PREDICTION OF

GEOTHERMAL TWO-PHASE SILENCER DISCHARGE SOUND LEVEL

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ABSTRACT

The operation of a geothermal steamfield or power station requires the intermittent discharge of process fluids to atmosphere to maintain stable operational control or to start-up or shut-down. The energy in the discharge is partially converted to sound which can impact on the receiving environment. Typically the design for two-phase or saturated water flows is a silencer consisting of a inlet jet pipe flowing into a horizontal duct to a vertical barrel. It is relatively simple, cost effective and the sound level design predictions have been approximated on previously installed units of similar size and duty.

With increasing environmental awareness there needs to be more certainty in the sound level prediction so that new plant is not operationally constrained or require modification after commissioning. A design prediction method is proposed that was determined from test data of operational silencers, process industry jet sound power calculations and an adapted model for viscous sound attenuation within the inlet duct. Limitations in the method, designer guidance and future investigation areas are also discussed.

1. INTRODUCTION

The conventional geothermal well steam-water silencer consists of an inlet jet pipe, inlet duct, vertical barrel with tangential entry and water duct (figure 1). This simple design has not changed in 55 years and is in wide spread use throughout New Zealand and the world. It is relatively simple and economical to manufacture. They are used to intermittently discharge either production wells to atmosphere for start-up or output tests, or separation plant discharges to atmosphere for start-up or plant upset reasons.

The description as a silencer is relative. It quietens the turbulent flow noise caused by the expansion of steam-water mixed flow into the duct. However to the environment beyond the plant area they less acceptable with a intrusive low frequency rumble. Because of this the steamfield plant owner can be restricted in hours of operation, have difficulty complying with consent conditions and incur greater capital cost to mitigate the sound levels with additional reduction devices or less than ideal plant relocation.

Production well pads which are sited to optimise reservoir production govern the location of well silencers relative to the surrounding environment. Separation plants are located for multitude of factors of which sound is usually one of the lesser. Currently early in the preparation of land use consent applications a sound budget is prepared based upon operating scenarios, expected locations and estimated sound power levels of the steamfield plant equipment. The inputs may be well defined from plant manufacture type tests for example reinjection pumpsets. Other items, for example the conventional well silencer are estimated on historic ad-hoc tests. As the silencer sound levels are strongly influenced by mass flow, enthalpy and inlet duct length as explained in this paper, wide variation of actual sound levels to historic can be experienced. This can be unexpected and costly to correct late in construction, or for example after deepening existing production wells. This could be mitigated by estimating conservatively high but the disadvantage of this can be to take too large of share of the sound budget away from other plant areas and impact the project's business case.

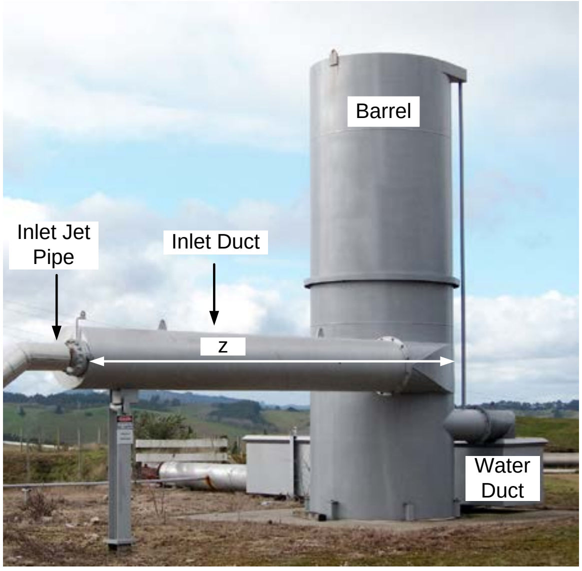

Figure 1: Geothermal Two Phase Silencer

This paper proposes a design method to improve the silencer sound prediction using process industry practice to determine jet sound power level, and sound absorption within the inlet duct analogous to the Beer-Lambert Law for light absorption, calibrated to experimental silencer data.

2. PROCESS FLOW DESIGN

The purpose of a silencer is to discharge geothermal flow in a controlled manner to atmosphere and water drain. The sound source is the sudden pressure drop of inlet flow generating flashed steam and this mixture accelerates up to sonic speed (approximately 500 m/s) at the vena contracta downstream of the inlet jet pipe. The exit velocity quickly decreases as it expands into the horizontal inlet duct. Here the steam superficial velocities are moderate at 70 to 150 m/s and near atmospheric pressure before slowing within into the vertical barrel down to 5 to 15 m/s. The tangential entry to barrel develops cyclone action that separates the water against the barrel walls, before with gravity assistance runs down to the base and out the water duct.

If the inlet duct or barrel is undersized relative to the inlet conditions, water will exit the barrel exit creating nuisance for plant maintenance and hot rain onto personnel. It can also cause increased back pressure in the base of the barrel and blowout the water duct steam seal resulting in inaccurate weir flow measurement and hot water splash hazard to personnel. There are a range of standard model sizes available to the designer whose selection is weighted towards the conservatively larger. The length of inlet duct is normally determined to decelerate the flow before reaching the barrel to prevent excessive cyclone velocity and water droplet exit from the top of the barrel.

Because the duct and barrel diameters are selected on the above flow velocities, and they are relatively large e.g. 0.6 to 3.3 metre for geothermal production wells. Adding this to the inlet jet's pipe size selection of 100 to 250 mm, then most of the sound power is concentrated in the lower frequencies below 250 Hz.

3. SILENCER SOUND CONCEPT

The kinetic energy in the vena contracta of the expanding jet of steam and water is partially converted to sound. This jet has turbulent shear eddies which for the typical size of jet pipes are heard as a low frequency roar. Although the conversion efficiency is very low in the range of 0.3 to 0.9 % for geothermal inlet pressures, the sound power levels are in the order of 150 to 160 dB. This is a similar source level to a fighter jet engine on takeoff.

The source sound reverberates within the inlet duct containing a mist regime (due to high superficial steam velocity) of two-phase flow travelling to the barrel. The water fraction of the flow in mass terms for well enthalpies in the range of 700 to 1550 kJ/kg is 87 to 50 % respectively. In volume terms it is only 0.4 to 0.06 %. The sound power is attenuated by viscous vibration of water mist. This attenuation dominates over any other silencer effect that may occur due to semi reverberant inlet duct and source sound that has most of its energy in the low frequency region.

The sound is discharged at the vertical barrel exit. There is little attenuation due to directivity to the observer due to the large barrel diameter and low frequencies (Day et al, 2009). The barrel exit sound level is the most dominant because the other sources of sound radiation from the inlet duct and barrel wall (approximately 105 dB) or induced suck leakage at the inlet pipe (approximately 110 dB) are at least 15 dB lower and are not significant in the measured far field levels.

The typical sound spectrum (figure 2) is weighted in the low frequency band with 80 % of the sound power below 250 Hz. The difference between the A and C weighted scale sound pressure levels is at least 10 dB, sometimes up to 20 dB. Distance tend to filter out the mid to high frequency content compared to the sound at source. This has the effect of emphasizing the low frequencies and the rumble perception. Low frequencies are more efficient at bending over obstacles or terrain and more easily pass through the lightweight fabric of typical New Zealand buildings.

Dry steam sound prediction methods have been published (Lazalde-Crabtree 1985) for silencers using reaction-absorption or plenum designs. Rock pits are widely used in the geothermal industry for power station venting and the performance is known. Additionally vendors have proprietary muffler designs. These designs use various techniques to reduce sound levels and filter low frequencies i.e. pipe diffusers, tortuous plenum passages, absorptive material. These have additional capital or maintenance cost, loss of flow capability, more difficult flow measurement and are not the first selected by the plant designer to reduce two-phase silencer sound levels.

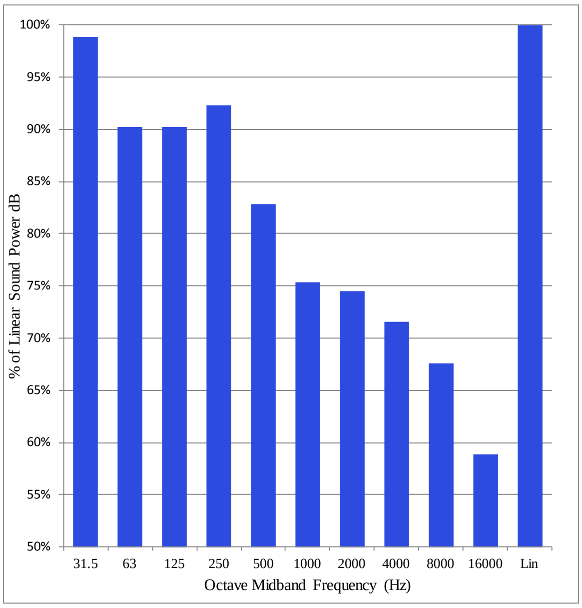

Figure 2: Typical Sound Spectrum

Two-phase sound prediction methods have not been previously published for the geothermal industry and this paper proposes a simple and quick means for the plant designer to judge whether the simple design is appropriate for the process conditions and physical location**.**

4. NUMERICAL SOUND PREDICTION METHOD

The aim of this sound prediction method is to improve the accuracy to an acceptable level while using simple process flow and acoustic calculations. It can be simply implemented on spreadsheets or programmable calculators. This calculation doesn't require the inlet pipe, duct and barrel diameters, the number of inlet ducts and barrels, or the thickness and materials of the silencer.

The inlet mass flow, pressure and enthalpy are normally measured during a geothermal wells output test using the James Method (James, 1970). The jet and inlet duct conditions are determined from the assuming adiabatic flashing to atmospheric conditions. The steam pressure in the inlet duct is assumed to be atmospheric and saturated.

$$x = (h - h_f)/\, h_{fg} \qquad (1)$$

$$m_s = m_i \, x \qquad (2)$$

$$m_w = m_i - m_s \qquad (3)$$

$$V_s = m_s \, v_g \qquad (4)$$

If the inlet duct pressure is lower than the critical pressure (P*) of the jet steam, the vena contracta will be at sonic velocity (~ 500 m/s). Additionally the jet is not confined, isentropic recompression exists and sound emitted is due to turbulent flow shearing. The sound power of steam jet entering the inlet duct can be determined using process industry methods described in standards and recommended practices (IEC 60534-8-3 & API RP 521). These have been adapted for this paper's prediction method. The API method is presumed to use the early work of Franken in the 1950s to determine conversion efficiency of the jets kinetic energy to acoustic.

$$P_* = P_j \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \quad (5)$$

$$W_j = \frac{\eta m_s c_j{}^2}{2} \quad (6)$$

c_j and γ are determined from steam properties

η is determined from figure 3 which is an conversion of the API RP 521 chart scale for sound pressure at 100 feet and numerically this is

$$\text{If } \left(\frac{P_j}{P_d}\right) > 2.8,\ \eta = 10^{0.53\log\left(\frac{P_j}{P_d}\right)-2.86)} \quad (7)$$

$$\text{If } \left(\frac{P_j}{P_d}\right) < 2.8,\ \eta = 10^{8.87\log\left(\frac{P_j}{P_d}\right)-6.59)} \quad (8)$$

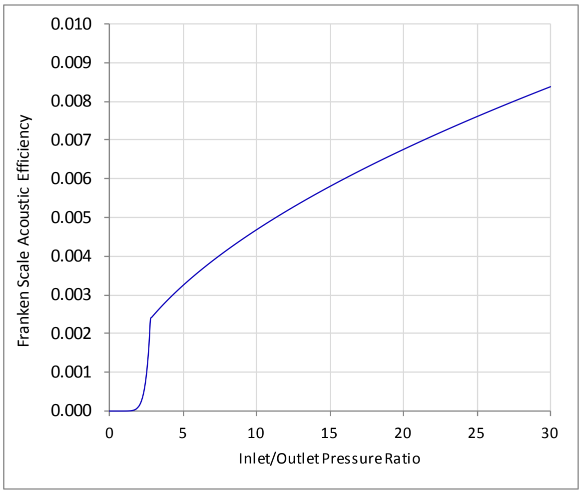

Figure 3: Franken Scale Conversion of API RP 521

Sound power is converted to power level (dB)

$$L_j = 10\log\left(\frac{W_j}{W_{ref}}\right) \quad (9)$$

The phenomena of sound wave scatter and absorption by material confined within a tube has been rigorously studied by others. The calculations are complex and so the authors sought a practical alternative and chose to test the analogous phenomena of light waves scatter and absorption.

The Beer-Lambert Law for inverse exponential power law intensity light attenuation through a concentrated solution in a tube has been adapted. The light attenuation coefficient is the mathematical product of absorptivity factor, tube length and concentration of solution in the tube.

$$TR = e^{\mathrm{E}zC} \quad (10)$$

$$Ln(TR) = EzC \quad (11)$$

where E is the absorptivity factor

z = tube length

C = solution concentration

When adapted for sound attenuation we have

The inlet duct length is shortened by the relative inlet duct and sound speeds. The effective length is

$$z' = \frac{z}{\left(\frac{c_a + u_d}{c_a}\right)} \quad (12)$$

C = water concentration in inlet duct steam flow

$$= \frac{m_w}{V_s} \quad (13)$$

The test result data has determined that the absorptivity factor is constant but the transmission ratio has an offset (*b*) which is apparently constant, due to 1) acoustic attenuation from the abrupt enlargement of the inlet duct into the barrel and 2) sound suppression in gas-water jet mixtures which is not well understood due to the complex physics interactions (NASA-HDBK-7005). Modifying equation (11) for the transmission ratio offset, effective length and water concentration we have

$$Ln(TR) = a(z'C) + b \quad (14)$$

where a is the absorptivity factor = -0.0175

b is the TR offset = -3.6066

To determine the barrel exit sound power

$$W_e = W_j TR \quad (15)$$

Sound power is converted to power level (dB)

$$L_e = 10\log\left(\frac{W_e}{W_{ref}}\right) \quad (16)$$

To determine the observers sound pressure level at distance requires the observers distance from barrel, directivity index of barrel exit and using the assumption of half sphere sound *propagation* (i.e. across flat ground and without atmospheric absorption for short distances). Because of the dominant low frequencies and large diameter barrel the directivity index (DI) will only be in the range of 1 to 3 dB (Day et al 2009, figure 2).

$$L_o = L_e - DI - 20\log(R_o) - 8 \quad (17)$$

5. EXPERIMENTAL DATA AND DISCUSSION

Process and sound data was derived from historic commissioning records and recent plant tests by the authors. The data is across a broad range typical of geothermal plant in 6 locations.

Table 1 – Experimental Data Range

	Minimum	Maximum	Unit
Inlet Pressure	7.0	26.6	bar.a
Inlet Mass Flow	27.5	177.8	kg/s
Inlet Enthalpy	713	1545	kJ/kg
Inlet Duct Length	5.6	14.1	m
Inlet Duct Diameter	0.61	1.2	m
Barrel Diameter	1.2	3.3	m
Barrel Exit Sound Power Level	118.8	140.9	dB

Well output test and plant flow measurement data was correlated to the timing of sound level measurement. Sound pressure measurements were captured at 10 or 20 metre horizontal distance from the silencer barrel wall to calculate the source sound power level. Other sound sources were measured to ensure that they were low enough to not contribute to the field measurement and could be discarded.

Table 2 contains the data inputs and calculation results to validate the prediction method. The empirical linear fit (figure 4) of inlet duct absorptivity coefficients are

a = -0.1705, b = -3.6066 and fit r^2= 0.96

Coefficient *b* is the apparent offset when the Beer-Lambert Law adaptation is used and it appears to be constant. Some of this offset is due to the abrupt enlargement from the inlet duct to barrel of approximately 4 dB. The remainder of the offset, 12 dB we postulate is due to complex water noise suppression inside the jet, which is beyond the scope of this paper.

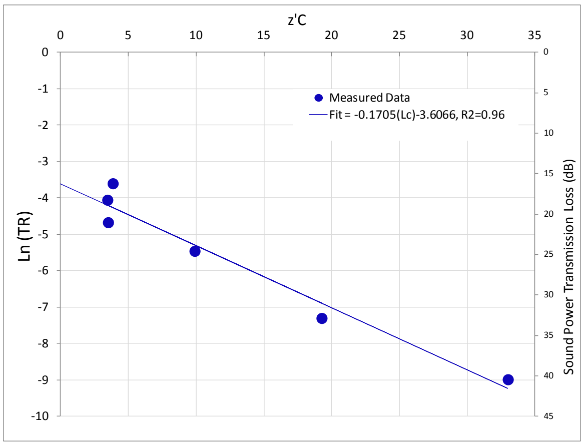

Figure 4: Measured Data Fit

We can conclude that the sound prediction model has good accuracy within ~ 2 dB of the experimental data. It is valid across a broad range of geothermal silencer process conditions.

6. FUTURE INVESTIGATION OF METHOD

Future improvements in the prediction method is expected to come from investigation into

a) very low inlet pressure and low enthalpies where the jet velocity is less than sonic.
b) the difference between dry steam and steam-water mixture sonic velocities. Initial calculations indicated that this factor lowers the prediction accuracy and doesn't reduce the apparent offset in the *b* coefficient.
c) the influence of sound breakout relative to the transmission ratio when long inlet ducts are used.
d) additional experimental data.

7. DESIGNER GUIDANCE

The greatest influences on the reduction of barrel exit sound power levels given typical geothermal process conditions are in priority are –

1) Lower inlet enthalpy
2) Longer inlet duct length
3) Lower inlet flow
4) Lower inlet pressure

During the preliminary design of the plant the engineer needs good pre-estimates of well enthalpy or plant process temperatures to predict silencer sound levels that contribute to the overall sound budget for new projects or existing steamfields.

8. CONCLUSION

A sound prediction method for geothermal two-phase discharge silencers has been developed and validated for a broad range of process conditions. It is relatively simple and quickly calculated to an accuracy of 2 dB.

Accurate sound level prediction allows the designer to mitigate the environmental sound impact of steamfield or power station developments.

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NOMENCLATURE

a	Absorption Attenuation Slope Coefficient
b	Absorption Attenuation Constant Coefficient
C	Water Concentration in Duct Steam Flow (kg/m3)
c_a	Steam Sonic Speed at Atmospheric Pressure (m/s)
c_j	Steam Sonic Speed at Jet Inlet Pressure (m/s)
DI	Sound Directivity Index (dB)
E	Absorptivity Factor
h	Inlet Flow Enthalpy(J/g)
h_f	Inlet Duct Water Enthalpy (J/g)
h_{fg}	Inlet Duct Evaporation Enthalpy (J/g)
L_e	Barrel Exit Sound Power Level (dB)
L_j	Jet Sound Power Level (dB)
L_o	Observer Sound Pressure (dB)
m_i	Mass Flow (kg/s)
m_s	Steam Flow (kg/s)
m_w	Water Flow (kg/s)
P_*	Steam Critical Pressure (bar.a)
P_d	Inlet Duct Pressure (bar.a)
P_j	Jet Inlet Pressure (bar.a)
R_o	Observer Distance from Barrel (m)
TL	Sound Power Transmission Loss (dB)
TR	Sound Power Transmission Ratio
u_d	Inlet Duct Steam Velocity (m/s)
ν_g	Inlet Duct Steam Specific Volume (m3/kg)
V_s	Steam Flow Rate (m3/s)
W_e	Sound Power of Barrel Exit (W)
W_j	Sound Power of Steam Jet (W)
W_{ref}	Sound Power Reference Level (10^{-12}) (W)
z	Inlet Duct Length (m)
z'	Inlet Duct Effective Length (m)
η	Franken Scale Jet Acoustic Efficiency
x	Duct Steam Mass Fraction
γ	Steam Specific Heat Ratio at Jet Inlet Pressure

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Table 2 – Data Inputs and Calculation Results

No.	m_i (kg/s)	P_j (b.a)	*h* (kJ/kg)	z (m)	z' (m)	Barrel Dia. (m)	Cal *Lj* (dB)	Field *Le* (dB)	*TR*	*TL* (dB)	*C*	*z'C*	Ln *TR*	Difference between Model & Measured *Le* (dB)
1	27.5	7.0	1363	5.6	4.90	1.83	157.6	141.9	0.02722	15.7	0.79	3.85	-3.60	2.9
2	28.3	12.4	1417	5.6	4.84	1.83	159.3	141.7	0.01732	17.6	0.71	3.45	-4.06	0.6
3	177.8	7.0	713	10.6	8.83	2.6	160.6	121.6	0.00012	39.0	3.74	33.0	-8.99	1.1
4	41.1	26.6	1545	7.25	6.16	2.3	162.9	142.6	0.00934	20.3	0.57	3.50	-4.67	-2.0
5	118.9	15.1	1033	14.1	12.76	3.3	163.9	132.2	0.00067	31.7	1.51	19.3	-7.30	-1.8
6	104.4	17.7	1227	12.9	9.76	2.6	164.9	141.2	0.00425	23.7	1.01	9.89	-5.46	-0.7