SELECTION OF TECHNOLOGY OPTIONS FOR BINARY CYCLE POWER PLANT

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ABSTRACT

Binary power plants are becoming increasingly common due to environmental constraints and extended range of resources that are being considered for development. There are also more options available for suppliers and technology.

This paper describes the range of technology options and the selection of them for particular resources. It covers optimization of the cycle and factors considered in the evaluation of plant.

The paper looks at some specific cycles that have been conceptually designed for recent projects.

1. INTRODUCTION

Binary power plants were originally developed to provide generation from lower temperature sources, with the geothermal fluid being in the liquid phase. They were naturally extended to generating power from the previously unutilized separated geothermal brine from flash steam power plants. Binary plants also became favored in certain circumstances because of the very low environmental footprint when used with air cooled condensers. Nevertheless in the context of geothermal power generation binary plants were a niche technology compared to dry steam or flash steam geothermal power plant.

However many of the large high enthalpy fields have been exploited and attention is turning to smaller or lower enthalpy resources. This trend has increased the range of suppliers of binary technology plant, and accompanying the diversity of suppliers is more flexibility in the configuration of binary cycles that are available in the market.

This paper looks at some of the options for the binary cycle across a range of resource enthalpies and efficiency and cost implications relative to steam plant.

2. POWER POTENTIAL OF GEOTHERMAL FLUID

In most cases a geothermal resource consists of a deep liquid resource at elevated temperature. In this liquid state the power potential of the geothermal fluid can be characterized by its temperature.

The appropriate technology for power production will depend critically on this temperature, and a common classification of the geothermal resource is based on deep liquid temperature as follows:-

- High temperature > 250
- Medium temperature 160 – 250
- Low temperature 80 – 160

The power potential is also dependent how much heat can be extracted from the fluid before reinjection, and on the ambient temperature at which heat from the power cycle is rejected.

These thermodynamic boundary conditions are shown in Figure 1.

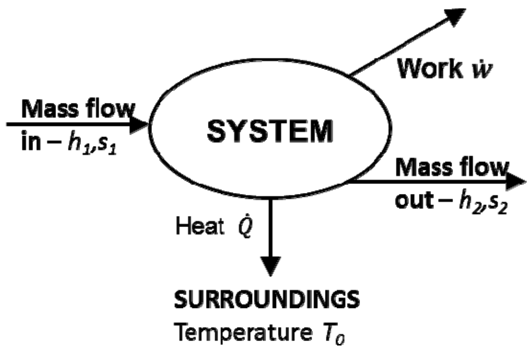

Figure 1: Steady flow process for a geothermal power generation system.

The second law of thermodynamics for open systems states that not all the energy given up by the mass flow can be converted to work (or power). Some of the energy in the fluid must be rejected as heat to the surroundings. The theoretical maximum power that can be generated by any cycle is known as exergy, and is given by the following equation:-

Specific exergy = $h_1 – h_2 – T_0 (s_1-s_2)$ kW per kg/s

Where

- *h* is the specific enthalpy of the fluid at each inlet or outlet, and
- *s* is the specific entropy of the fluid at each inlet or outlet

The specific exergy is the power from each kg/s of geothermal fluid flow. The unit is sometimes shown as kJ/kg, but using kW per kg/s makes the power generation potential explicit.

This equation is remarkably simple considering it encapsulates how the fluid behaves as heat is given up, that is cooling or condensing, and is independent of any power cycle.

Figure 2 compares the power potential of geothermal steam or water as the heat source assuming an ideal cycle, with the fluid rejected to the environment as water at 20 C, using the exergy equation. The Carnot efficiency is included, which is independent of the heat source and depends only on the hot and cold temperatures available. The Carnot efficiency is calculated from $(T_1 – T_0)/T_1$. It inherently assumes all the heat is added to the power cycle at the hot temperature, and all the heat is rejected to the environment at the cold temperature.

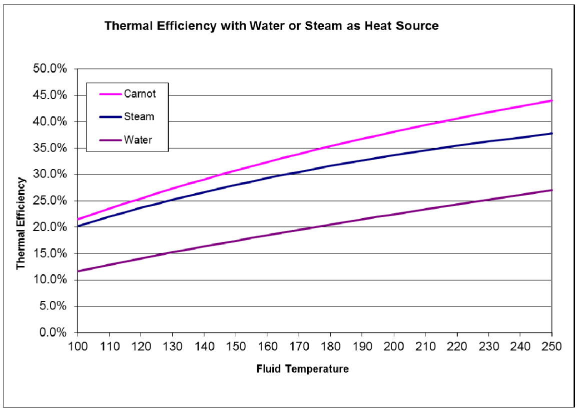

Figure 2: Ideal cycle thermal efficiencies.

The thermal efficiencies are generally low, due to the relatively low temperature of geothermal fluid compared to combustion based heat sources. The exergy of steam as the heat source is close to the Carnot efficiency as a large portion of the heat is given up at constant temperature. The exergy of water is significantly lower as its temperature reduces as the heat is given up. The exergy of a liquid is equivalent to a series of Carnot engines operating between each temperature point of the cooling geothermal fluid and the environment. Integrating the Carnot efficiency with respect to temperature of the fluid can be shown to reproduce the exergy equation.

2.1 Geothermal fluid at the wellhead

From the liquid state geothermal deep fluid typically flashes as it rises up the well, and this is a necessary characteristic to drive well production without down-hole pumps. The exergy at the well head can be calculated by considering the steam and brine phases separately using the equation above.

The proportion of steam and brine at the well head, and hence the exergy, will be dependent on well head pressure. The well head pressure will be less than the maximum possible due to the compromise between well head pressure and well flow, as characterized by the well deliverability curve. The well head pressure will also be determined by long term considerations of the sustainability of the well production and impact of the required rate of makeup well drilling.

Where we have done optimizations of power potential by considering the well head pressure in combination with power cycle efficiency, the results have been heavily dependent on the effect of well head pressure on fluid production rate.

A second effect on the available exergy is the constraint on minimum brine reinjection temperature necessary in order to avoid silica deposition. This has a double effect, reducing the heat that can be removed for conversion to power, and reducing the efficiency of conversion due to the temperature difference between the secondary fluid condensing temperature and the brine reinjection temperature.

These geothermal resource impacts need to be kept in mind as a constraint on available power and conversion efficiency.

3. POWER CYCLE CONSIDERATIONS

We have considered the constraints on the potential power available due to the nature of the geothermal resource. Practical power cycles introduce another series of constraints on power generation. An ideal power cycle picks up heat and generates power from each temperature point of the geothermal fluid as the temperature drops. Any temperature reduction that does not produce power reduces exergy.

Starting with the liquid or two phase fluid from the well, losses in exergy occur in the following ways:

- piping pressure drop, particularly where the pressure drop lowers temperature
- temperature reduction when brine or two phase fluid is "flashed" to a lower pressure to develop steam
- temperature differences in heat exchangers across which heat is transferred
- mismatch between the temperature profile of the source fluid as heat is extracted and the secondary fluid which leads to high temperature differences

To show the effect of the above points, the power potential of double flash steam was calculated for the range of fluid enthalpies typically encountered in geothermal power plant. Steam can be directly expanded in efficient steam turbines to generate power. First flash and second flash pressures were selected for each geothermal fluid enthalpy based on experience from optimisation work done for a number of conceptual studies.

Figure 3 shows the exergy efficiency of the dual pressure steam, which is the exergy of the steam divided by the exergy in the deep fluid. The specific exergy of the deep fluid and the double flash steam is shown on the secondary vertical axis.

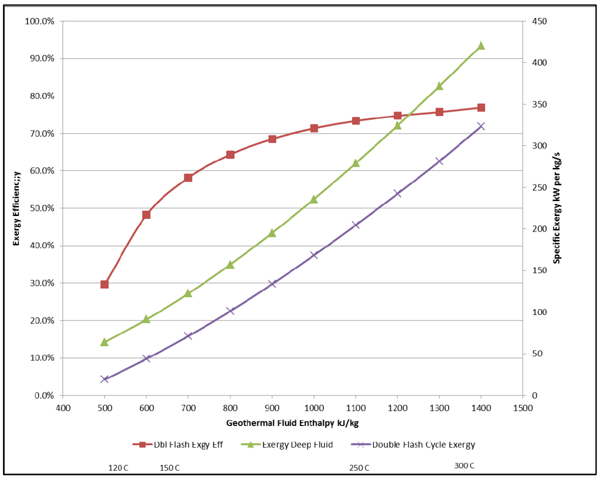

Figure 3: Exergy efficiency and exergy of double flash steam.

While the exergy efficiency of the double flash steam is high for high temperature resources, it starts to drop off for moderate temperature resources and steeply drops for low temperature resources. The main cause of this is that the second flash pressure cannot be too low due to practical pipe size issues and hence the separated brine temperature is typically no less than 100°C, while the reference temperature used in this case was 20°C.

For binary plants, it is not necessary to separate steam to generate power, instead it is the secondary fluid that must be heated and vaporised before power can be generated. The problem becomes finding the best match between the geothermal fluid temperature profile and the required temperature and heat profile of the secondary fluid.

For low to moderate temperature geothermal fluids, pentane is commonly used as its boiling temperature is lower than water and matches geothermal fluid temperatures at reasonable operating pressures for a power cycle. Getting a good match to the geothermal fluid must consider that the vaporising of the binary fluid takes place at constant temperature while the binary fluid's temperature increases linearly during preheating. The heating and vaporization portions of the binary fluid are shown on the isopentane temperature-entropy diagram in Figure 4, between points 2 and 3.

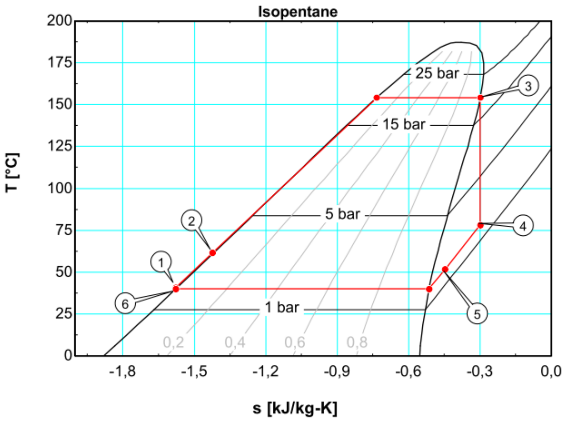

Figure 4: Isopentane temperature entropy diagram with power cycle shown.

4. BINARY TECHNOLOGY OPTIONS

There are a wide range of technology options that could be used or have been used worldwide. The best selection is strongly dependant on the fluid enthalpy and other practical factors of the geothermal resource.

In addition to enthalpy, the main factors affecting technology selection are:

- Brine chemistry especially in relation to the lower temperature limit before silica scaling becomes a problem
- NCG content in relation to the cost and parasitic load of vacuum extraction in condensing steam cycles
- Commercially proven technology that is low technical risk and cost effective
- Scale of development

For a particular resource the above considerations will guide a short list of technology options and configurations that could provide the best selection. Each technology option on the short list is then modelled and matched to the resource to give a valid comparison. Care must be taken when doing this as optimising a configuration makes a significant difference to the power output and if not done correctly this can skew the comparisons.

The options include retrieving heat from liquid phase geothermal fluid and single or double flash separation of the geothermal fluid before the heat is transferred to the secondary cycle. The power cycle options include combination of steam turbine and binary plant, and single or double (cascaded) binary plant.

Another key technology option is wet or dry cooling. Air cooled condensers have been used on a large majority of binary plant, probably due to the environmental drivers that hastened initial uptake of the technology, such as not needing a water supply and the lack of vapour plumes. However dry cooling systems have a high temperature difference between condensing temperature and ambient dry bulb temperature to keep size and costs down. Wet cooling has advantages including lower cost for a wet cooling system and the fact that a wet cooling system approaches the lower wet bulb temperature. Not only does this give lower cooling temperatures, but wet bulb temperatures vary less throughout the day, making off design performance less of an issue. For these reasons, we have considered wet cooling as the reference cooling system for this paper.

4.1 Technology selection for low enthalpy fluid

The geothermal fluid is typically in the liquid phase, either from the well or from separation for an upstream. Due to the low temperature of the fluid the temperature range available to the cycle is low, and only very low thermal efficiencies are possible. Efficiency of conversion is therefore very important to make a project viable, and many specialised cycles have been considered to achieve this.

Proposed higher efficiency technologies at low enthalpy include supercritical secondary cycle and mixtures of motive fluids to give a sliding boiling point (Kalina cycle).

They are more costly and still undergoing research and development. Applications have involved subsidies or grants to make viable. Our experience in New Zealand and Asia for commercial plant have been limited in these low enthalpy applications, and we won't discuss this further.

4.2 Technology selection for medium enthalpy fluid

Various combinations of separated steam and brine ORC, and double flash steam and brine ORC can be used depending on the geothermal fluid enthalpy and minimum brine temperature before reinjection.

In this enthalpy range there will usually be at least one level of steam and brine separation. The high limit on separation pressure is given by considerations of well deliverability and resource sustainability. Reducing separation pressure below these limits gives up exergy as the steam temperature is also reduced. Accordingly we usually seek to maintain separation pressure close to the sustainable limit.

Once the steam pressure is selected, the secondary fluid cycle pressure is selected to give a reasonable temperature difference between the steam and secondary fluid in the vaporizer.

In this enthalpy range, where there is separated steam and brine, both streams can be used in a two phase binary cycle, with the steam used primarily for vaporising the secondary fluid, and the brine used to preheat the secondary fluid.

At the lower end of the enthalpy scale, approximately 800 kJ/kg, there will be insufficient steam available to vaporise the secondary fluid. One method to address this is to lower the separation pressure to generate more steam. Lowering the pressure also lowers the steam temperature, and the secondary fluid pressure and temperature is lowered accordingly.

However, lowering the geothermal fluid temperature lowers the exergy available. An optimisation needs to be done to find the balance between higher separation pressure to maintain power potential and lower separation pressure to reduce temperature differences between the geothermal and secondary fluids.

A recent example of this is modelling done for a geothermal plant in the 800 kJ/kg range.

With pressures up to 7 bara available, the two phase binary cycle produced approximately 21MW net.

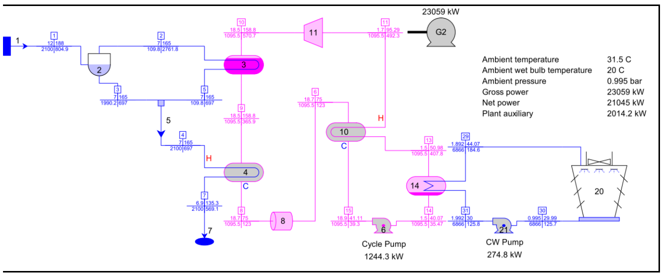

Figure 5: Thermoflex™ model of binary cycle with 800 kJ/kg fluid and 7 bara steam.

The minimum brine return temperature was approximately 100°C and it can be seen that not all the heat available was able to be taken up in this cycle.

The separation pressure was then lowered to utilise more of the heat in the geothermal fluid.

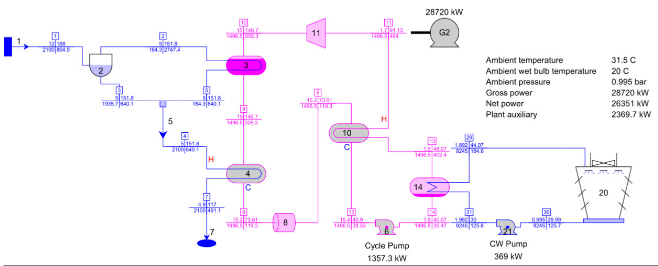

Figure 6: Thermoflex™ model of binary cycle with 800 kJ/kg fluid and 5 bara steam.

Lowering the separation pressure to 5 bara increase net power to approximately 26 MW. Although lowering the pressure still further would produce more power, the steam line sizes over long distances will start to become large and uneconomic.

In this situation, an alternative approach is to consider double flash steam system with cascaded binary plant. This will keep the geothermal fluid temperature high while allowing a better match with the secondary fluid cycles.

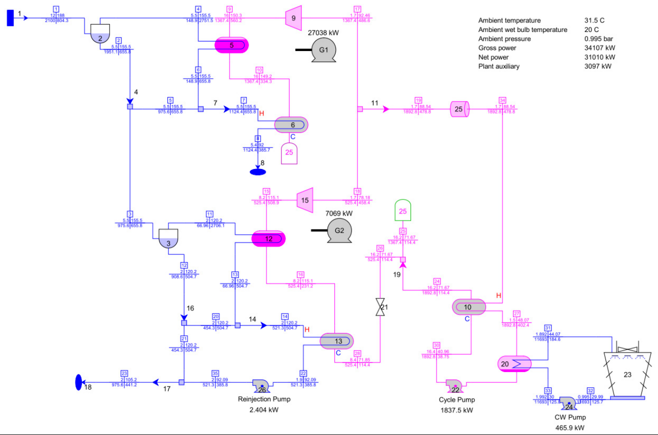

Figure 7: Thermoflex™ model of binary cycle with 800 kJ/kg fluid and dual flash 5.5 and 2 bara steam.

Optimisation gave a net power output of 31 MW at a separation pressure of 5.5 bara and a second flash pressure of 2.0 bara. The second flash can be done near the power plant, minimising the piping distance of the lower pressure steam.

Although double flash steam plant is more complex, on the secondary fluid side modular binary plant can be used at each of the pressure levels to minimise complexity.

At the higher end of the moderate enthalpy range, the challenge is there is more heat in the steam than is needed to vaporise the secondary fluid. One approach to mitigate this is to increase separation pressure to the maximum that the resource can sustain.

In practice due to resource pressure limits, binary cycles are used where a portion of the secondary fluid preheating is done by steam in the vaporiser, sacrificing the optimum match between steam and vaporisation of the secondary fluid.

A recent example of this type of cycle is shown in figure 8.

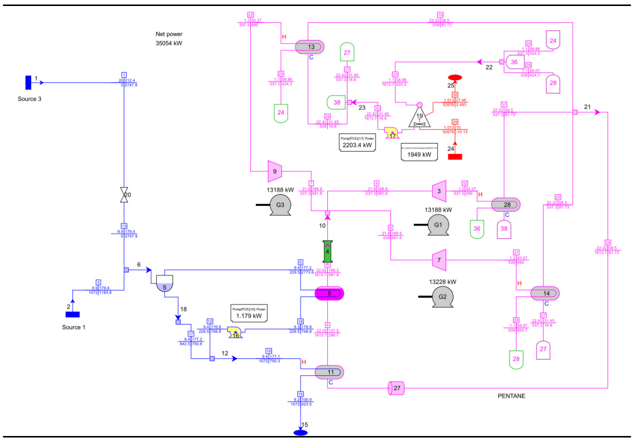

Figure 8: Thermoflex™ model of binary cycle with 1180 kJ/kg fluid and 9.9 bara steam.

For this plant, note that the secondary fluid is heated a further 32°C in the vaporizer before reaching saturation temperature.

Despite the lowered efficiency, there is merit in standardising on the range of designs that can be adapted to the particular geothermal reservoir, so that costs are kept low while achieving near optimum outputs.

4.3 Technology selection for high enthalpy fluid

Typically steam plant would be favoured due to the high power potential from the separated steam and high efficiency of the axial flow steam turbines (at larger sizes), and the lower capital cost of steam turbines at higher steam pressures (low steam volume). Depending on limitations on brine temperature before reinjection, single or double flash steam plant could be favoured.

It is possible for binary cycles to get close to the output of steam plant, even double flash steam plant. At high enthalpy, there will be too much heat in the steam to match the vaporization requirements of the secondary fluid. To get a better match between geothermal fluid and secondary fluid, a form of secondary fluid regenerative feed heating can be used, where vapour is extracted from the turbine, or from between two turbines in series, and used to assist in the preheating of the binary fluid. This is even more valuable when the temperature the brine can be reduced to is limited. However at the scale of generating plant typically encountered, binary plant have tended to be higher cost than steam plant, and would be competitive only where there are special considerations such as very high non-condensable gases.

Another scenario is where liquid is brought to the surface because the deep aquifer is confined and under higher pressure than expected from the static head of water at the depth. This higher pressure can be sufficient to drive the liquid to the surface without flashing. In addition, the cost and parasitic load to reinject geothermal fluid at these high pressures could be very high. In this case, the high temperature geothermal fluid is kept in the liquid state at high pressure and a binary cycle with secondary fluid is necessary. Figure 9 shows a power cycle developed to address these issues.

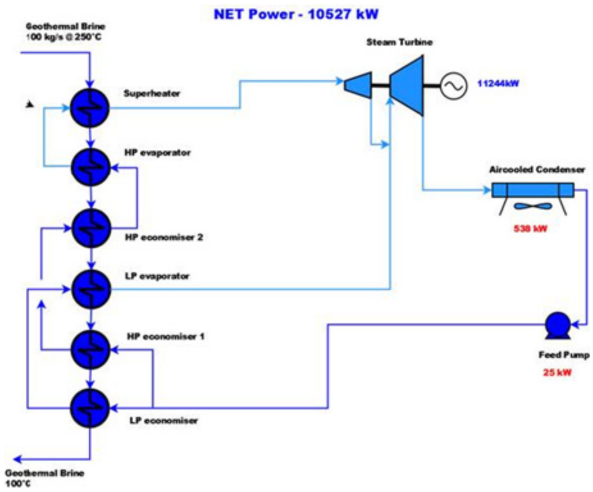

Figure 9: Block diagram of binary cycle with 250°C liquid and secondary dual flash.

A dual level steam generation system was used to keep as low as practical the temperature differences between the cooling geothermal fluid and the secondary fluid being heated. In this case water was selected as the secondary fluid, as at these temperatures higher efficiency was obtained with water than pentane. In addition, the high cost of organic fluid was a driver considering the large scale projects that were envisaged.

Of interest for this application is the potential benefit of two phase expansion of the secondary fluid to increase potential power output. A model of this cycle is shown in Figure 10.

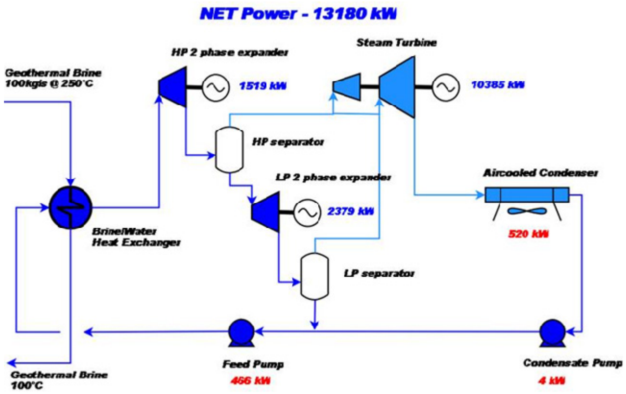

Figure 10: Block diagram of binary cycle with 250°C liquid and secondary two phase expansion.

Efficiency is significantly increased, but dependent on two phase expander technology. This technology is nearing commercial reality but only at small scale.

5. EVALUATION

Efficiency is important but cannot be considered in isolation. Upfront capital cost is a major driver for geothermal plant as their economics are largely determined by capital costs versus generation delivered. There is no fuel cost as such but the well drilling and makeup well costs are impacted to a degree by the efficiency of the plant, via its effect on the quantity of geothermal fluid needed to generate the power.

The technology selection should aim to find a low cost technology that is best matched to the resource, and this will usually mean uncomplicated designs. A careful selection of separation pressures, motive fluid and a combination of modular cycles will likely give a design that has a reasonable efficiency at minimum cost.

Off design performance has been an area where air cooled binary plants have not performed well, but this can be addressed with wet cooling systems where possible, and the deployment of turbine technologies such as inlet guide vanes.

6. CONCLUSION

Binary plant cycles have been usually designed by the vendors. We act as advisors to owners and often prepare conceptual designs for owners based on wide considerations of the particular resource, owner's investment strategy and risk mitigation issues. In this space we are a link between multiple vendors and their specialised design skills and the overall needs of the owners.

Preparing conceptual designs quickly at the early stage of a project involves using knowledge of where the losses arise in converting geothermal heat into a power cycle, and exploring computerised cycle models that get close to achievable net power output. At the same time practical pinch and approach temperatures for the heat exchangers are used that keep size and cost close to optimal.

The ideal technology selection for binary plant is likely to be modular design with flexible design elements to match the condition, as well as some inherent flexibility for off design operation.

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