Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Cold Ends in Geothermal Power Plants

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Keywords: cold end, design, operating experience

Cold end of a power plant refers to the condenser and the systems required for condensing the steam, or binary vapor, flowing from the turbine and for maintaining the required pressure in the condenser. The design of the cold end for geothermal power plants is site specific and adapted to the conditions for each power plant. Important items are e.g. the characteristics of the resource, power generating process, ambient conditions and environmental requirements. The efficiency of the power generating cycle is highly dependent on the cold end, which consumes most of the parasitic load of the power plant and frequently cold end constructions are prominent and important for the appearance of the power plant. An overview of the available cold end designs is presented along with discussion on the characteristics of the major types. The cold end designs are reviewed from the point of effective utilization of the resource, operation, water balance, gas abatement, cogeneration of heat and power and environmental issues. Discussion and review will include experience of operating different types of cold ends.

1. INTRODUCTION

Selecting types of process components is always challenging for a geothermal power plant. This selection depends on the design conditions for each plant and usually some flexibility for changed conditions in the future must also be considered and built into the system. Based on the plant's design conditions the designers decide the suitable types of process components according to their experience and knowledge. Different conditions and restrictions for a plant can change the selection of suitable type of individual components. This decision is not always obvious and what is believed is not always the same as what turns out to be the suitable selection. Combinations of different individual components can make things more complicated and more difficult to realize which setup is the best after all.

Cold end components, such as air-cooled condensers or cooling tower and its plum, are in many cases the most prominent parts of a geothermal power plant. Extraction and treatment of Non-Condensable Gases (NCG) are often part of the cold end. Condensed steam from condenser can be valuable in other parts of the power plant, such as in scrubbing, as make-up water, pH treatment of separate water, etc.

2. COLD END AND EFFICIENCY OF POWER GENERATION

Most geothermal power generating processes are Rankine cycles and the cold end is the heat sink of the power generating system. The cold end may consist of one or more of the following components: condenser, cooling tower, water pumps, water make-up, gas extraction, etc.

The effect of the cold end on the efficiency of the power generating process can be seen by looking at the Carnot efficiency. The Carnot efficiency shows the highest efficiency that a heat engine can have operating between two thermal energy reservoirs at temperatures T_L and T_H.

$$\eta_{th} = 1 - \frac{T_L}{T_H} \tag{1}$$

Where η_{th}, T_L and T_H are Carnot efficiency, sink temperature and source temperature respectively. The sink temperature is the temperature of the cold end. The colder the heat sink, the higher the efficiency of the power generating cycle. The effect is shown in Figure 1, which shows the Carnot efficiency as a function of the sink temperature for two different source temperatures. The effect on the efficiency is more the lower the source temperature.

Ambient conditions are important for the design of the cooling system and dry bulb or wet bulb temperatures are used. The power cycle is optimized with respect to the power output produced, parasitic load and practical limitations. The design conditions must take into consideration the most extreme conditions, giving the maximum and minimum outputs from the plant. The power output fluctuates around the average output.

3. COLD END OPTIONS

An overview of cold end used in geothermal power plants is presented in this section. In this overview the cold end is divided into condenser on the one hand and different types of coolant and source of coolant on the other.

3.1 Condensers

A condenser is a heat exchanger where vapor from the turbine is transferred into liquid by removing the latent heat with the help of a coolant. As the operating pressure of the condenser is lowered, the enthalpy drop of the vapor coming from the turbine increases. As a result, the generated power increases. The coolant in geothermal power plants is either water (wet cooling) or air (dry cooling). Air cooled condensers are usually not an option for steam turbines but are often used in binary power plants. Wet cooling may though also be preferred for binary plant, since the investment cost is lower, the footprint is smaller, parasitic load is smaller and the output is not as dependent on ambient condition as is in dry cooled condensers. Dry cooling may however be necessary especially in areas of limited water resources.

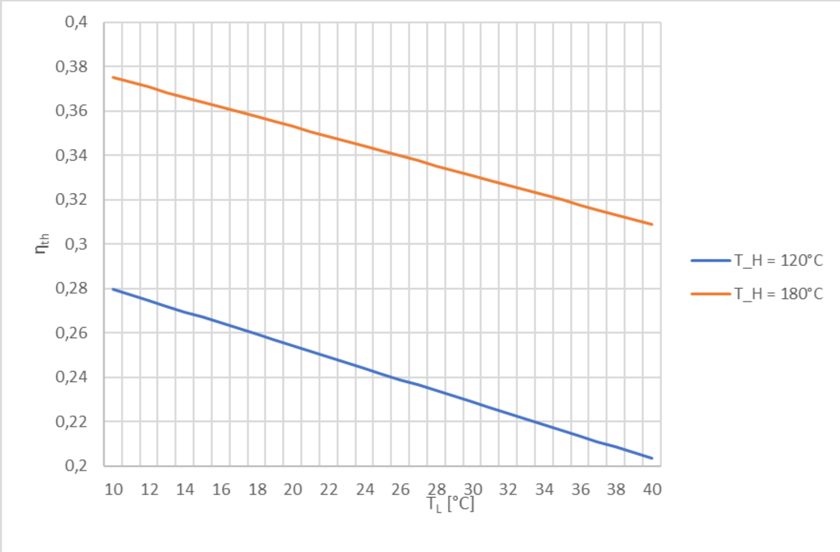

Figure 1. Carnot efficiency as a function of sink temperature.

3.1.1 Direct contact condenser

In a direct contact condenser, cooling water is sprayed into the steam from the turbine. This is an effective cooling method, small difference between the temperature of the cooling water and the temperature in the condenser and the condenser is relatively small and capital cost is low. The construction of the power station must be adapted the restriction given by the direct contact condenser such as:

- It must be lower than the turbine to reduce risk of flooding of the turbine
- Pumps pumping water from the condenser must be below the condenser to have proper NPSH for the pumps
- Cooling water basin must be above the condenser

Condensate is mixed with the water from the direct condenser and the water is contaminated with non-condensable gases. Oxygen and other gases are released from the cooling water when it is sprayed into the steam adding to the load of the gas extraction system and the oxygen makes gas abatement more difficult.

Due to the effectiveness and the low capital cost direct contact condenser are most popular in geothermal power plants around the world where the geothermal steam is used directly in the turbine. Direct contract condenser cannot, however, be used in binary power plants.

3.1.2 Surface condenser

Surface condenser is a shell and tube heat exchanger, where the cooling water flows inside the tubes and vapor is on the shell side. The condensate and non-condensable gases do not mix with the cooling water, such is the case in direct contact condenser. Minimum temperature difference must be between the tube and shell side which reduces the effectiveness and surface condensers are more expensive than direct contact condensers.

- Do not give any special restriction on the construction of the power station
- Condensate from the condenser can be used in other processes in the power plant such as in scrubbing, as make-up water, pH treatment of separate water, etc
- Gas extraction and gas abatement only has do deal with non-condensable gases associated with the geothermal fluid
- Less power is required for pumping circulation water compared to direct condenser
- If heat from condenser is to be used in a cogeneration of heat and power the condenser must be of surface type

Surface condensers are required for binary power plant.

3.2 Coolant

3.2.1 Air

Air can be the cooling media in surface condensers which are then called ACC as described in section 2.1. Sometimes water spray is also used in combination with air in air cooled condensers.

3.2.2 Water

Water is an effective media to cool condensers and is most widely used. Most usually the cooling water is circulated through cooling tower, where it is cooled down, and into the condenser where heats up again before being piped back to the cooling tower. The cooling towers are discussed in the following section.

In some cases the water can be fresh water from a river or a water resource. An example of this is cogeneration of heat and power, where fresh water is used for cooling condenser and at the same time is preheated to be used as water in district heating. This is the case in Nesjavellir and Hellisheiði power plants in Iceland. Seawater can also be used for the cooling as is done in Reykjanes power plant in Iceland.

3.2.3 Cooling towers

In cooling towers water is cooled by air. The cooling can be through heat exchanging and through evaporation of water. Three types of cooling towers may be considered: wet cooling towers, dry cooled cooling towers and hybrid cooling towers.

Wet cooling towers

Mechanical induced draft wet-cooling tower is the most common choice for geothermal power plants. Other types include crossflow and natural or forced/assisted draft cooling tower. In the cooling tower, the warm water from the condenser is sprayed over a fill. The heat exchange is both through heat exchange between the water and air but also by evaporation of water. The fill material is designed to increase the surface area between the water and air by forming either a film of water or by breaking up the water droplets. In induced draft cooling tower, the air is drawn through the tower by fan located on top of the tower in Figure 3 a schematic drawing of a counter flow mechanical induced draft wet-cooling tower is shown.

In natural draft towers, the air movement is created by natural movement of the air by its density decreasing with the air heating up. Natural draft towers are rarely considered for geothermal power plant, since they are generally only considered economical for relatively large power production unit sizes. Forced draft tower have the fan located at the cooling tower inlet which results in poor air distribution compared to induced draft. Therefore, they are generally only considered where space and height of structures is limited.

As with the condenser, the size of the cooling tower mainly follows the heat load. However, the wet-bulb temperature of the inlet air significantly influences the cooling towers ability to reject heat to the atmosphere. Therefore, a cooling tower with a low wet-bulb temperature will be considerably smaller than a tower with higher wet-bulb temperature, despite the heat load being the same. Other factor can influence the size such cooling water temperature range, airflow and fill type.

Fills are generally categorized as being film, trickle or splash. In recent year, film fills have become the most popular for their desirably heat transfer characteristics. They are however extremely vulnerable to fouling and poor water and air distribution. In application with risk of fouling, either trickle or splash fills should be used. External water source can be scarce in some areas and therefore the condensate is sometimes used as make-up water on the cooling tower. This can cause scaling in the cooling tower fill and therefore foul resistant fill, such as trickle or splash fill can be used. Splash fill are only considered when fouling problems are severe, due to impure cooling water. Capital and operational cost, and efficiency is similar to the film fill tower and the trickle fill selection should not have any significant effect on the power plant cost or its efficiency.

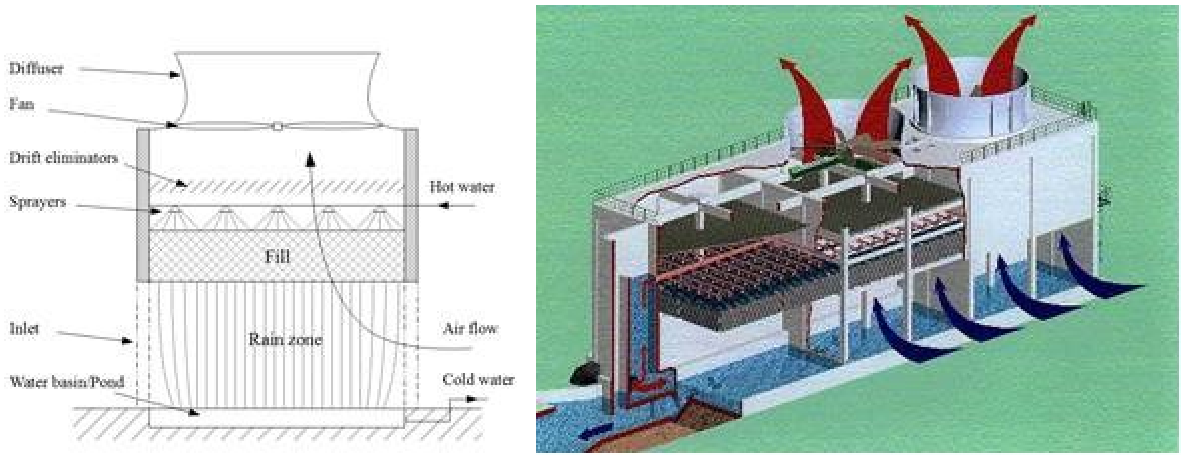

Figure 2: Counter flow mechanical draft wet-cooling tower.

In a wet cooling tower, the water lost through evaporation under the average meteorological condition is around 70% of the condensate and usually at least 5% additional can be expected to be needed for blowdown of the cooling tower and other losses. Thus, it can be assumed that, if no other water source is available, 75% of the steam used by the geothermal steam turbine is required as a make-up for a wet cooling tower.

In a binary power plant make-up water may not be as readily available as condensate in a steam power plant. This may exclude the possibility of using wet cooling tower in such power plants.

Dry cooling tower

Wet cooled systems are more effective in terms of heat rejection than dry cooled systems. However, wet-cooled systems lose a fraction of the cooling water through the evaporation of water, blowdown, wind and drift because of liquid carryover into the discharge airstream. In many modern conventional thermal power plants this loss of water is not acceptable due to limited water availability at plant site. Therefore, use of dry cooling has been increasing, rendering significant technical improvements of dry cooling systems (Electric Power Research Institute, 2002). Dry cooling tower have not been used in geothermal power plants primarily because of

- High investment cost
- Large construction
- Low efficiency
- High parasitic load

Dry cooling tower is not included further in the following discussion on cold end combination.

Hybrid cooling tower

Hybrid cooling towers are occasionally used in geothermal power plants, mainly to eliminate visible plume from the cooling tower and are a kind of compromise between wet and dry cooling tower. In a hybrid cooling tower, the warm cooling water from the condenser flows through air cooled heat exchanger, rejecting a part of the heat before the water falls through the wet section, see Figure 4. The evaporation is mainly proportional to the heat rejection where if more heat is rejected in the dry section, less water will be lost to evaporation. A typical hybrid cooling tower increases the condensate recovery of up to 40% by rejecting part of the heat through a dry heat exchanger before the cooling water is sent through the wet section of the cooling tower. This does however require additional fan power, i.e. higher parasitic load, the cooling tower is considerably larger and more expensive.

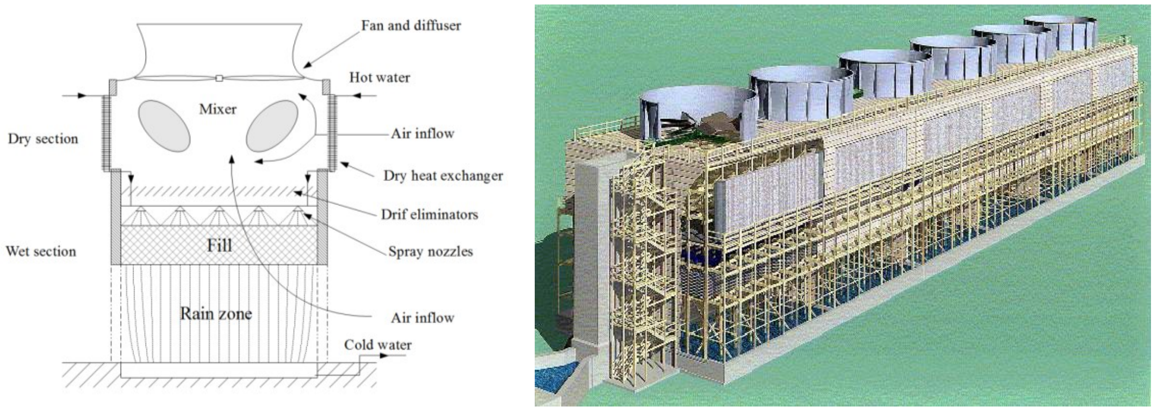

Figure 4: Hybrid cooling tower

The usual reason for choosing a hybrid cooling tower is plume abatements and/or water conservation. The plume from the cooling tower is often considered negative visual affect and may cause icing in the vicinity of the cooling tower in cold areas. Many regulators around the world require power plants that are located near or in towns and cities to be plume free. The plume from hybrid cooling tower is less than the plume from a conventional wet cooling tower as the air contains less water roughly corresponding to less cooling by evaporation. A hybrid tower for water conservation is however designed with the aim of conserving certain amount of water instead of making sure that the tower is plume free. Mixing of the dry and humid air stream is not important for water conservation, whereas mixing is essential for plume abatement.

3.3 Cold end subsystems

Geothermal steam always contains some non-condensable gases (NCG). The NCG content in the steam can vary up to 10% by weight but is usually around 1% and lower. For steam power plants the NCG need to be extracted from the condensers. These gas extraction systems (GES) are generally considered as part of the cold end. There are three types of gas extraction systems commonly used in geothermal power plants, steam jet ejectors, liquid ring vacuum pumps (LRVP) and a hybrid system consisting of both steam ejector and LRVP working in series. Steam ejectors have no moving parts and are the simplest and most reliable gas extraction system. Ejectors have the lowest capital cost but use significant amount of steam as motive steam. Steam ejector sets usually consist of two ejectors in series with intercondensers after both stages. LRVP are positive displacement pumps using water as seal liquid. LRVP have the highest capital cost but the efficiency is higher than for ejectors. Hybrid gas extraction systems have steam ejector as first stage and then LRVP on the second stage, with intercondenser between the two. Hybrid gas extraction system utilizes part of the benefits of both types of systems, often making it the most economical system. The intercondensers for the GES are normally of the same the type as the main condenser; i.e. surface type intercondensers are used if the main condenser is surface type and vice versa. In case of a direct contact condenser, the used cooling water from the GES is usually sent into the condenser. This cooling water from the GES can increase the cooling water amount inside the condenser by a few percents which needs to be pumped out.

Cooling of the lube oil system for the turbine and generator and cooling of the generator itself is normally with surface heat exchangers that use the cooling water. Air cooling of the oil or generator is possible but usually impractical for geothermal plants. These turbine and generator coolers maybe not necessarily considered part of the cold end.

4. SUMMAR OF COLD END COMBINATIONS

As mentioned in section 2, the cold ends in geothermal power plants are a combination of a condenser and a cooling media. The possibilities of cold end options and combinations are listed in Tables 1, 2 and 3.

Table 1. Cold end options.

Condenser	A. Direct Contact Condenser (DCC)
	B. Surface Condenser (SC)
Coolant	1. Air (A)
	2. Water (W)
	3. Wet Cooling Tower (WCT)
	4. Hybrid Cooling Tower (HCT)
	5. Dry Cooling Tower (DCT)

The cold end of a geothermal power plant consists of a condenser and a coolant which were described in sections 2.1 and 2.2. The possible combinations for geothermal steam plants are listed in Table 2 and for geothermal binary power plants in Table 3.

Table 2. Cold end options for steam power plants.

Steam power plants					
Cold end combination	**Effectiveness**	**Operation**	**Water balance**	**Gas abatement**	**Environmental issues**
DCC + WCT	Effective condensation. Wet cooled direct contact condensers have more efficient heat exchange than wet cooled surface condensers due to the direct mixing of steam and circulating water. Lower capital cost than surface condensers.	Less prone to fouling than surface condensers since they have no tubes. Air releases from the cooling water in the condenser. When oxygen rich cooling water mixes with the condensed steam, sulphur scaling can occur in the condenser and cooling tower. This makes scrubbing of H_2S from the gas more difficult.	If a direct contact condenser is used, the condensate mixes with the oxygen rich cooling water and the excess water is usually recovered as overflow in the cooling tower.	Emissions will escape through the cooling tower, and stripping occurs. Around 20% of the NCG may be expected to go with the condensate to the cooling tower and around 80% of the NCG passes through the gas removal system. Oxygen and other gases from the cooling water released in the condenser making gas abatement more difficult.	The oxygen rich cooling water is not suitable for deep reservoir injection (mixed with brine). The excess cooling water is therefore rather disposed of in shallow wells i.e. above the reservoir, or away from the reservoir to avoid contamination.
DCC + HCT	Effective condensation. Lower capital cost than surface condensers.	Less prone to fouling than surface condensers since they have no tubes. Air releases from the cooling water in the condenser. When oxygen rich cooling water mixes	Sama applies as for DCC + WCT, only less cooling water is needed.	Emissions will escape through the cooling tower, and stripping occurs in proportion to the water use. Oxygen and other gases from the	The oxygen rich cooling water is however not suitable for deep reservoir injection (mixed with brine). The excess cooling water is therefore rather disposed of in

Steam power plants					
Cold end combination	**Effectiveness**	**Operation**	**Water balance**	**Gas abatement**	**Environmental issues**
		with the condensed steam, sulphur scaling can occur in the condenser and cooling tower. This makes scrubbing of H_2S from the gas more difficult.		cooling water released in the condenser making gas abatement more difficult.	shallow wells i.e. above the reservoir, or away from the reservoir to avoid contamination.
SC + A	Air cooled steam condensers are unlikely to be feasible for a geothermal power plants due to high cost and high parasitic load. Pressure drop from turbine to and through the condenser reduces the power output	Maintenance of fans	With an air cooled steam condenser, all the condensate is recovered and can be used for reinjection.	Treatment of gases is easier in surface condenser than direct contact condensers. Dependent on gas extraction system.	Air cooled steam condensers cover significantly larger surface area compared to wet-cooled cold ends and can be expected to have higher structures and very large pipes.
SC + W	This type of cold end can be very effective, especially for cogenerating geothermal heat and power plants. Pumping power for water site dependent.		When external water is accessible.	Treatment of gases is easier in surface condenser than direct contact condensers. Dependent on gas extraction system.	Water is usually not available for cooling of this type.
SC + WCT	Lower parasitic load than in most other combination.		If the power plant uses a surface condenser the condensate is isolated and does not come in contact with the cooling water. In this way the condensate that is not used as make up water can be used in other processes of the power plant and injected. By assuming that three fourth of the condensate is required for make-up water, then one fourth will be injected.	Treatment of gases is easier in surface condenser than direct contact condensers. Dependent on gas extraction system.	Plume from WCT can be a visual pollution in rural areas and can cause icing hazards on nearby roads in cold areas.
SC + HCT	Work cycle less efficient than with wet cooling tower. Larger dry section requires more parasitic load.		Possibility to preserve water. The evaporation is proportional to the heat rejection. If more heat is rejected in the dry section, less water is lost to evaporation.	Treatment of gases is easier in surface condenser than direct contact condensers. Dependent on gas extraction system.	The usual reason for using hybrid cooling tower is plume abatements and/or water conservation. Higher structures than WCT and DCT.

Table 3. Cold end options for binary power plants.

Binary power plants					
Cold end combination	**Effectiveness**	**Operation**	**Water balance**	**Gas abatement**	**Environmental issues**
SC + A	Air cooled surface condensers are usually more suitable for binary power plants than flash plants. For the same size units, this type of system has higher cycle efficiency than a condensing steam cycle because it uses both the brine and the steam for power generation. Air cooled surface condensers are however usually more expensive and have higher parasitic load that wet cooled condensers.	Maintenance of fans. Output varies with ambient temperature and wind.	Ideal when access to water is limited.	Closed system so near zero emissions from the power plant, given that the pressure in the system is high enough to prevent gas release.	Less environmental issues than wet cooling but larger footprint and more parasitic load.
SC + W	This type of cold end can be very effective, especially for cogenerating geothermal heat and power plants. Pumping power for water site dependent.		When external water is accessible.	Closed system so near zero emissions from the power plant, given that the pressure in the system is high enough to prevent gas release.	Water is usually not available for cooling of this type.
SC + WCT	More effective than hybrid- and dry cooling towers.	Make up water for the cooling tower may not be available	Here it is not possible to use condensate from the geothermal fluid like in steam power plants so access to external cooling water is necessary.	Closed system so near zero emissions from the power plant, given that the pressure in the system is high enough to prevent gas release.	Plume from WCT can be a visual pollution in rural areas and can cause icing hazards on nearby roads in cold areas.
SC + HCT	Work cycle less efficient than with wet cooling tower. Larger dry section requires more parasitic load.	Make up water for the cooling tower may not be available	Possibility to preserve water. The evaporation is proportional to the heat rejection. If more heat is rejected in the dry section, less water is lost to evaporation.	Closed system so near zero emissions from the power plant, given that the pressure in the system is high enough to prevent gas release.	The usual reason for using hybrid cooling tower is plume abatements and/or water conservation. Higher structures than WCT and DCT.

5. COMPARISON OF COMMON COLD ENDS FOR STEAM PLANTS

Direct contact condensers have more efficient heat exchange than surface condensers due to the direct mixing of steam and circulating water and consequent lower temperature difference between the cooling water and condenser. Direct contact condensers also have lower cost and are less prone to fouling since they have no tubes. The gas cooling part may however be problematic due to sulfur precipitation. Surface condensers can be figured to have lower parasitic load than direct contact condensers since the circulating water pumps that must overcome the condenser tube side pressure drop may require less power than hotwell pumps which must draw suction from the low direct contact condenser pressure.

The comparison of parasitic loads can be explained with following example in Table 4, for the two condenser types which are generally used in power plants where geothermal steam is used directly in turbines. The data in this example can apply for a modern single flow geothermal steam turbine with axial exhaust and steam inlet pressure of approx. 8 bar_a and 1% NCG in the steam. Pump efficiency is assumed around 0,75. Similar construction of wet cooling tower and arrangement of cooling water piping is assumed, and the pressure drop of piping system and pump head margin has been omitted for the comparison of parasitic load requirement for the pumps. Thus, the actual power consumption of these pumps will be higher, when all design conditions have been accounted for, but it is believed that this increase is similar for these two condenser type systems. The result of this comparison depends mostly on the pressure drop of the condenser tube side. The value of 0,5 bar pressure drop of the condenser tube side is in the lower range for the two-pass condenser assumed. Higher pressure drop will reduce the difference or even reverse the results especially for condenser with multiple passes.

Table 4: Example showing comparison of parasitic loads for a direct contact condenser and a surface condenser.

Generator output	50.000 kW	
Turbine steam consumption	90 kg/s	
Condenser type	direct contact	surface
Cooling water flow from condenser	2.800 kg/s	
Pressure drop of condenser tube side	-	0,50 bar
Resulting parasitic load contribution to circulation pump(s)	-	183 kW
Condenser pressure	0,10 bar_a	
Required pressure increase from hot well to atmospheric	0,90 bar	
Water level difference between condenser and cooling tower	3 m	-
Resulting parasitic load contribution to hot well pump(s)	439 kW	11 kW
Sum of parasitic load contribution from the condenser	439 kW	194 kW
Difference in parasitic loads for the two condenser types	0	-245 kW

The result is lower parasitic load if surface condensers are installed compared to direct contact condenser. Other positive advantage of surface condenser is a higher purity stream of water as condensate, unmixed with the circulating water that contains oxygen and water treatment chemicals. Any fraction of the condensate not used as cooling tower makeup can be used more efficiently for purposes such as steam wash, gas abatement or improving injection properties of separated water, seal water in liquid ring pumps, etc. Oxygen and other gases from the cooling water will be released in a direct contact condenser. This will result in higher load on the gas extraction system and more difficult gas abatement.

6. OPERATION EXPERIENCE

The output of power plants where cooling towers are installed, is relatively stable. Usually maximum wet bub temperature is a design condition and speed of cooling fans can be reduced if the wet bulb is lower. In binary plants with air cooled condenser the output can fluctuate +/- 20 – 30% with ambient conditions and is also sensitive to wind.

Sulphur deposits from geothermal fluids which are rich is H_2S and can cause operational problems in condensers and cooling towers. Sulphur exchanges between sulphate and hydrogen sulphide depending on its concentration, pH and temperature. The reaction is rapid under acidic conditions but is slow in alkaline environments. Elemental sulphur can deposit in direct contact condensers, where gases come into contact with oxygen. Sulphur can also sometimes plug the water distribution nozzles on top of cooling towers. (Tassew, 2001)

There are cases of algae formation in wet cooled surface condensers. This can cause decrease in the cooling system efficiency and interfere with water flow. This has been a problem in geothermal power plants in Iceland. Shock treatment once or twice each week with chlorine, such as NaOCl solution, can be employed to inhibit biological growth and deposition in the circulating water system and associated equipment. Where the makeup water source is water with dissolved minerals, dosing of hydrochloric acid (HCl) can be employed to prevent e.g. calcium deposit.

Vegetation formation in cooling towers is mitigated with chemical treatment. The treatment is site specific and adopted to condition in each power plant.

In some plants, deaerator system has been added with the purpose of reducing the gas in the condensate from a surface condenser. Normally the condensate from surface condenser is adequately deaerated, i.e. contains low concentration of geothermal gases, and secondary deaerator system is not necessary.

In cold climate ice can form in the cooling tower and snowstorms can add to this problem. This ice formation can be reduced by reducing the speed of fans, stop them or in extreme condition run the fans in opposite direction.

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