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Assessment of Evaporative Cooling Enhancement Methods for Air-Cooled Geothermal Power Plants

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C. Kutscher
National Renewable Energy Laboratory

D. Costenaro
Washington University in St. Louis

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National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Assessment of Evaporative Cooling Enhancement Methods for Air-Cooled Geothermal Power Plants

Charles Kutscher and David Costenaro

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

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Geothermal, power plant, evaporative cooling, air-cooled condensers

Abstract

Many binary-cycle geothermal power plants are air cooled because insufficient water is available to provide year-round water cooling. The performance of air-cooled geothermal plants is highly dependent on the dry bulb temperature of the air (much more so than fossil fuel plants that operate at higher boiler temperatures), and plant electric output can drop by 50% or more on hot summer days, compared to winter performance. This problem of reduced summer performance is exacerbated by the fact that electricity has a higher value in the summer. This paper describes a spreadsheet model that was developed to assess the cost and performance of four methods for using supplemental evaporative cooling to boost summer performance: 1) pre-cooling with spray nozzles, 2) pre-cooling with Munters media, 3) a hybrid combination of nozzles and Munters media, and 4) direct deluge cooling of the air-cooled condenser tubes. Although all four options show significant benefit, deluge cooling has the potential to be the most economic. However, issues of scaling and corrosion would need to be addressed.

Introduction

In the spring of 2000, the National Renewable Energy Laboratory (NREL) issued a request for proposals for the construction of small-scale (300 kW to 1 MW) geothermal power plants in the western United States (Kutscher 2001). One of the projects selected for funding was a 1-MW binary-cycle plant at Empire, Nevada. The proposers intended to employ air-cooling and augment summer heat rejection with some form of evaporative cooling. NREL staff developed a spreadsheet model to provide a cost-and-performance comparison of the alternatives that would be immediately useful for the Empire design and that would also be robust enough for use by other plant designers.

Model Description

The model was developed using Microsoft Excel. Excel has the advantages of allowing for easy curve-fits of system and component data, as well as tabulation of weather data. Also, the Visual Basic macro language allows for detailed psychrometric and economic calculations. A table of plant net-electric output as a function of dry bulb temperature is input on one sheet, and Excel determines a best fit to the data. The data itself can be obtained from actual measurements for an operating plant. In the case of our model of the proposed 1-MW Empire plant, we performed runs of the ASPEN chemical process computer program to obtain that data. [Engineering Equation Solver (EES) is a lower-cost alternative that can also be used for this purpose.] Weather data (dry bulb temperature and either wet bulb temperature or relative humidity) for each hour of a typical day of each month are also input to the spreadsheet. In the case of the Empire plant, weather data from Reno was used. Pressure drop and evaporative performance data were obtained from the manufacturer of the evaporative media, and these were also curve-fit in Excel.

The cost analysis of each system included determining the capital costs of equipment and installations, as well as routine maintenance and ongoing costs, e.g., water consumed. These costs were weighed against the value of the additional electricity the plant could produce with each system installed. Performance and cost data for each system were collected and evaluated using five key economic indicators: total life-cycle cost (TLCC), net present value (NPV), levelized cost of electricity (LCOE), simple payback (SPB), and internal rate of return (IRR).

The baseline condenser system for the Empire (based on the conceptual design) consists of 15 induced-draft fans drawing air through ten 60-foot-long tube bundles. ASPEN Simulation Software was run for the entire Empire plant and used to find out how net output was affected by the ambient temperature. The geothermal fluid inlet temperature was assumed to be 245°F. This produced the linear correlations shown in Figure 1. As the ambient temperature increases, plant performance drops considerably. The enhancement systems were modeled so that the plant would behave as if the ambient temperature was the temperature resulting from the cooling hardware. The corresponding performance for each hour of a typical day for each month was then determined from this curve. The plateau in the graph shows that an upper limit in performance is reached at low temperatures. This is because atmospheric pressure is set as a lower limit on condenser pressure to prevent air from entering the working fluid. The plant was run through a typical day of each month. It was assumed that the evaporative cooling systems would only be used from May through October and drained for the other months. The model assumed that the system would turn on whenever the value of additional electricity generated exceeded the cost of operating the system.

In developing the model, we investigated the impact of adding evaporating cooling media on fan performance and condenser airflow rate. When media is added, this steepens the fan head vs. volumetric flow rate curve, and the intersection with the fan curve occurs at higher value of head and a lower flow rate. The overall impact of this shift depends on the original fan operating pressure. Consider a case in which the original fan static head is 0.5 in. WC. With 8-in. thick Munters packing, the fan head may rise from 0.5 in. WC to 0.7 in. WC. However, axial fans have flat horsepower vs. flow rate curves, so the parasitic power is virtually unchanged. The total flow rate will drop by about 7%. This will slightly decrease the overall heat transfer coefficient in the condenser and the expected log mean temperature difference; however, ASPEN simulations show that these

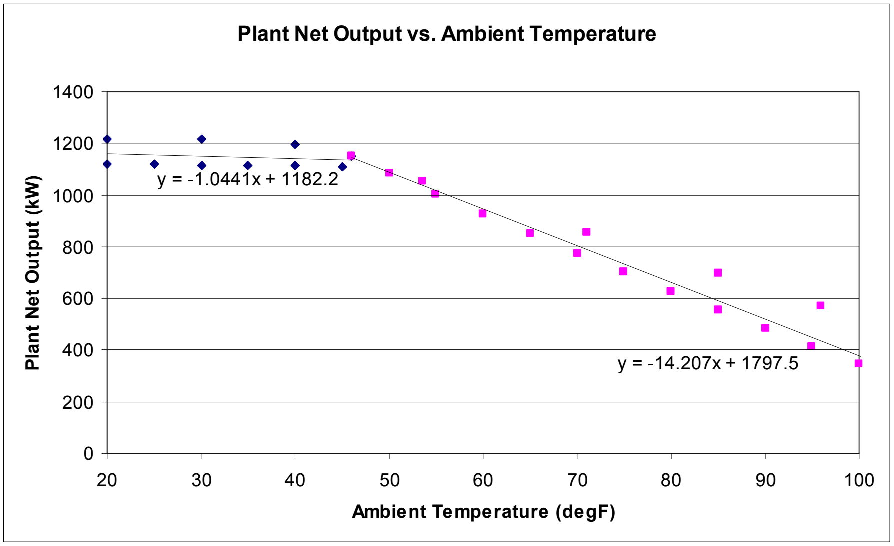

Figure 1. Plant net output as a function of ambient temperature for proposed new binary-cycle geothermal power plant in Empire, Nevada.

effects reduce power output by only about 2% for this example case. Although this loss in power is significant enough to justify bypassing of the evaporative media when it is not needed, it is a relatively small effect compared with increases in power output of 50% and more due to the lowering of the effective ambient temperature by virtue of the evaporative cooling. Because this effect depends on fan selection and because it is small, it has been neglected in the analysis presented here. For cases in which the original design pressure drop for the fan is less than 0.3 in. WC, the results in this paper would tend to slightly overestimate the performance of a system with Munters packing.

Systems Studied

The following four systems were studied:

1. The **spray cooling** method operates by having a high pressure water pumping system hooked up to an array of strategically placed, atomizing nozzles that mist the air as it enters the condenser. (See Figure 2.) The water droplets, split by impaction pins on the special nozzles, have diameters on the order of microns and evaporate very quickly and effectively. The incoming air can thus be cooled 95% and more from the T_{db} to the T_{wb} (i.e., 95% saturation efficiency). Manufacturers such as Mee Fog Inc. and Munters claim that evaporation is so effective that there is no danger of water droplets impinging on the downstream condenser tubes. Also, no return-water loop is used because of the limited amount of unevaporated water. Depending on the chemistry of the water, however, the nozzles may require regular cleaning. A recent investigation of spray cooling enhancement is reported by Maulbetsch and DiFilippo (2001).

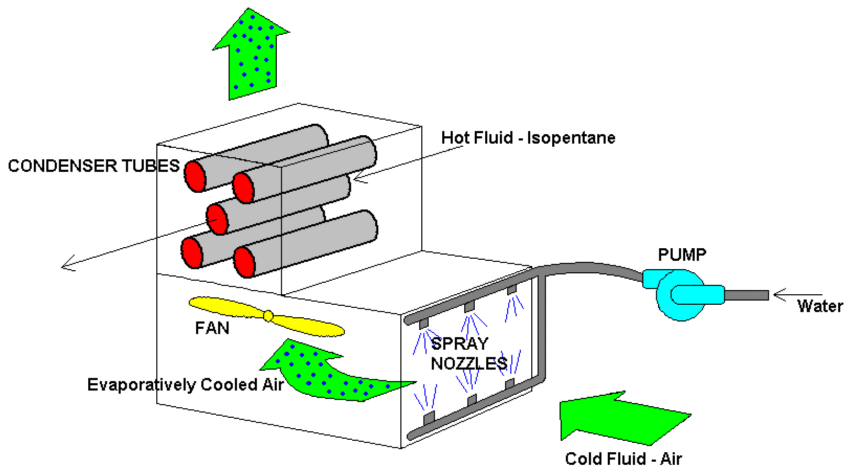

Figure 2. Spray nozzle evaporative cooling system.

2. The **Munters cooling** method involves covering the intake area with an evaporative cooling media and running the system like a typical evaporative or “swamp” cooler, as shown in Figure 3. Water is pumped at ordinary pressures to a distributing cap that spreads the water over the top of this honeycomb-like, porous media. As the water drips down and through it, air passes through, perpendicular to the media, and absorbs moisture. A pan collects excess water and recirculates it. As the water evaporates, though, it leaves deposits and minerals behind. To prevent this from building up, Munters recommends that water be bled off from the cycle at (depending on the water chemistry) between 10% and 50% of the amount of water that is evaporated. Therefore, the water that must be supplied is equal to the amount of water that is evaporated plus 10% to 50% of that for the bleed-off stream. Saturation efficiencies can range from around 60% to 98% as the media thickness increases. A mist eliminator can be placed downstream of the Munters packing to prevent any droplets picked up by the airflow from impinging on the condenser tubes and scaling or corroding them. This analysis assumed an air approach velocity of 500 ft/min, which Munters considers sufficiently low that droplets will not be entrained in the exit air. When the system is not in use, it is advantageous to have some sort of bypass for the airflow to avoid the pressure drop associated with the packing. Complete packaged systems similar to this, called Combinaire systems, can be purchased from Hudson Corporation (Smith 1972).

3. The **hybrid cooling** method combines aspects of the spray cooling and the Munters cooling methods. (See Figure 4.) A less sophisticated array of spray nozzles, with water at a lower pressure, heavily mists the intake air. The droplets are not atomized to the small diameters of the spray method and so are not evaporated as completely. The water that isn’t evaporated here, though, impinges onto a thin layer of Munters packing. A velocity of 500 ft/min was assumed to prevent droplets in the exit air. As the air passes through the Munters packing, it becomes more humid while experiencing a lower pressure drop than the pure Munters method because the packing is thin. The water is recirculated in a manner similar to the pure Munters cooling scheme. This method is

widely used in the poultry industry to cool chicken coops. Munters sells a system that combines spray nozzles with 2 in. of CELdek media under the brand name MI-T-Fog.

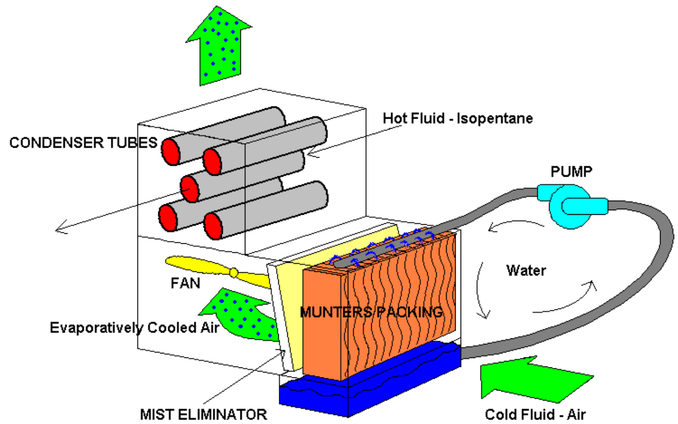

Figure 3. Munters packing evaporative pre-cooling system.

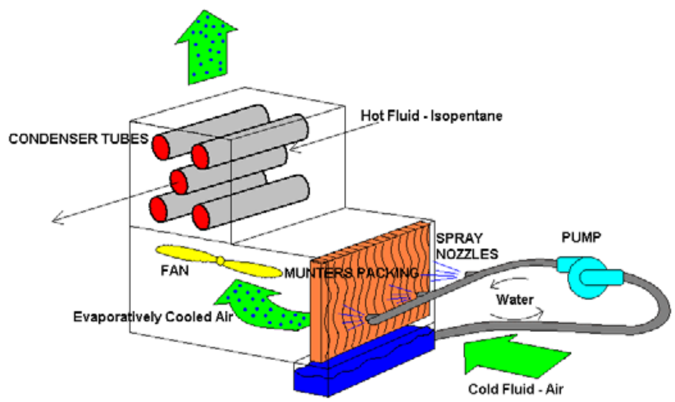

Figure 4. Hybrid (nozzles/Munters packing) evaporative pre-cooling system.

4. In the **deluge cooling** method, pumped water is sprayed onto the tubes from above. (See Figure 5.) The water that does not evaporate as it drips down is recirculated. This method is fundamentally different from the previous two methods in that evaporative cooling occurs directly on the condenser tubes, rather than in the air before it reaches the tubes. Consequently, the thermal resistance associated with the air boundary layer is effectively eliminated. Also, much more heat can be transferred to the air stream because the air continues to pick up moisture as it goes through the condenser. Rather than the air approaching saturation at the inlet, as for the other systems, the air now approaches saturation at the higher outlet temperature. The air can thus hold considerably more moisture, and this additional moisture results in greater latent heat transfer.

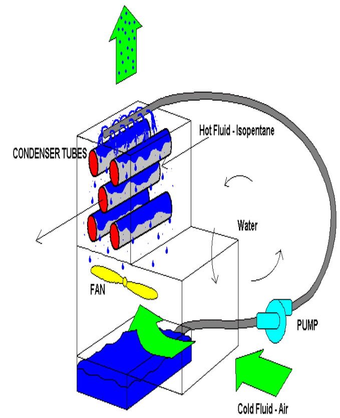

Figure 5. Deluge evaporative cooling system.

In studies done in the 1980s at Pacific Northwest National Laboratories (PNNL), large increases in heat transfer rates were observed using this method. Using these studies as a model, an expression for the thermodynamic driving potential was correlated to the enhancement ratio. The enhancement ratio is defined as the ratio of the amount of heat transfer when deluged to the amount of heat transfer when dry. This ratio was routinely between 3 and 7. These results were obtained using a finned-tube heat exchanger similar to the condensers under consideration (Hauser 1982).

With water in direct contact with the condenser tubes, scaling and deposition are a significant concern. When the system is shut down, the water that is still on the tubes will evaporate and leave deposits behind. To use clean treated water at all times is extremely expensive. The PNNL researchers proposed use of a small, reverse-osmosis purifier to accrue a tank full of clean water over the course of the day. Whenever a system is shut down, the condenser tubes are rinsed with the pure water, greatly reducing the amount of scaling. This rinse system would require a separate piping and pumping system. Alternatively, condenser tubes (preferably with extruded as opposed to tension-wound fins) could be coated with a protective layer. Because of the high heat transfer rates available, only one condensing unit needs to have the equipment installed.

Water was assumed to cost $1 per 1,000 gallons for this study. In order to reflect the value of electricity as a function of the weather, the electricity price was varied according to the schedule used for Standard Offer 4 (SO4). Actually, a fixed rate for electricity is often negotiated for new plants, with the value of the fixed rate depending on how well a plant performs during summer peak periods. Using the SO4 results provided a way to factor this time-of-generation effect into the model. However, more work is needed to determine a better way to do this. It may be beneficial to perform the analysis for every hour of the year in order to better account for the coincidence of high air temperatures and high electric demand. The spreadsheet model could be readily changed to calculate for every hour of the year. In this case, run times would increase from 30 seconds to 15 minutes. Although hourly weather data is available, we do not currently have a source for appropriate hourly electricity rates.

Results

A plot of the monthly performance for each system, without any enhancement, is shown in Figure 6. Note that without any enhancement, monthly electric energy production drops from 850,000 kilowatt-hours in the winter to 550,000 kilowatt-hours in the summer. The three evaporative pre-cooling systems raise the summer output up to approximately 750,000 kilowatt-hours. The deluge cooling is the only one that brings the output all the way up to winter performance, and it even does a little better than that. This is not surprising because the deluged air-cooled condenser acts like an evaporative water-cooled condenser. In this dry climate, the wet bulb temperature provides a more attractive sink temperature than the dry bulb temperature (even in the winter time), although the condenser pressure is already about as low as it can go in the winter.

Figure 6 shows that any evaporative enhancement strategy in the summer can have a significant impact on plant output. It also illustrates the superiority of water cooling over air cooling. Clearly, air cooling should only be used when there is low or no water availability. For cases of low availability, use of water in the summertime makes good sense from a performance standpoint.

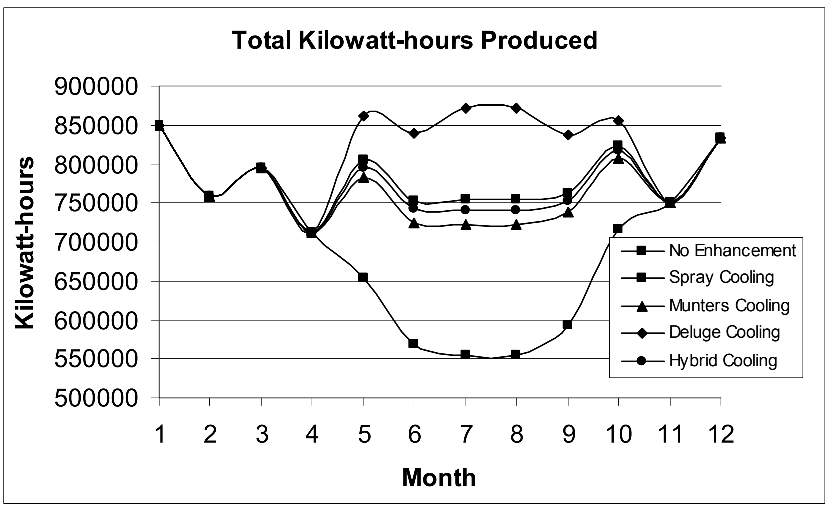

Figure 6. Monthly electricity production for evaporative cooling enhancement methods.

Table 1 shows the economic results for each system. Payback periods range from one year for the deluge system to seven years for the Munters packing. The deluge system not only performs well, but also its estimated costs are low. The initial cost for spray nozzles, piping, pump, catch basin, and controls is only $37,000. In addition, there is an estimated maintenance cost of $22,000 per year. The cost of deluging an air-cooled condenser is thus small compared to the other systems. In particular, the Munters system, which uses 8 in. of Munters packing, is expensive because the Munters media costs $30 per cubic foot and must be replaced every five years. So purely on a cost-performance basis, the deluge system looks very attractive. It is important to note that the assumptions used for costs in this study have a major impact on the final comparison. On-site installation cost estimates are given on a site-specific basis, and we believe they are subject to negotiation. The ultimate payback for these systems is thus strongly dependent on the particular situation.

Table 1. Economics Results for the Various Evaporative Enhancement Methods.

	System 1 - Spray Cooling	System 2 - Munters Cooling	System 3 - Deluge Cooling	System 4 - Hybrid Cooling
Total Capital Cost [$]	$155,977	$184,530	$37,139	$134,911
Additional kWh produced per year with system [kWh]	1,013,085	855,851	1,496,471	947,359
Total Value of Additional Electricity [Present Value $]	$413,888	$348,856	$622,823	$386,562
TLCC - Total Life-Cycle Cost [Present Value $]	$307,084	$331,449	$182,948	$209,469
NPV - Net Present Value [Present Value $]	$106,804	$17,407	$439,875	$177,093
LCOE - Levelized Cost of Additional Energy [Additional Cost per year / kWh gained per year]	$0.0469	$0.0599	$0.0189	$0.0342
SPB - Simple Payback Years	5	7	1	4
IRR - Internal Rate of Return	23.2%	16.0%	164.8%	32.1%

There are practical considerations that must be considered, however, and these are difficult to factor into the cost-performance numbers. For systems using spray nozzles, some water is lost in windy conditions. Overspray can lead to water runoff on the ground and create muddy conditions. The amount of cleaning that nozzles will require depends on the quality of the water used. The deluge system is especially worrisome to plant operators because corrosion of the finned tubes can result in an expensive tube bundle replacement. If finned tubes are to be deluged, they should be of the extruded type, so corrosion cannot occur under the fins. NREL and Brookhaven National Laboratory are experimenting with thin protective coatings that can be used with condenser tubes.

Conclusions

Air-cooled geothermal power plants can benefit significantly from the use of some evaporative cooling enhancement in the summer. A system in which the water directly contacts the condensate tubes has the highest performance and is economically the most attractive. However, concerns with condenser tube scaling and corrosion must be addressed.

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C. Kutscher and D. Costenaro

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Washington University in St. Louis
One Brookings Drive, St. Louis, MO 63130

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