the wells is apportioned to well testing using the improved silencer, the payback period is 4.7 months.

Table 5: Cost comparison

Silencer Type		Details	Quantity/Well	Unit Cost	Total Cost of Ownership
Improved silencer-Cyclone type		Separator/silencer	1	11,000,000	11,320,000
		Flow line cost	1	320,000	
Improved silencer-Gravity type		Separator/silencer	1	11,000,000	11,320,000
		Flow line cost	1	320000	
Old twin silencer		Separator/silencer	2	10,000,000	10,640,000
		Flow line cost	2	640,000	

Table 6: Benefits of improved silencer in comparison to the old silencer

Item	Benefit
Direct benefits	Additional generation capacity confirmation from areas not initially possible due to noise issues
	Better accuracy in well parameters for power plant design
Indirect benefits	Savings associated with project delays
	Savings associated with avoidance of penalization as a result of complaints from the community and other stakeholder issues/ environmental regulation compliance
Intangible benefits	Improved employee safety
	Improved in-house capability in design & employee satisfaction
	Miscellaneous benefits e.g good image for sustainable exploitation of geothermal resources.

Table 7: Costs and revenue estimation

Category	Details	Unit cost	Quantity	Costs in first year	Total revenue
Cost of Ownership	Acquisition cost 2 silencer prototypes	11,000,000	2	22,000,000	Tariff, 7kshs/kwh
Operation costs	Installation costs; 5 technicians, 1 engineer 5 man days	250,000	8	2,000,000	
	Discharge monitoring; 2 tech and 1 engineer for 60 man days	150,000	8	1,200,000	8 wells/year
	Vehicles and machinery engagement and operation costs	160,000	8	1,280,000	
	Well stimulation costs	150,000	8	1,200,000	Average 5 MWe per well Total of 40 MWe 5% of total revenue
Total				27,680,000	70,080,000

CONCLUSION

Noise emissions remain a critical issue while discharge testing geothermal wells and therefore there is need to improve on discharge test equipment used currently in Olkaria. A part from reducing the impacts associated with noise pollution on the personnel working at the wells and other stakeholders within the geothermal area, improved noise attenuating silencers also reduce delays in well testing of future wells and therefore enabling the company to meet field development targets. The following conclusions is made with regard to the improved well test equipment in Olkaria:-

- Delays in well test programs can be avoided by using the newly improved silencers for testing wells in Olkaria. This affects field development plans as well as confirmation of additional generation capacity.
- Noise reduction is achieved by use of the improved silencers which is within the limits of noise regulatory authority and that the silencers can be used in wells located in closer proximity to the local community without violations of these regulations.
- The new well test equipment has enabled testing of wells in noise sensitive areas, which was not possible in the past and may be used in future in other areas with similar stringent noise regulations.
- Better separation efficiencies and parameter accuracy is achievable with this new well test equipment ensuring quality and reliability of discharge data collected. However, it is recommended that the well should be tested using two twin old separator/silencer in an effort to achieve the same wellhead pressures and proof this assertion.
- The cost of ownership for the newly improved silencer is comparably same as the old silencer. However, the benefits of using the newly improved silencer far much outweigh the slight difference in price.
- Cyclone type separator/silencer is better than the Gravity type prototype in terms of noise reduction, separation efficiency and structural stability and therefore recommended for use as a well testing equipment in the Olkaria geothermal field.

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