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SIMPLE STRATEGIES FOR MINIMIZATION OF COOLING WATER USAGE IN BINARY POWER PLANTS

Carl J. Bliem
Gregory L. Mines

Idaho National Engineering Laboratory
EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

ABSTRACT

The geothermal resources which could be used for the production of electrical power in the United States are located for the most part in the semi-arid western regions of the country. The availability of ground or surface water in the quantity or quality desired for a conventional "wet" heat rejection system represents a barrier to the development of these resources with the binary cycle technology. This paper investigates some simple strategies to minimize the cooling water usage of binary power plants. The cooling water usage is reduced by increasing the thermal efficiency of the plant. Three methods of accomplishing this are considered here: increasing the average source temperature, by increasing the geofluid outlet temperature; decreasing pinch points on the heat rejection heat exchangers, increasing their size; and using internal recuperation within the cycle. In addition to the impact on water usage, the impact on cost-of-electricity is determined. The paper shows that some of these strategies can reduce the cooling water requirements 20 to 30 % over that for a plant similar to the Heber Binary Power Plant, with a net reduction in the cost-of-electricity of about 15%.

INTRODUCTION

It is recognized that geothermal resources, at best, represent a fairly low-grade energy when compared to the burning of a fossil fuel. Maximum power cycle temperatures are on the order of 400 to 475 K, whereas fossil energy provides temperatures in excess of 800 K. The geothermal source, although provided by nature, is generally expensive to produce. For these reasons, optimum systems used to convert this geothermal energy to electric power should utilize as much of the energy contained in a unit mass of geofluid as possible. More sophisticated "value analyses" and "market penetration" studies which examined the impact of improvements on the cost of power and on the future utilization of geothermal-electric power, confirm this fact (1,2). Therefore, the net geofluid effectiveness, the amount of net electrical energy produced by the power plant per unit mass of geofluid, has been taken as the prime thermodynamic performance parameter in most analyses. The "value analysis" is a methodology for examining the relative impact of different options or systems on the cost-of-electricity. It is used in this work to evaluate the impact of the different strategies to minimize cooling water usage in binary plants.

For moderate temperature hydrothermal resources, binary power plants are more efficient than flash steam plants, and have been selected as the type of plant to be studied for the current investigation. Prior to 1980, a number of investigators have shown this and have looked at different fluids to use in the binary cycle for optimum performance (3,4,5). More recently, Hughes and Khalifa (6) considered a number of working fluids for a wide range of resource temperatures for wellhead units. They primarily considered pure fluids, including only a few mixtures. At resource temperatures near those predicted for the Heber plant, Demuth (7,8) and Demuth and Kochan (9) performed studies of use of mixtures of the saturated hydrocarbons (alkanes) and found that the mixtures gave improved performance over the corresponding pure fluids. Bliem (10) showed that the same results were true if halocarbon mixtures (Freons) were used. All of these studies perform a thermodynamic optimization of the geofluid effectiveness.

The Heber Binary Power Plant is a binary, geothermal power plant which has made use of many of these basic ideas. In the Heber system, a working fluid mixture of isobutane and isopentane is heated at a pressure above the critical pressure; most studies have indicated that this is the best mode of heat addition for organic Rankine cycles used in this application. The plant may be considered as a state-of-the-art plant at this time. References (11) and (12) describe the plant in greater detail.

The geothermal resources which could be used for the production of electrical power in the United States are located for the most part in the semi-arid western regions of the country. The lack of ground water in the quantity or quality desired for a conventional "wet" heat rejection system is a barrier to the development of these resources with the binary geothermal cycle technology. Reducing the requirements for cooling water makeup addresses these concerns. Reducing the cooling water requirements will also reduce the cost associated the the disposal of the waste produced generated in treating the lower quality make-up water. The handling of those wastes is likely to become a significant operating cost in the future as public environmental awareness and the resulting constraints increase. Reducing the cooling water requirements may also be expected to reduce the parasitic power requirements associated with a particular heat rejection system, increasing the net power production.

There are a number of strategies to minimize cooling water usage in a given application. Design of the heat rejection system to partially or totally rely on dry cooling is one method. This potentially decreases the performance of a given system by raising the cycle heat rejection temperature. There may be ways to integrate cycle operation and heat rejection functions to optimize performance. This is an area which the Department of Energy's Heat Cycle Research Program plans to study over the next few years.

One simple method of reducing heat rejection and, therefore, cooling water usage is to increase the cycle thermal efficiency. Note that this is not the same as increasing the net geofluid effectiveness. The effectiveness defined above is the product of the thermal efficiency and the change in enthalpy (energy removed from) of a unit mass of geofluid flowing through the plant. The effectiveness is maximized by increasing the thermal efficiency or by removing more heat from each unit mass of geofluid flowing through the plant. The optimum is a trade-off of these quantities because the thermal efficiency decreases as the amount of energy removed from the geofluid increases.

A number of cycle performance improvements have been studied, first, for the Heber Advanced Binary Plant and later by the Heat Cycle Research Program. These improvements include use of mixtures as working fluids; integral, countercurrent phase change; supercritical heating; exhaust gas recuperation (7,8,9,10). This paper discusses the impact of these performance improvements on the reduction in heat rejected from the cycle and its impact on the cost of electricity. A supercritical, recuperated cycle using the best working fluid mixture gives approximately a 30% reduction in heat rejection (cooling water usage) per unit power produced than the Heber Binary Plant. This configuration gives a decrease in the cost of electricity of about 10% compared to the Heber Plant.

The paper first presents a brief discussion of the configurations of binary system including a simple Rankine cycle, a cycle with working fluid preheating using the energy in the turbine exhaust recuperatively and use of energy in a turbine bleed configuration. Different strategies are then discussed and results are shown for each strategy. Finally, conclusions are reached concerning the most practical approaches.

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BINARY GEOTHERMAL CYCLE DESCRIPTIONS

The working fluid in a binary geothermal electric power plant undergoes the processes of a Rankine thermodynamic cycle. Figure 1, which is a schematic diagram of a simple Rankine cycle, illustrates these processes as well as the major components of the plant. Starting at the condensate storage tank, the working fluid is pumped from the condenser pressure to the heater pressure. Heat from the geofluid is used to vaporize the working fluid in the heater (a tubular heat exchanger). This vaporization can occur at supercritical pressures (without discrete phase change) as in the Heber plant, or at a subcritical pressure where the working fluid is boiled. The working fluid leaving the heater is superheated to the desired turbine inlet temperature. The working fluid leaving the heater flows through the turbine, producing work at the turbine shaft to drive the electric generator which is coupled to the turbine. The turbine exhaust is then condensed in the condenser (after being desuperheated, if

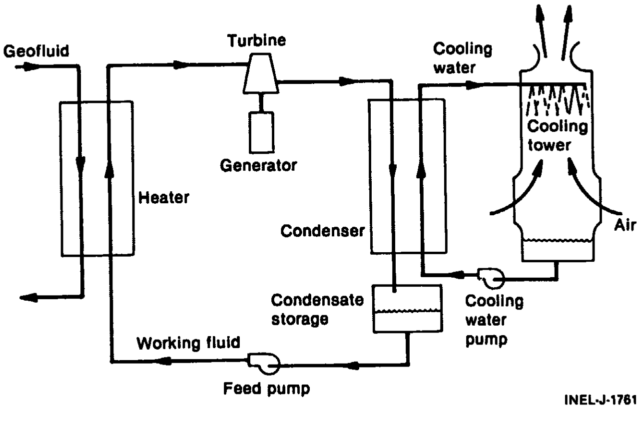

Figure 1. Simple Binary Geothermal Cycle

necessary) by transferring heat to the cooling water. This heat is then rejected to atmospheric air using a wet cooling tower, and the condensed working fluid is returned to the condensate storage tank to complete the cycle.

Limitations on the minimum temperature at which geofluid can be returned from the power plant have been imposed in certain situations. With geofluid at 455 K (360 F), as in the Heber plant, restricting the exit geofluid flow to 344 K (160 F) should keep the geofluid above the point at which amorphous silica precipitates from the solution. The Heber plant, at times, was under this type of constraint. In many instances, there is enough energy in the turbine exhaust at a high enough temperature with which to preheat the working fluid going to the heater. This type of recuperation is shown in Figure 2. Another form of recuperation is shown in Figure 3. Here, recuperation is performed by a direct contact heat exchanger (open feedwater heater) in which fluid bled from the turbine is mixed with the working fluid to be preheated.

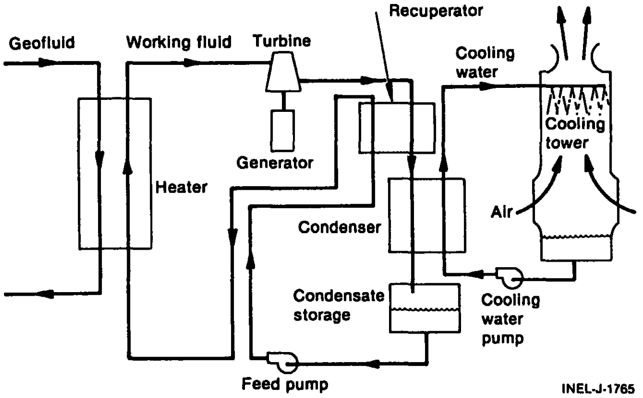

Figure 2. Binary Geothermal Cycle with Turbine Exhaust Recuperative Preheating.

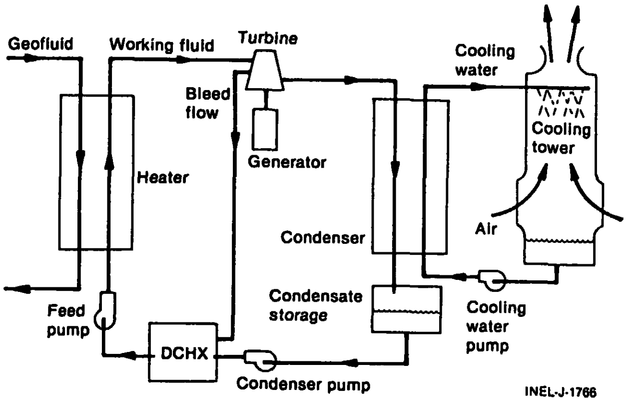

Figure 3. Binary Geothermal Cycle with Turbine Bleed Regenerative Preheating.

Demuth and Kochan (9) have shown that if an exhaust gas recuperator is used to preheat the working fluid, there is practically no loss in geofluid effectiveness when compared with the case in which no constraint was applied to the geofluid leaving the plant. (This result was confirmed by Bliem (10) for halocarbon mixtures.) The use of turbine bleed was also considered in Reference 9.

STRATEGIES TO REDUCE COOLING WATER USAGE

If cooling water usage is to be eliminated, dry cooling must be used. This has been done in geothermal power plants such as the plants at Mammoth, California and Steamboat Springs, Nevada. If cooling water is available, but it is desired to minimize its usage, a number of strategies may be followed

As mentioned previously, the simplest method of reducing cooling water makeup is to improve the thermal efficiency of the plant. It can be shown that the amount of heat rejected by a system divided by the net work is equal to one less than the reciprocal of the thermal efficiency. Increasing the plant thermal efficiency from 15% to 16% gives a reduction in the heat rejected per unit work produced of 6.25%.

There are a number of ways to increase the plant thermal efficiency. The first method considered here is to increase the average heat source temperature. Increasing the heat source temperature (geothermal fluid) and decreasing the heat sink temperature will increase thermal efficiency. The heat source considered here is a liquid source. To increase the average heat source temperature, the outlet temperature of the geofluid must be increased if the inlet temperature is fixed. It should be noted that this may well decrease the net geofluid effectiveness because it decreases the amount of heat removed from each unit mass of geofluid.

A second method of increasing the thermal efficiency is to decrease internal thermodynamic irreversibilities within a cycle. This can be done by the proper selection of working fluids and operating parameters, as well as by decreasing the minimum approach temperatures between fluids in heat exchangers (pinch points). This will increase the size of heat exchangers and may possibly increase the cost-of-electricity by increasing the plant capital cost. This effect must be investigated for particular cases because the power produced will increase also.

The third method of increasing the thermal efficiency involves the use of recuperative heat transfer within the cycle to preheat working fluid. The second and third systems described in the previous section (See Figures 2 and 3.)

are of this type. The Kalina "System 12", which was recently introduced as a potential geothermal power cycle uses recuperation also. It has previously been shown that this strategy improves the geofluid effectiveness when geofluid outlet temperatures are constrained because of problems with silica deposition. The strategy will also decrease the cooling water makeup requirements as a "fringe benefit".

In the next section, these three strategies of improving thermal efficiency are examined for a liquid geothermal resource at 360 F (similar the the Heber resource).

RESULTS AND CONCLUSIONS

In order to quantify the performance gains by each of the strategies listed above, one set of geofluid and ambient conditions was analyzed. The parameters were chosen to represent those conditions for the Heber Plant. The results do not, however, represent actual operational conditions for the plant because of some simplifying idealizations described in previous work (8) were assumed in the analyses and are summarized below. The operating conditions used in the analysis are:

Geofluid resource--Liquid resource at 455 K (360 F)
Turbine inlet pressure--4.14 MPa (600 psia)
Heat rejection--Wet bulb temperature at 289 K (60 F)

In addition, the following "ground rules" and simplifications were adopted:

1. Heat exchangers were shell-and-tube.
2. Geofluid pumping requirements (at a given geofluid flow rate) were assumed the same for all cases and those parasitics were not included.
3. Component and piping frictional pressure drops were neglected.
4. Pump and turbine efficiencies were assumed to be 80 and 85%. For simplicity, the electrical motor and generator efficiencies were taken to be 100%.
5. Pinch points (minimum approach temperature differences) in the heaters were assumed to be 5.5 K (10 F). In the condensers, both 5.5 and 2.8 K (10 and 5 F) were used as explained below.
6. Wet cooling towers were assumed which provided cooling water to the condenser at 294 K (70 F). The cooling tower parasitic power was estimated by methods described in Reference (8).
7. Turbine expansions contained no liquid. (Dry turbine expansions). An alternate strategy of expansion through the vapor dome is presently being investigated in the Heat Cycle Research program.

The Heber plant, which was used as the base case, used a mixture of 90 mole percent isobutane and 10 mole percent isopentane. The condensation took place on the shell side of horizontal heat exchangers and was, therefore, differential condensation and not counterflow. (Differential condensation occurs when the liquid which condenses is separated from the remaining vapor. In order to totally condense, the vapor must be cooled to the condensation temperature of the lighter component.) For the assumptions listed above, the net geofluid effectiveness for this "reference" configuration is 17.04 W hr/kg (7.73 W hr/lbm) geofluid (net plant power per unit geofluid flow). The net plant power includes the turbine power and the working fluid pumping and accounts for the cooling tower parasitic power requirements.

References 8 and 9 investigated this type of system from a thermodynamic point of view to maximize the net geofluid effectiveness. A working fluid of 96% isobutane and 4% heptane by mass was found to be optimum with no constraints on the geofluid outlet temperature. The results, summarized in Reference 13, show that with the dry turbine expansion, the geofluid effectiveness is 20.50 W hr/kg (9.30 W hr/lbm), a 20% increase.

Table 1 shows the cases considered in the study. Case A is the case referred to in the preceding paragraph. Cases B, C and D represent the first strategy of forcing the average geofluid temperature to be higher by limiting the minimum geofluid temperature. Cases E, F and G are similar, but using the third strategy of an exhaust gas recuperator. Cases a through g are similar cases with a pinch point half that in cases A through G (the second strategy).

Thermodynamic analyses for each case were made using the assumptions mentioned above. The improvement in cooling water usage was estimated from the change in heat rejected per unit net

Table 1. Definition of Cases

Case	Condenser Pinch Pt. [F]	Geofluid Outlet Temp. Constraint [F]	Recuperation
A	10	none	No
B	10	160	No
C	10	170	No
D	10	180	No
E	10	160	Yes
F	10	170	Yes
G	10	180	Yes
a	5	none	No
b	5	160	No
c	5	170	No
d	5	180	No
e	5	160	Yes
f	5	170	Yes
g	5	180	Yes

work from the calculation. Table 2 is a summary of thermodynamic results.

Each of these cases shows a significant decrease in heat rejection over the Heber Plant. (The cooling water makeup requirements are assumed to be proportional to the heat rejected.) This reduction in heat rejected results from the increased thermal efficiency resulting from using the optimum mixture for a working fluid and counterflow condensation. A number of trends are evident from this data:

> Strategy 1. Raising the geofluid outlet temperature (with a fixed inlet temperature) decreases the heat rejected and the cooling water makeup for the cases with or without recuperative preheating of the working fluid.
>
> Strategy 2. Recuperative preheating of the working fluid for a given geofluid outlet temperature and pinch point decreases cooling water makeup requirements.
>
> Strategy 3. Use of smaller pinch points in the condenser for other conditions fixed lower the cooling water makeup requirement.

None of these results is unexpected because each of these tends to increase the thermal efficiency of the plant. The question of the cost effectiveness of each strategy remains. A look at the change in cost-of-electricity is necessary to complete the picture.

The impact on cost-of-electricity was assessed using the "value analysis" concepts of Reference 1. Here incremental changes in cost-of-electricity are estimated by considering changes in the amount of power produced and in cost of capital equipment for systems with the same geofluid flow (same field). Because this is an incremental analysis, the field costs (either as fuel costs or as the actual field cost) are the same in both cases and do not effect the answer. The only O&M cost considered is the cooling water makeup. Other O&M costs are assumed to cancel out in the differencing

Table 2. Thermodynamic Results

Case	Geofluid Flow	Heat Rejected	UA Heaters	UA Condenser	UA Recup.	UA Total	Turbine Ex. Area
A	0.831	0.833	0.893	1.035	0.000	0.969	1.050
B	0.901	0.809	0.800	0.963	0.000	0.887	1.003
C	0.939	0.801	0.802	0.931	0.000	0.871	0.993
D	0.981	0.794	0.846	0.900	0.000	0.875	0.975
E	0.823	0.725	0.885	1.046	0.080	1.014	1.049
F	0.843	0.703	0.843	1.015	0.090	0.982	1.035
G	0.866	0.681	0.808	0.982	0.100	0.954	1.016
a	0.792	0.796	0.852	1.699	0.000	1.304	1.061
b	0.870	0.778	0.763	1.571	0.000	1.194	1.025
c	0.907	0.770	0.773	1.518	0.000	1.170	1.005
d	0.950	0.765	0.786	1.467	0.000	1.149	0.992
e	0.788	0.690	0.836	1.702	0.160	1.383	1.062
f	0.808	0.669	0.798	1.651	0.178	1.348	1.047
g	0.831	0.650	0.770	1.603	0.196	1.319	1.034

Ratios are relative to the Heber Binary Plant

Table 3. Percentage Change in Cost-of-Electricity

Case	Power Change	Cap Cost Change: Cw makeup	Heater	WF comp.	Turb.	Turb. piping	Gen. Struct.	Cond.	Recup.	Cooling tower	Ind cap	Total Dcoe/coe
A	-0.1688	0.0000	0.0023	0.0012	0.0052	0.0018	0.0036	0.0116	0.0000	0.0001	0.0026	-0.1403
B	-0.0988	-0.0018	-0.0038	-0.0036	0.0024	0.0009	0.0021	0.0076	0.0000	-0.0029	0.0003	-0.0978
C	-0.0610	-0.0028	-0.0052	-0.0059	0.0012	0.0005	0.0013	0.0056	0.0000	-0.0044	-0.0007	-0.0713
D	-0.0186	-0.0037	-0.0051	-0.0083	-0.0001	-0.0001	0.0004	0.0036	0.0000	-0.0060	-0.0015	-0.0395
E	-0.1768	-0.0020	0.0024	0.0017	0.0054	0.0019	0.0038	0.0121	0.0032	-0.0031	0.0027	-0.1488
F	-0.1574	-0.0028	0.0000	0.0001	0.0046	0.0016	0.0034	0.0106	0.0036	-0.0045	0.0020	-0.1388
G	-0.1344	-0.0037	-0.0022	-0.0015	0.0035	0.0013	0.0029	0.0091	0.0040	-0.0059	0.0011	-0.1259
a	-0.2083	0.0001	0.0023	0.0011	0.0065	0.0023	0.0044	0.0333	0.0000	0.0001	0.0050	-0.1531
b	-0.1299	-0.0018	-0.0041	-0.0039	0.0036	0.0013	0.0028	0.0273	0.0000	-0.0030	0.0024	-0.1052
c	-0.0927	-0.0027	-0.0051	-0.0061	0.0023	0.0008	0.0020	0.0248	0.0000	-0.0044	0.0015	-0.0797
d	-0.0499	-0.0037	-0.0062	-0.0085	0.0010	0.0004	0.0011	0.0221	0.0000	-0.0059	0.0004	-0.0493
e	-0.2121	-0.0020	0.0018	0.0013	0.0067	0.0023	0.0045	0.0335	0.0064	-0.0031	0.0054	-0.1554
f	-0.1921	-0.0028	-0.0004	-0.0002	0.0057	0.0020	0.0041	0.0314	0.0071	-0.0044	0.0046	-0.1450
g	-0.1630	-0.0036	-0.0023	-0.0018	0.0048	0.0017	0.0036	0.0293	0.0078	-0.0058	0.0038	-0.1315

Base Case: Heber Binary Plant

procedure. The details of the analytical method are given in Reference 1. Fractional effects on cost-of-electricity are assessed in terms of data from a number if independent sources as are the effect on the cost-of-electricity of the fuel, capital and O&M costs. Table 3 is a summary of the components of the cost-of-electricity incremental change. The reference in each case is the Heber Plant.

Some general conclusions can be made about the cost-of-electricity:

1. It is generally not cost effective to limit the geofluid outlet temperature if it is not otherwise constrained.
2. Use of a recuperator is cost effective when used along with the restriction on geofluid outlet temperature.
3. The optimum pinch point is probably between 2.8 and 5.5 K. Some configurations are more cost-effective with one pinch point and some with the other.

Putting the results together, Figure 4 shows each case with the decrease in cost-of-electricity on one axis and the decrease in cooling water makeup on the other axis. In general:

Strategy 1. The increasing of the geofluid outlet temperature gives a small decrease in cooling water makeup requirements but an increase in cost of electricity. (Cases B, C and D compared to case A.) This will not be cost effective.

Strategy 2. The use of a recuperator along with limiting the geofluid outlet temperature gives a substantial decrease in cooling water makeup with a small decrease in the cost-of-electricity. (Cases E, F and G compared with case A.)

Strategy 3. Decreasing the pinch point in the condenser gave an increase in cost-of-electricity as well as a decrease in cooling water makeup. The choice of 5.5 K (10 F) condenser pinch points is too large and an optimum is lower than this value.

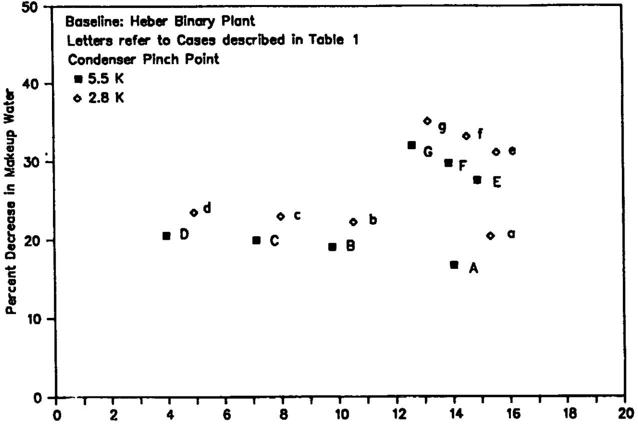

Figure 4. Composite Performance.

SUMMARY CONCLUSIONS

In summary:

1. Optimizing the performance of the binary cycle with respect to geofluid effectiveness results in high cycle thermal efficiency and reduced heat rejection requirements (cooling water makeup), except where the entire gain is to lower the geofluid outlet temperature. Note that all of these systems have heat rejection requirements at least 15% less than that for the Heber Plant.

2. Of the strategies considered, the use of recuperators gave the most significant reduction in heat rejection requirements and did not adversely impact the cost-of-electricity. For the cases selected there was a 40% reduction (referred to the Heber plant) in makeup water, contrasted with a 20% reduction for the standard supercritical cycle without recuperation. There was no appreciable reduction in cost-of-electricity when the recuperator was added.

3. Utilization of the advanced plant concepts and recuperation would be expected to reduce heat rejection requirements for the reference "Heber-type" plant by approximately 30%.

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