ECONOMIC OPTIMISATION OF COOLING SYSTEMS FOR GEOTHERMAL POWER STATIONS

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ABSTRACT

The power output of a geothermal power plant using an atmospheric cooling system is dependent on the design wet bulb temperature selected to size the plant and the prevailing ambient wet bulb temperature. Selection of a design wet bulb temperature which is not exceeded by the ambient wet bulb temperature will ensure full power output but will require a large and costly cooling system which will operate at well below its design capacity for the majority of the time. Alternatively, selection of a design wet bulb temperature which is exceeded by the ambient wet bulb temperature for a percentage of the time will require a less costly cooling system but will result in reduced power outputs and consequently a loss of power generation revenue. Thus, final selection of the design wet bulb temperature is essentially an economic compromise between the high capital cost associated with cooling systems designed for high ambient wet bulb temperatures and the loss of power generation revenue associated with cooling systems designed for low ambient wet bulb temperatures.

This paper summarises the procedures for optimising the selection of the design wet bulb temperature and the cooling system approach to minimise the direct and indirect generation costs associated with an atmospheric cooling system for a geothermal power plant.

INTRODUCTION

It is a characteristic of geothermal power plants that the capital cost is significantly higher than for conventional thermal power plants. However, in contrast to the conventional thermal power plant the energy source is 'free' and the annual operating costs are confined to the operating and maintenance costs, and in some circumstances the cost of redrilling geothermal wells. Therefore, geothermal power generation costs comprise a low annual operating cost component and a high annual capital cost component. To the designer, reducing these power generation costs is a matter of maximising the number of electricity units generated for every unit of capital cost expended.

For the majority of large geothermal power plants condensing turbines are used to reduce the flow of geothermal steam needed to generate a unit of electricity. For example, for the same generator output and for typical inlet steam pressures the geothermal steam requirements for a back pressure turbine are approximately 65 per cent greater than for a condensing turbine operating at typical vacuum conditions. This improvement in the efficiency or cycle heat rate (kJ heat per kWh of electricity generated) is an effective way of reducing the generation costs by reducing the capital costs associated with the exploitation of the geothermal reservoir.

The atmospheric cooling systems associated with geothermal condensing turbines comprise the following principal components:

- Condenser
- Cooling tower, lake or river
- Gas extraction equipment
- Cooling water circulating pumps
- Circulating pipework and valves.
There are several types of geothermal cooling systems in operation around the world. Each type has its own merits and is best suited to its particular application for reasons of design, location, environment and cost. For instance at Larderello in Italy barometric condensers are used with natural draft cooling towers and axial flow gas compressors. At the Geysers in the USA surface condensers, can pumps, cross flow mechanical draft cooling towers and steam ejector gas extractors are used while at Hatchobaru in Japan low level direct contact condensers, counter flow cooling towers and steam ejectors in series with radial blowers are used.

Atmospheric cooling systems for geothermal condensing turbines form a significant proportion of the total plant costs. The low cycle efficiencies associated with low pressure geothermal plants result in cooling systems which are approximately 1.25 the capacity of the equivalent conventional condensing turbine system. In addition, the predominant use of the more efficient contact condenser for geothermal power plants results in cooling systems contaminated by corrosive geothermal fluids. To combat this problem and to ensure an acceptable operating life for the cooling system designers must select special, and often very expensive, materials.

This paper recognises that the capital cost of geothermal atmospheric cooling systems is significant in relation to the overall cost of geothermal power development and analysis the various atmospheric and design parameters which influence the operating and capital costs with a view to minimising the generation costs.

**OPTIMISATION OBJECTIVES**

The performance of atmospheric cooling systems is directly influenced by the atmospheric conditions, or more particularly the ambient wet bulb temperature. Thus the selected design capacity is based on historical records of the atmospheric conditions prevailing at the power station site. The wet and dry bulb temperature distribution curves illustrated in figure 1 show the type of information necessary to make these design decisions. Assuming this information is statistically significant and applies to the selected power station site, the designer can establish for what percentage of the year the wet or dry bulb temperature is equalled or exceeded. More importantly the cooling system performance and hence the power station output can be measured with accuracy for the entire year.

![Dry Bulb and Wet Bulb Temperature](image)

Fig. 1 _Dry Bulb and Wet Bulb Temperature._

Figure 2 illustrates the power station output as a function of the design wet bulb temperature. In figure 2(b) the ambient wet bulb temperature never exceeds the selected design wet bulb temperature (T1) and, consequently, full station output is always available. In this case a very large and costly cooling system is provided to maintain full power station output at an ambient condition which probably only occurs less than 1 per cent of the year. As a result the cooling system will operate at well below its design capacity for the majority of its operating life.

Alternatively, in figure 2(a), the ambient wet bulb temperature exceeds the design wet bulb temperature (T1) for a percentage of the year. A cooling system designed for this wet bulb temperature (T1) will have a smaller cooling capacity and be less expensive. However, there will be periods during the year when the rated power station output is not maintained and there will be a reduction in revenue associated with the lost generation.
The cost of lost generation represents the cost of the geothermal steam which must be wasted to atmosphere when the power plant is not capable of full rated output.

In economic terms there is clearly a compromise between the condition shown on figure 2(a) and the condition shown on figure 2(b). Selection of a design wet bulb temperature ($T_1$) which is exceeded by the ambient wet bulb for a percentage of the year results in a low capital cost cooling system but incurs lost revenue for the period of the year when $T_1$ is exceeded. Selection of a design wet bulb temperature ($T_2$) which is not exceeded results in a high capital cost cooling system and no lost generation. Figure 3 shows these two conditions and illustrates how the optimum design wet bulb can be selected to minimise the capital and operating costs associated with an atmospheric cooling system.

The procedure to identify the optimum design wet bulb temperature involves an independent economic analysis of a range of selected design wet bulb temperatures. For each of these selected design temperatures there is an optimum cooling system approach temperature (the temperature difference between the temperature of cooling water leaving the cooling tower and ambient wet bulb temperature) which minimises the operating costs associated with the cooling system auxiliary power requirements and the cooling system capital costs. This is an essential part of the optimisation procedure which must be completed before the economics of each design wet bulb condition can be compared, as shown in figure 3.

The objective of this paper is to summarise the procedures for an economic analysis which optimises the design wet bulb and cooling system approach to minimise the direct and indirect costs of an atmospheric cooling system for a geothermal power station.

**Fig. 2** STATION OUTPUT AS A FUNCTION OF DESIGN WETBULB TEMP
Selection of the condenser vacuum would follow. This would involve a separate analysis of the associated variables and design conditions including, among others, the turbine output, the cycle heat rate, the non-condensible gas content of the geothermal steam, auxiliary power requirements and erosion of the final stage blades. This optimisation, therefore, is based on a constant design condenser vacuum. However with little modification the procedures set out in this paper could consider all the design variables, including those from the reservoir, to optimise the turbine inlet pressure, the condenser vacuum as well as the cooling system parameters.

The optimisation procedures discussed in this paper are applicable to any type of geothermal atmospheric cooling system. However, for the purposes of this paper a cooling system comprising the following principal plant items will be considered:

- Mechanical draught cooling tower
- Direct contact low level condenser
- Circulating cooling water pumps
- Steam ejectors
- Circulating pipework and valves

The plant layout incorporating these plant items is shown in figure 4.
The relationship between the cooling system variables and the capital cost and power consumption of each of the plant items is shown below. The power consumption formula shown are based on theory while the capital costs are mainly based on information received from the plant item manufacturers. The symbols used are listed in Table 1.

Table 1 List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Units</th>
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<tbody>
<tr>
<td>Cc</td>
<td>Condenser cost constant</td>
<td>$/kg sec(^{-1})</td>
</tr>
<tr>
<td>Ce</td>
<td>Ejector cost constant</td>
<td>$/\degree C</td>
</tr>
<tr>
<td>Cp</td>
<td>Pump cost constant</td>
<td>$/kg sec(^{-1})</td>
</tr>
<tr>
<td>Ct</td>
<td>Cooling tower cost constant</td>
<td>$/kg sec(^{-1})</td>
</tr>
<tr>
<td>Cw</td>
<td>Pipework cost constant</td>
<td>$/kg sec(^{-1})</td>
</tr>
<tr>
<td>n</td>
<td>Flow constant</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Pipework flow constant</td>
<td></td>
</tr>
<tr>
<td>Pf</td>
<td>Fan power constant</td>
<td>KW/kg sec(^{-1})</td>
</tr>
<tr>
<td>Pp</td>
<td>Pump power constant</td>
<td>KW/kg sec(^{-1})</td>
</tr>
<tr>
<td>Q</td>
<td>Cooling system flow rate kg/sec</td>
<td></td>
</tr>
<tr>
<td>Rf</td>
<td>Rating factor</td>
<td></td>
</tr>
<tr>
<td>t.off</td>
<td>temp. water leaving cooling tower</td>
<td>\degree C</td>
</tr>
</tbody>
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Cooling Tower

The cooling tower performance at the various design conditions was based on performance curves obtained from cooling tower manufacturers. Alternatively, the performance could be modelled using the technique described by Shaffer (1977). A typical performance curve is shown in figure 5.

\[ \text{Capital Cost (\$)} = \text{Ct} \times \text{Rf} \times Q \quad (1) \]
\[ \text{Fan Power (KW)} = \text{Pf} \times \text{Rf} \times Q \quad (2) \]

Condenser

\[ \text{Capital Cost (\$)} = \text{Cc} \times Q \quad (3) \]

Cooling Water Pumps

\[ \text{Capital Cost (\$)} = \text{Cp} \times Q^h \quad (4) \]
\[ \text{Pump Power (KW)} = \text{Pp} \times Q \quad (5) \]

Steam Ejectors

\[ \text{Capital Cost (\$)} = \text{Ce} \times \text{t. off} \quad (6) \]

Circulating Pipework and Valves

\[ \text{Capital Cost (\$)} = \text{Cw} \times Q^m \quad (7) \]
ECONOMIC OPTIMISATION PROCEDURE

The economic optimisation procedure is shown diagramatically in figure 6. The flow diagram shows all the steps involved and highlights the stages at which the cooling tower approach and the design wet bulb temperature are optimised. A computer programme, based on the illustrated flow diagram (fig 6) and written in the BASIC language, was developed and applied to select the design parameters for the Kamojang Geothermal Power Project.

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Shaffer, C.J., 1977, Floating Power Optimisation studies for the cooling system of a geothermal power plant, ERDA, Idaho National Engineering Laboratory.
