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Design Considerations and Technology Utilized on Geothermal Power Plant Turbines for Efficient, Reliable Operation

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ABSTRACT

The cost for geothermal resource exploration, drilling and plant construction represents one of the big financial risks in the development of a geothermal power plant. The second risk is to ensure the equipment used to convert this thermal energy into electrical power meets the challenge of this demanding application. This paper will get into the design challenges that are unique to geothermal steam applications which must be addressed to ensure long term reliable power generation.
Covered in this paper are the issues such moisture erosion, materials selection, steam chemistry limits, impact of steam field depletion and options for geothermal cycles available today.

INTRODUCTION

There have been many papers written that describes the various cycles for geothermal plants. Ref. DiPippo (2005) and Leger (2012). The first decision to be made by a developer or their engineer is to decide if the plant will utilize a direct cycle (dry steam or flash plant), a binary cycle or combined cycle. If the resource is superheated steam then the obvious choice is an Open-Loop Rankine cycle. At moderate temperatures, which is the case in many locations in Indonesia where there is a mixture of vapor and liquid. That mixture must be flashed and the liquid separated from the vapor. This paper will focus on the open-loop Rankine cycle which has the greatest population currently in Indonesia as well as world wide and likely to be the predominant cycle for upcoming projects. This direct steam cycle means that the steam turbine is exposed to geothermal vapor and all of the impurities and non condensable gasses that are in the steam.

When the resource temperature is lower than 140 °C (284 °F), the option to use a combined cycle or binary plant should be considered which utilize an Organic Rankine Cycle (ORC). This is covered in Ref. Dickey (2011) and Leger (2012) and will not be discussed in this paper.

MAXIMIZING AVAILABLE ENERGY

Geothermal turbines differ from conventional steam turbines due to very low inlet enthalpy and high moisture content. A flash plant steam turbine rated at 30 MW could have the same last stage blade height as an industrial steam turbine rated at 100 MW. There is a very small range of available energy from the inlet enthalpy to the enthalpy at the exhaust. For this reason, extra care is taken to minimize any pressure drops in the inlet piping and valves. A 1% drop in inlet pressure could result in a 0.5% loss in output.

Another option that is often considered in the early phases of development of a geothermal resource is to consider the use of a turbine that exhausts to the atmosphere. The exhaust enthalpy at atmospheric pressure is such that about 50% of the available energy is lost. This means that if a condensing turbine was used in place of a non condensing turbine, the output could be doubled. It is much more efficient to run a condensing turbine.

However, there are situations when this configuration could make sense. These atmospheric exhaust turbines (also referred to as Non Condensing) are less expensive to build because there are fewer stages due to the reduced energy range and the back end blading is very short due to the high specific volume as the steam expands. Another plant cost benefit for atmospheric exhaust plant is the fact that there is no “Cold End”, that is no: condenser, condensate pumps, Non Condensable Gas (NCG) removal system or cooling tower. This approach may be the best way to give a resource some long term load testing to validate the well(s). Operation of such a unit can also be used to power drill rigs and remote camps that otherwise would have to depend on diesel engines for this power. It is believed that the environmental impact of exhausting the steam and gases is no worse than the impact of the exhaust of the diesel engines and the trucks that delivers the fuel.

TURBINE INLET COMPONENTS

Geothermal steam, as mentioned above, is at low temperature and pressure resulting in relatively high mass flow. The high mass flow means that the turbine inlet valves must be large. Geothermal turbines have inlet components that are up to 10 times as large as conventional plants. Also critical to the plant efficiency is minimizing strainer and valve pressure drops. Strainers are selected to protect the turbine from solid particles in the steam but must be designed to minimize fouling which would have and impact on performance.

The turbine is designed to convert the thermo-dynamic energy of the steam to electrical power. The inlet valves must be designed to minimize pressure drops and to close quickly. Not an easy task for large valves. These valves are also the safety shut off system and therefore, must be able to close tightly. Geothermal turbines also normally run parallel to the grid and run wide open, as any throttling of the steam results in loss of available energy. Therefore, the valve of choice for geothermal service is a triple offset butterfly valve. These valves are used for stop (open and close only) and control (discrete valve position) service. Often a smaller butterfly valve is used for start up and synchronizing of the turbine which is installed parallel to the main control valve.

The control valves must be positioned by the turbine control. The system requires valve position feedback. Quick closing features often include large springs that provide a failsafe system upon loss of control oil. Hydraulic systems must take into account the amount of force required and the size of the actuator is impacted by the pressure of the control oil. Therefore, it is quite common to have hydraulic pressures in the range of 100 bar (1450 psi). These high pressure valves use independent hydraulic power units equipped with redundant trip solenoids that further assure safe operation and tripping of a geothermal unit. See Figure 1 for a picture of a high performance butterfly valve with a high pressure actuator.

Figure 1: Butterfly valve with high pressure actuator.

SILICATE SOLUABILITY

One of the factors that must be taken into account when the cycle options are considered is the amount of silicate in the resource. Long term reliability and capacity of a geothermal flash plant and piping depends on avoiding the precipitation of silica. The precipitation of silica is a function of time, concentration and temperature. Time is easily extended by the addition of acid to the geothermal brine, but must done to avoid reaching unacceptable levels of pH that can have adverse effects on the steam turbine materials.

When brine is flashed in a steam separator, trade-offs are made to get the best combination of steam enthalpy and flow. Typically around 12 % of the total mass flow leaves the separator as steam. The rest of the liquid still has energy. The temptation to flash the brine a second time to improve the overall cycle efficiency is rarely done due to the solubility of amorphous silicates that precipitate at low temperatures. This can result in significant fouling of the turbine. One example of silicate fouling of an operating unit in Indonesia can be seen in Figure 2 below.

Figure 2: Stage 1 blade scaling Gunung Salak 55 MW turbine. Ref: Adiprana (2010)

When the steam path is fouled by these silicates the result can be a loss in flow passing capability and reduction in efficiency with a bottom line result of lower output of the turbine generator set. Another impact is the potential of building up a stage thrust when the turbine design is based on reaction technology. A 5% increase in fouling can double the stage trust. If the turbine is a double flow design, the risk of overloading the turbine's thrust bearing is mitigated because there is a corresponding thrust caused by the stage on the other flows section. This is one of the benefits of a double flow design.

A common practice to clean these deposits is the occasional addition of water ahead of the turbine valves to increase the moisture content. This cleaning process called "Water Washing" can take up to several days to break up the scaling that occurs. The successful results are indicated by an increase in output. Adding water to the turbine will help clean the deposits but will add further risk for erosion of the blades and diaphragms. Another risk is plugging the drains orifice or piping in the typical geothermal turbine. Drain designs will be discussed later in this paper. When water washing a single flow turbine, the turbine thrust bearing temperatures should be closely monitored as water is added to the inlet piping.

STEAM CHEMISTRY

The chemistry of the steam needs to be taken into account not only for the steam turbine but for the entire steam field piping, separator, scrubber, demister and steam strainer. There are techniques to cleanup the steam by water washing and other abatement processes to improve the chemistry. The sooner the steam is cleaned; the need for exotic materials that can be extremely expensive can be minimized. It is also recommended that on-line monitoring of steam chemistry be included in the plant design as a way to check the effectiveness of the system and determine if there is a problem

Figure 3 is an example of the impact on stage 1 of a turbine when the steam chemistry was out of tolerance resulting in nearly complete plugging of the first stage nozzle of this impulse turbine.

Figure 3: Stage 1 blade scaling on impulse steam turbine in geothermal service

Each turbine should be designed to meet the expected steam chemistry from a geothermal resource. Steam cleaning, steam treatment and abatement can be expensive but may be the only way to ensure the expected capacity factors for the plant. Table 1 lists acceptable levels of steam chemistry that could avoid the need to use very expensive materials.

Table 1: Geothermal Steam Guidelines for long term availability

Geothermal Steam Purity Guidelines		
Type	**Element**	**Limit**
Steam	pH	5.5 to 7.5
Chemical Elements	Cloride (Cl), ppm	< 4.
	Sulfate (SO_4), ppm	< 1
Total Dissolved Solids	TDS, ppm	< 5
Individual Solids	Silica (SiO_2), ppm	< 4
	Calcite ($CaCO_3$), ppm	< 4
	Calcium (Ca), ppm	< 2
	Total Iron (Fe), ppm	< 1
	Sodium (Na), ppm	< 2

STEAM PATH DESIGN SIZING

When the steam path for a steam turbine is designed, it takes into account the inlet steam conditions: pressure, temperature and flow; the exhaust pressure, the turbine speed and any off-load points. The number of stages is selected to get the optimum velocity ratio of the wheel speed and the steam velocity. The wheel pitch velocity can be impacted by changing rotating speed or the diameter of the wheel. It is the designer's task to evaluate all of the variables to select the correct number of stages and the proper blade sizes.

In most situations, considering the flow to the exhaust section and the exhaust pressure will drive the design. The aerodynamic and mechanical design of tall blades is a time consuming task and can take many iterations. Most manufactures have come up with a family of tall back end blading and casings that match the design volume flow. The back end blade selection often dictates the rotating speed of the machine and if the design requires a single flow as shown in Figure 4 or double flow configuration as shown in Figure 5.

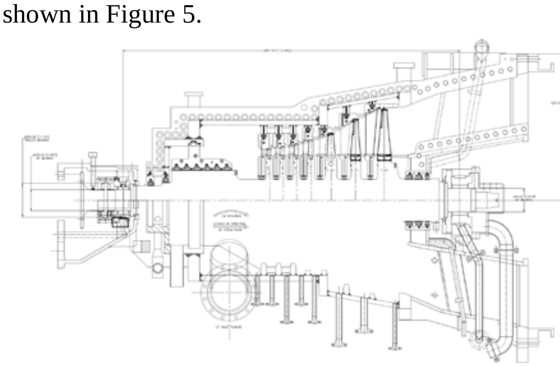

Figure 4: Single flow impulse turbine with an axial exhaust

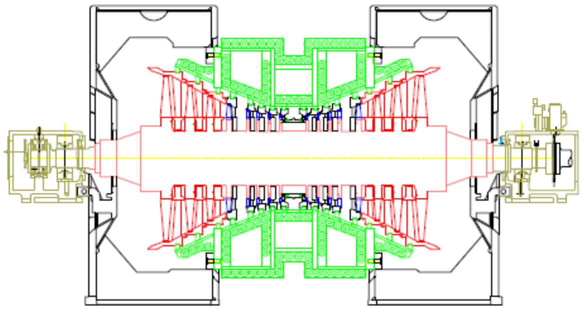

Figure 5: Double flow, dual flash impulse turbine Siemens SST-500 GEO

HIGH PRESSURE STAGING DESIGN

A steam turbine can be considered as an orifice in the steam line. The larger the orifice, the more flow it will pass. Just as with a garden hose, the higher the inlet pressure, the more flow it will pass. The challenge for the turbine designer is to pick the number of stages and wheel diameters to optimize the performance and then select high pressure nozzle areas to pass the required volume flow. This is where close coordination between the plant designer and the turbine engineer is necessary. The first stage nozzle area essentially determines the flow passing capability for the turbine at the specified conditions. If additional output is required once this nozzle area has been fixed, it will take more pressure or higher temperature to pass more flow or utilize the increased available energy. Conversely, if the inlet pressure falls, the turbine will not be able to pass the same amount of flow as it would with full pressure.

Figure 6 shows the nozzles for stage 1 of an impulse turbine.

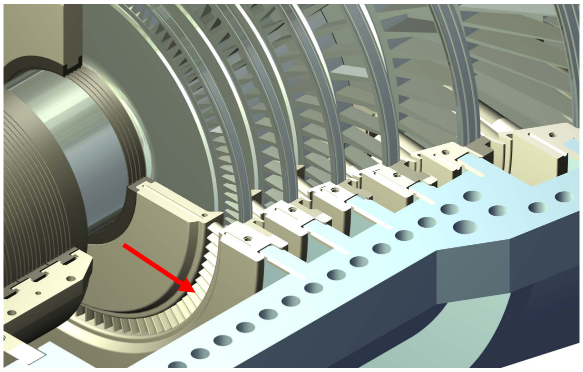

Figure 6: Stage 1 nozzles of an impulse steam turbine

One option used in the past for marine turbines when they wanted additional power without the concern for efficiency was to install an inlet after the first stage that could be used to admit additional steam. This is called a stage 1 bypass or overload valve. This feature has been included in some geothermal units. This results in a longer rotor span and slightly poorer performance during normal operation.

It is very important to understand what inlet conditions are specified because this drives the sizing of the first stage of the turbine.

DESIGN OF GEOTHERMAL STEAM PATH

The risk of fouling is constant in geothermal steam turbines. Because of this, the author's company, Siemens, has elected to standardize on impulse technology for geothermal applications. Impulse designs have fewer stages and can tolerate generous nozzle pitching that is not as sensitive to fouling.

For each turbine the designer must review the centrifugal stresses on each row of blades and its corresponding wheel. Material allowable limits must take into account the potential of pitting caused by the ever presence of chlorides and H_2S. There is a significant reduction in the allowable stresses when this is taken into account.

After the centrifugal stress analysis has been completed, the vibratory stresses must be calculated. Based on operation experience many manufacturers of geothermal steam turbines have gone to integral covers on the rotating blades. Integral covers dampen potential vibration modes and reduce the resultant stress without introducing opportunities for corrosion failure. Blades with integral covers (see Figure 6) is a design improvement compared to the traditional practice of using peened tenons to hold covers. Exposed tenons have the risk of eroding over time in geothermal service.

Stationary nozzles and rotating blade materials are selected based on the resource chemistry and the blade stresses.

The most challenging conditions seen in the author's experience are those of direct steam applications in the stages that the steam goes from dry to wet. These "transition" zones have all kinds of chemicals coming out of solution. The challenge is to pick a material that will survive this situation. Figure 7 shows such a stage where the incorrect Inconel alloy was used.

This is also an example of the necessity for materials research. Field testing with actual geothermal conditions with samples under stress is another way to get a better understanding of the potential of materials reaction. It has been found that small changes in the blade chemistry can make a big difference in the ability of the material to survive in a hostile geothermal environment.

Figure 7: Stage in the transition section of a direct steam impulse steam turbine

On taller blades one of the major concerns is erosion of the blade tip caused by high velocity water in this area. Figure 8 shows a blade tip that suffered water cutting due to inadequate water removal and insufficient protection of the base material.

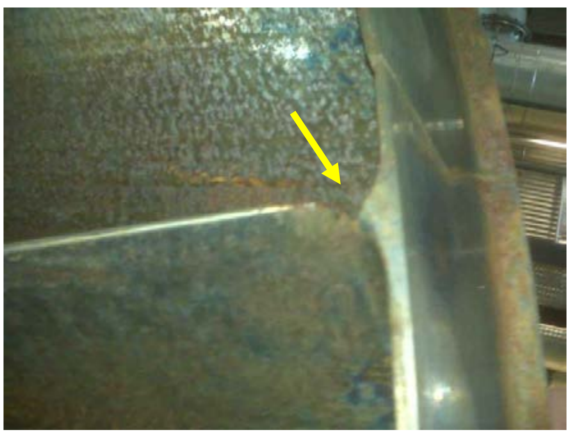

Figure 8: Blade tip erosion on an integral covered reaction blade

Options to minimize this include: different base material, improved placement of erosion resistant strips of Satellite® or flame hardening.

MOISTURE REMOVAL

Another way to reduce erosion is to remove some of the moisture using mechanical features called moisture separators that pull moisture out of the steam. Figure 9 shows a modern geothermal steam path with moisture separators.

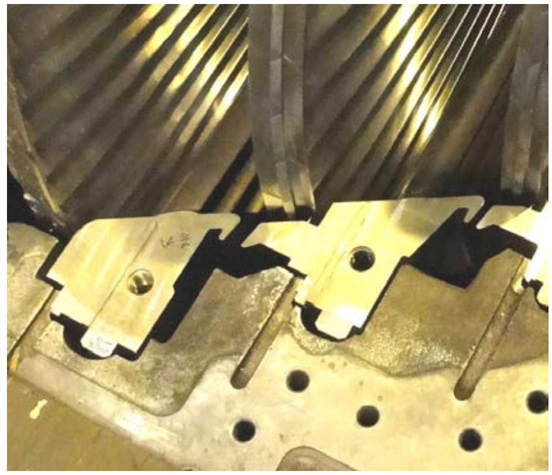

Figure 9: Moisture separators on an impulse geothermal steam turbine

For all flash plants, the inlet steam to the turbine is at the saturation line or wetter depending on the effectiveness of the demister in the inlet system. As steam expands and energy is removed from the steam, the moisture content increases. The process of moisture removal starts with the moisture separators mentioned above. The next step is to pipe this chamber outside the turbine. This pipe should be sized with some margin to ensure that it can pass the required flow. The next element in a proper drain system is to provide an orifice in the line to limit the amount of water or steam that is removed. The key is to remove the moisture but none of the steam. The orifice can be resized during commissioning if necessary.

In addition to the erosion reduction resulting from moisture removal there is also a thermodynamic benefit called the "Reheat Effect". This occurs when moisture is removed at a specific pressure. When the percent moisture is lowered, it increases the enthalpy of the steam to the subsequent stage.

During start up or when a turbine is being water washed there is added moisture and the potential of solid particles from scaling coming free that will find its way in the drain system. This could quickly clog the drain orifice and the result would be a complete loss in the effectiveness of the moisture removal features. The concept used by the author's company incorporates s a bypass line and valves to allow the orifice to be isolated so it can be cleaned while the flow passes through a valved bypass line.

The author has seen many examples of poorly designed drain systems and ineffective piping arrangements. The next step to a properly designed system is to pipe the drain line to the condenser hotwell.

Water not only has an adverse impact on life of the rotating blades, it can also have a big impact on the stationary parts if the design and material selection is not adequate. Water jet machines are used today to cut everything from plastics to stainless steel. The same concept of high velocity and the presence of moisture can cause severe water cutting erosion inside the steam path. This erosion intensifies as the % of water and the differential pressure increases. The designer must consider using stainless steel diaphragm rings or stainless steel inlay in areas that are at risk. Figure 10 below shows an example of a carbon steel diaphragm that was destroyed by water erosion. In this case, the water jet then impinged on the rotating blade and caused further damage.

Figure 10: Outer Ring of carbon steel diaphragm with extreme water cutting erosion

TALL BLADE DESIGN

Tall blade design and proper blade damping along with material selection are keys to long term reliability. One feature that has proven to be effective in multiple geothermal units is the use of integral locking covers, also called "Z" locked covers on tall blades. This feature when used with axial entry dovetails has proven to have superior blade dampening which reduces vibratory stresses. This design results in a wider operating range of exhaust pressure and is more tolerant to off-frequency operation. Figure 11 shows an example of Z-lock covers on a geothermal condensing unit.

Figure 11: Integral covers with Z lock feature at the blade tip

The use of these integral locking covers and axial entry dovetails results in "continuous couple" shrouds which is a technique used for years on aircraft engines. Figure 12 below shows the result in relative blade response for the various shrouding options.

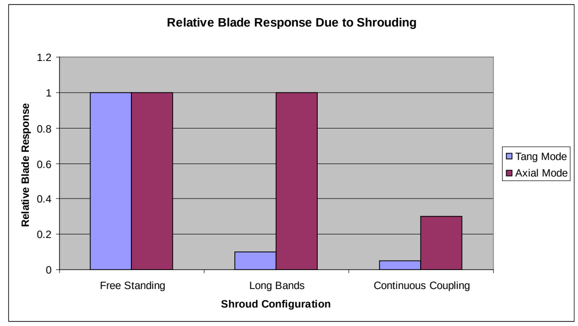

Figure 12: Relative Blade Response for cover configuration and dovetail design

OTHER SAFETY CONSIDERATIONS

Safety must be a fundamental criterion in the design of the machinery and associated auxiliaries. Safety factors are used for materials that take into account the centrifugal and vibratory stresses as noted above. Rotor dynamics and thermal growth are other factors that must be analyzed for each unit. The clearances for a geothermal unit are typically set larger than for standard units due to the need to tolerate the risk of fouling.

Avoiding rubs as a turbine is started and run thru critical speeds is very important on any turbine design, but more important because rub-tolerant bronze material sometimes used on conventional turbines cannot be used due to H_2S attack. Rubs going through critical speeds must be avoided. Rotor designs and rotor materials must be designed to minimize stress concentrations and be resistant to erosion.

The control and trip systems must be designed to provide overspeed and equipment problem protection. Issues like entrapped energy between the turbine and the valves must be considered and taken into account when locating the valves. The valves and the hydraulic power unit must include trip solenoids and properly sized drains to ensure the valves close quickly. The starting and loading of the turbine must be done per the OEM instructions to avoid long term cyclic stress impact. The generator and rotor system must be checked to ensure survival if there is a phase to phase short. A torsional analysis should also be done that also includes the impact on the tall blade frequencies.

The last point that should be discussed is the need to properly vent and purge moisture from a turbine when it is shut down. If hot geothermal condensate is allowed to remain in the turbine casing it can cause extensive damage very quickly to the casing and the turbine steam path. Removal is often accomplished by opening the exhaust vents and pumping dry air into the turbine casing to dry up the turbine internals.

SUMMARY

The technology, materials and experience available today, properly applied, should result in availability levels in the high ninety percentile. Since geothermal power generation is base load, Geothermal Power Generation has among the highest capacity factors for renewable energy sources,

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