THE HIGH VALUE OF LOW-PRESSURE GEOTHERMAL STEAM

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SUMMARY - Over the pressure range of 1-20 bar abs where most geothermal power plants operate, a 10% pressure loss of saturated steam causes a power loss of about 12 kWe/(kg/s) steam flow rate (i.e. electrical energy loss of 12 kJ/kg steam). For example, a steam pressure loss from 10 to 9 bar abs (1 bar drop = 10% loss) causes an electrical energy loss of 12 kJ/kg (at 80% turbine efficiency and 0.1 bar abs condenser pressure); but a pressure loss from 1 to 0.9 bar abs (0.1 bar drop = 10% loss) causes a loss of 13 kJ/kg. This is worth about $4000/year per kg/s of steam at 5 cents/kWh and 80% plant factor. Hence, pressure loss of low-pressure steam costs much more than the same pressure loss of high-pressure steam. Therefore, attention should be paid to reducing pressure loss in low-pressure geothermal steam.

1. INTRODUCTION

The most valuable type of geothermal resource is one that can be used for power production. Unfortunately, this type of resource is rare considering the large number of geothermal energy resources, and the vast amount of geothermal energy available. Hence, these rare resources should be used efficiently.

Most geothermal fields for power production are wet fields producing two-phase steam-water fluids at the wellheads from wells about 1-2 km deep. Saturated steam is then separated from the water, and the steam is transmitted in long steam pipelines to steam turbines for power production. The saturated steam pressure is commonly around 7 bar abs but can be as low as 1.1 bar abs as in Wairakei LP (low-pressure) steam, or as high as 25 bar abs as in Rotokawa. It is common for the steam pressure to drop 10-20% *after* travelling several km in pipelines from the separators to the steam turbines. The pressure loss is due mainly to friction, and the pipe wall roughness is a major contributing factor.

Figure 1 shows that the pipe wall roughness could increase 5 to 20 times and the friction factor up to 200% due to corrosion and deposition scales after some years of operation (Lee et al, 1997). To reduce the friction factor, it was recommended that the pipe walls be cleaned every 10 years. However, it is found that 0.1 bar pressure loss from LP steam of 1 bar abs costs as much as 1 bar pressure loss from high-pressure (HP) steam at 10 bar abs. Therefore, the high value of LP steam warrants more attention be paid to reducing pressure loss in LP steam. For example, a 5-year old 1200mm diameter steam pipeline had a Darcy friction factor of 0.009, while a 20-year old one had 0.014 (Lee at al, 1997). So, the pressure loss in the older pipe can be reduced by 35% if it is cleaned of the corrosion and deposition scales. At the current flow conditions, this translates to about $15,000/year at 1 cent/kWh.

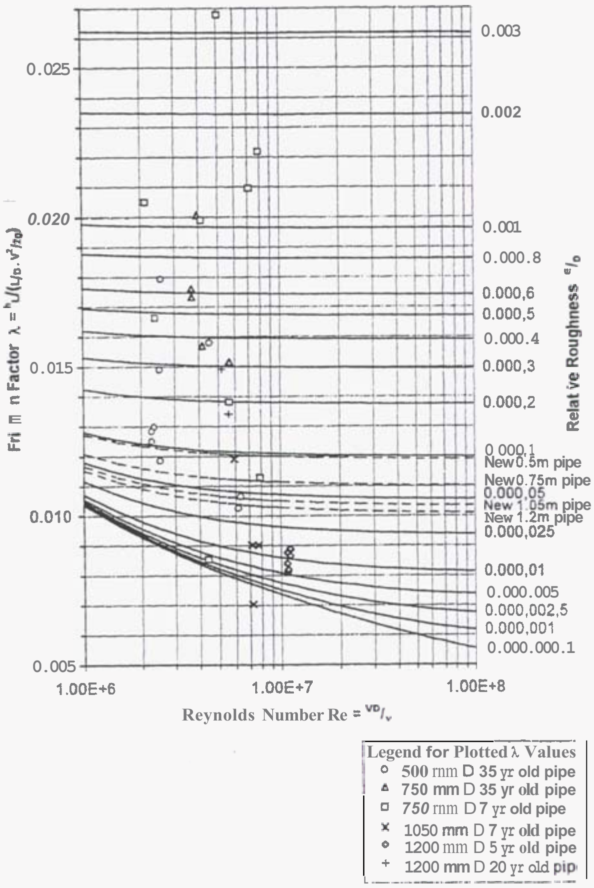

Figure 1: Measured and predicted friction factors plotted on Moody diagram (Lee et al, 1997)

This paper looks at geothermal steam piping costs, costs of steam pressure losses, and attempts to explain the high value of low-pressure geothermal steam.

2. STEAMPIPING

Geothermal main steam transmission pipelines are generally large (nominal diameter (DN) 500-1100 mm) and thin wall (8-13 mm). A steamfield in production may have tens of km pipelines and hundreds of pipe supports. Koorey (2000) and Niu (2001) attempted to reducing piping cost by maximising pipe support spans. The maximum spans are limited by the local stresses at the pipe supports due to the thin pipe walls. Reinforcing saddles can be used at the supports to increase the support spans. The maximum span for large diameter (DN>500 mm) pipelines is about 20 m.

Although the method for pressure drop prediction in single-phase flow is well established using a Moody diagram to indicate friction factor, the accuracy of pressure drop prediction in geothermal steam pipelines depends very much on the accuracy of the pipe wall roughness heights used. While the wall roughness of a new pipe is known reasonably accurately, a geothermal steam pipeline, after many years of service, will have corrosion and/or deposition scales that change the pipe wall roughness dramatically. For example, Wairakei 40-year old 750mm DN steam main lines have wall roughness of 0.23-0.83 mm (Lee et al 1997) whereas a new pipe has 0.046 mm (Moody diagram). Although the wall roughness may increase by 20 times, the increase in friction factor is only about 2 times. i.e. the pressure loss is doubled. This-shows that the inside walls of steam pipelines need to be cleaned after a period of service (about 10 years), depending on steam quality, corrosion and deposition rates.

3. COST OF STEAM PIPING

The total installed cost (excluding valves and engineering costs) of piping varies between US$2.5-3.1/kg (US$5.0-8.7/DIF (diameter-inch-foot)) for 250 mm DN (10") to 1050 mm DN (42") pipes based on a 1997 Philippines geothennal project as shown in Figure 2. The cost is inclusive of thermal insulation and pipe supports but excluding valves and engineering costs. Installed cost of piping in $/kg is reasonably constant over the diameter range compared to $/DIF.

4. COST OF STEAM PRESSURE DROP

For a typical wet geothermal field producing saturated steam in the range of 1-20 bar abs, a 10% steam pressure loss causes a power loss of 12±1 kWe per kg/s steam (i.e. an electrical energy loss of 12±1 kJ/kg steam) as shown in Fig. 3. This is equivalent to 24% power loss, assuming 80% turbine efficiency and a condenser pressure of 0.1 bar abs (see Fig. 4). Fig. 3 also shows that the power loss is not affected significantly by condenser pressure for the Same percentage pressure loss, but that the power loss is doubled when the percentage pressure loss is doubled.

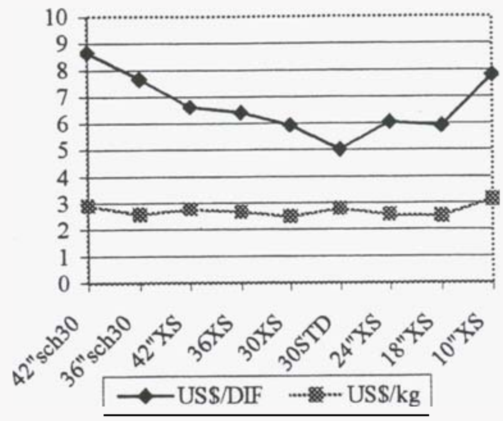

Figure 2: Cost of installed pipe 1997 (excluding valves & engineering) (Data from Sinclair Knight Merz Ltd)

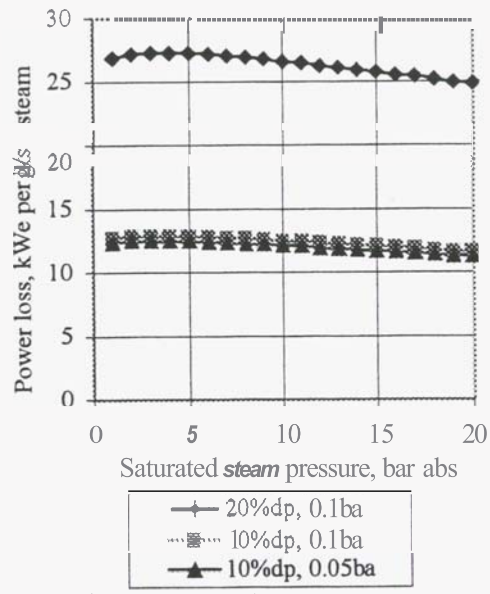

Figure 3: Power loss due to steam pressure loss (% pressure drop (dp), condenser pressure, bar abs) @ 80% turbo-generator efficiency

For example, at 10 bar abs turbine inlet saturated steam pressure and 0.1 bar abs condenser pressure, the electrical energy produced is 553 kJ/kg. At 9 bar abs (10% pressure loss), energy produced is 541 kJ/kg. So, the energy loss = 553-541=12 kJ/kg. Similarly, for 0.05 bar abs condenser pressure, the energy loss = 615-603=12 kJ/kg. The effect of condenser pressure between 0.05-0.1 bar abs on energy loss due to 10% steam pressure loss is therefore insignificant (2.5%). [However, the effect of condenser pressure on power output is significant for a constant steam turbine inlet pressure (at 10 bar abs, power loss = 615-553=62 kJ/kg=11%)]. The equivalent annual revenue loss is between $4000-$6000 per kg/s steam as shown in Fig. 5 (5 cents/kWh & 80% load factor and 6 cents/kWh & 90% load factor). Doubling the percentage steam pressure loss marginally more than doubles the power loss hence the revenue loss.

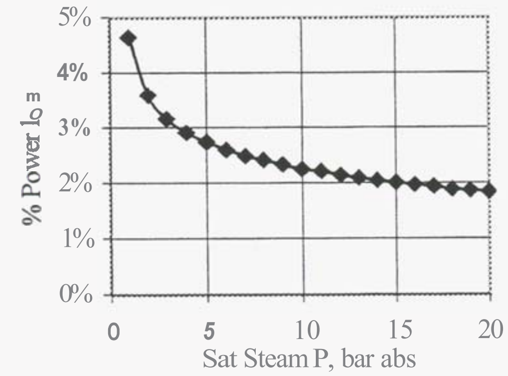

Figure 4: % Power loss due to 10% steam pressure loss @ 0.1 ba condenser and 80% turbine efficiency

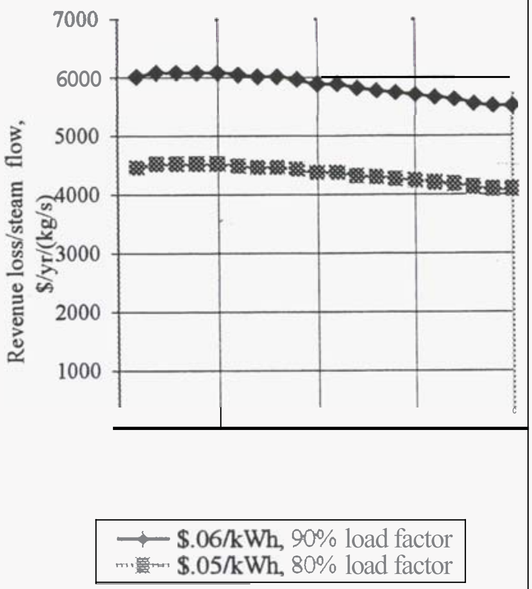

Figure 5: Revenue loss due to 10% steam pressure loss @ 0.1 bar abs condenser pressure and 80% turbine efficiency

A 10% steam pressure loss of low-pressure steam is relatively smaller in term of magnitude of pressure loss but causes marginally higher power loss and revenue loss compared to high-pressure steam. That is, 0.1 bar pressure loss at 1 bar absolute steam costs as much as 1 bar pressure loss at 10 bar absolute steam. In other words, pressure loss at low steam pressure costs much more than the same pressure loss at high steam pressure.

5. PRESSURE DROP DUE TO DRAIN POTS

Lee (1981) showed that Wairakei's shallow drain pots were 40% efficient (water flow rate removed/water flow rate upstream of drain pot), deep drain pots were 80% efficient, and a drain pot with a baffle plate had 95% efficiency. The pressure drop coefficient ($\Delta P/½\rho v^2$) across a drain pot is about 10%. For a typical steam pressure of 7 bar abs and steam velocity of 40 m/s, the pressure drop across a drain pot is only 300 Pa (0.003 bar).

6. PRESSURE-ENTHALPY DIAGRAM

To explain the almost constant power loss over the pressure range of 1-20 bar abs due to a constant percentage of steam pressure loss in Figure 3, it is best to look at the steam exergy on a pressure-enthalpy (P-h) diagram in semi-log plot as shown in Figure 6. The saturated steam exergy based on 0.1 bar abs condenser pressure is plotted. Exergies for supercritical steam of 500°C and 600°C over 100-300 bar abs are also plotted for comparison. A typical wet geothermal field total mass output for a 100 MWe power station is also plotted.

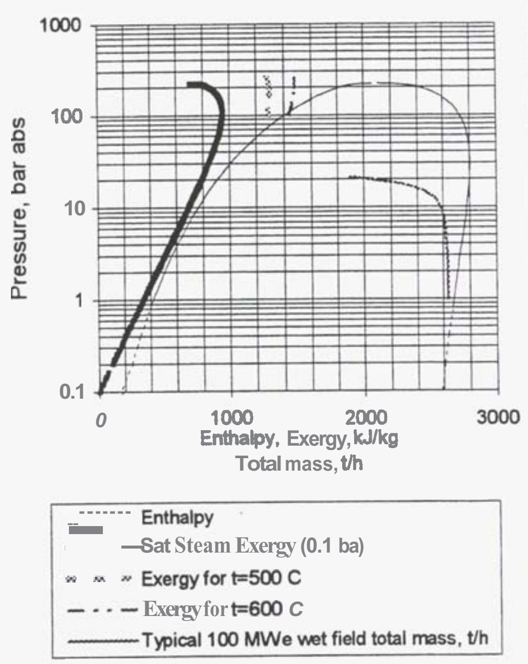

Figure 6: Steam-water Pressure-Enthalpy diagram

The saturated steam enthalpy is almost a straight line from 1 to 20 bar abs on Figure 6. Similarly, the saturated steam exergy line is also nearly a

Straight line over the same pressure range. A straight line with the pressure on log scale clearly shows that a constant percentage of pressure loss over the pressure range will give a constant exergy loss. For example, a 10% pressure loss from 10 to 9 bars gives the same vertical height as a 10% pressure loss from 1 to 0.9 bar, and therefore the same exergy differential on the linear horizontal exergy scale. Since power or electrical energy is proportional to exergy by the turbine efficiency factor, this explains the almost constant power loss for a constant percentage of steam pressure loss in Figure 3.

It is interesting to note that the exergy of saturated steam at a pressure near the critical point, say 200 bar abs, is actually less than that at 100 bar abs where approximately the maximum occurs. Similarly, for supercritical steam at constant temperature, a maximum exergy exists with respect to pressure.

The total mass curve on Figure 6 clearly shows the typical constant mass flow at low wellhead pressure (WHP) but rapid decline with high WHP. This means that over the low-pressure range of 1-10 bar abs WHP, the pressure loss in a steam pipeline does not significantly affect the total mass flow from the wells. At high WHP (>10 bar abs), to maintain a constant pressure at the turbine inlet, higher pressure loss in the steam pipeline will require higher WHP which may reduce the well output significantly. However, the operating pressure is selected at the maximum power potential point which is likely to be between 1-10 bar abs for the typical mass curve in Figure 6. Hence, Figure 3 is valid even when total output characteristics of wells are taken into account.

7. CONCLUSIONS

Installed cost of mild steel piping for geothermal fluid transmission in 1997 was about US$3/kg for DN 250-1050 mm (10"-42") including pipe supports and thermal insulation but excluding valves and engineering design.

A 10% saturated steam pressure loss will cause a power loss of about 12 kWe/(kg/s) of steam over the pressure range of 1-20 bar abs. This is worth $4000-$5000/year per kg/s of steam at 5 cents/kWh and 80% plant factor. Pressure loss of low-pressure steam costs more than the Same pressure loss of high-pressure steam, hence the high value of low-pressure geothermal steam.

The constant power loss due to a constant percentage of saturated steam pressure loss can be explained by the straight line exergy plot on the semi-log pressure-enthalpy diagram.

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