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Geothermal Preheating in Fossil-Fired Steam
Power Plants

by

H. Ezzat Khalifa, Ronald DiPippo and Joseph Kestin

Brown University

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ABSTRACT

In this paper we present a thermodynamic analysis of a hybrid fossil geothermal power plant in which the low-grade geothermal energy is used for preheating the feedwater in a fossil-fired steam power plant. By restricting the geofluid to sensible heat addition, the entropy production in this process can be reduced. This results in an overall improvement in the utilization of the two energy sources.

The performance of the hybrid system is studied in terms of suitably defined figures of merit. These include criteria for the choice of the appropriate hybrid utilization strategy, given the finite nature of geothermal and fossil resources. The paper also addresses the question of optimum bleed conditions in a cycle comprising both geothermal and regenerative feedwater heating.

PRELIMINARY CONSIDERATIONS

Geothermal energy is regarded as low-grade energy in comparison with the high-grade energy derived from the combustion of fossil fuels. The hydrothermal geothermal resources in the western United States, considered for near-term exploitation, are predominantly of the liquid-dominated type and produce geofluid at temperatures seldom exceeding 300°C (1)^{*} and typically of the order of 200°C .

The utilization of low-grade energy poses a number of problems, most of which find their origin in the large entropy production associated with bringing the working fluid to its operating conditions (2, 3). This can be further clarified by considering the two systems currently employed for geothermal energy conversion, viz, the flash-steam system and the binary fluid system.

In the first system the working fluid (steam) is produced through an irreversible, isenthalpic process; furthermore, the steam separated after this process is, at best, dry and saturated. Thus the expansion process in the turbine occurs in the wet region with the accompanying losses and blade erosion. On the other hand, the binary-fluid system involves a transfer of heat from the geofluid to an organic working fluid. Owing to the considerably different nature of the two fluids, a pronounced pinch occurs in the heat exchanger, and the temperature difference between the two fluids diverges noticeably at either end of the heat exchanger. The entropy production associated with such a heat transfer process can be so large as to degrade the already low availability of the geofluid.

The present authors have discussed the hybrid fossil-geothermal energy conversion concept before (2, 3). Although there are many ways in which

^{*}Numbers in parentheses designate References at end of paper.

fossil and geothermal energy can be utilized simultaneously (3), we shall restrict the analysis in this paper to one arrangement, namely, the geothermal preheat system* shown in Fig. 1. In this system, the low-grade geothermal energy is used for preheating the feedwater in an otherwise conventional, fossil-fired steam power plant. The geothermal heat exchanger, therefore, replaces some or all of the regenerative feedwater heaters in the conventional cycle, whereas the fossil fuel is confined to the high-temperature heat addition process in the steam generator.

By restricting the geofluid to the heating process in the liquid region the temperature distribution in the heat exchanger will not develop a pinch point. This occurs because of the similarity of the thermodynamic and transport properties of the geofluid on the hot side of the heat exchange surface and the feedwater on the cold side. Not only does this simplify the design of the heat exchanger, but it also results in a significant improvement in the utilization of geothermal energy as we will demonstrate below.

PERFORMANCE PARAMETERS

The performance of an energy conversion system receiving both low-grade and high-grade energy cannot be rationally described in terms of thermal efficiencies and coefficients of performance ordinarily defined for cycles receiving heat from a single reservoir (5). A quantity of heat added at a low temperature is not thermodynamically equivalent to the same quantity of heat added at a higher temperature. For this reason the performance of a hybrid system should be described in terms of parameters that reflect the different "thermal ranks" of the two resources. This is achieved by assessing the two resources on

* A companion paper (4) deals with another hybrid arrangement known as the fossil-superheat system.

the basis of their exergy or available work (5) rather than on the basis of their "energy" or "heat content".* In an open system the available work (5) relative to a dead state ($P_o, T_o, \dots$) is given by

$$W^o = H - H_o - T_o (S - S_o) \quad (1)$$

If the process comprises a chemical reaction such as the combustion of a fossil fuel in which the reactants and the products exist at (P_o, T_o) then

$$W^o = H_o(R) - H_o(P) - T_o [S_o(R) - S_o(P)] \quad (2)$$

in which R and P refer to reactants and products, respectively. Eq. (2) can be rearranged to read

$$W^o = G_o(R) - G_o(P) = -\Delta G(P_o, T_o) \quad (3)$$

where G_o is the Gibbs free energy at (P_o, T_o). For the fossil fuels of interest in the power generation industry, ΔG is slightly greater than but not much different from the calorific value of the fuel (the heat of combustion), i.e.

$$\Delta G \approx \Delta H \quad (4)$$

The available power from a hybrid power plant consists of two parts: the geothermal part,

$$\dot{W}_g^o = \dot{m}_g [h_g - h_o - T_o (s_g - s_o)] \quad (5)$$

and the fossil part,

$$\dot{W}_f^o = -\dot{m}_f \Delta G_f \approx -\dot{m}_f \Delta H_f \quad (6)$$

*The use of such expressions as "BTU value" and "heat content" is, unfortunately, common. These expressions are remnants of the discredited caloric theory of heat.

In these equations $\dot{m}_g$ and $\dot{m}_f$ represent the mass flow rates of the geofluid and the fossil fuel, respectively, whereas h_g and s_g are the specific enthalpy and entropy, respectively, of the geofluid at the wellhead. The total available power from the two resources is

$$\dot{W}_t^o = \dot{W}_g^o + \dot{W}_f^o \quad (7)$$

In an actual energy conversion system, the power output will depend on the rate of entropy production, $\dot{\theta}$, in the system. This is expressed by

$$\dot{W} = \dot{W}^o - T_o \dot{\theta} \quad (8)$$

It is customary to express the power losses in actual systems through the introduction of utilization factors, η_u . Thus,

$$\dot{W} = \eta_u \dot{W}^o \quad (9)$$

The values of the utilization factors for various types of energy conversion methods are established for state-of-the-art systems. For example the state-of-the-art value of the utilization factor for fossil fuels is about 0.35 - 0.40. This is determined by the thermal efficiency of advanced steam power cycles (0.4 - 0.45) (6) as well as by the efficiency of modern steam generators (~ 90%). On the other hand, the state-of-the-art utilization factor for geothermal energy ranges (7) from 0.5 to 0.7. This is commensurate with the performance of dual-flash systems ($\eta_u \approx 0.5$) and binary-fluid systems for which a utilization factor as high as 0.7 is possible (7).

The maximum power that can be generated from the separate use of a fossil fuel input ($\dot{m}_f$) and a geofluid input ($\dot{m}_g$) is given by

$$\dot{W}_s^* = \dot{W}_f^* + \dot{W}_g^* = \eta_f^* \dot{W}_f^o + \eta_g^* \dot{W}_g^o, \quad (10)$$

in which η_f^* and η_g^* are the utilization factors attainable in state-of-the-art fossil and geothermal energy conversion systems, respectively. Therefore we can define an overall utilization factor

$$\eta_{fg}^* = \dot{W}_s^* / \dot{W}_t^o \quad (11)$$

If the same inputs are fed to a hybrid plant, the overall utilization factor becomes

$$\eta_h = \dot{W}_h / \dot{W}_t^o, \quad (12)$$

in which $\dot{W}_h$ is the power output of the hybrid plant. This hybrid plant will be thermodynamically superior to the two separate plants only if

$$\eta_h > \eta_{fg}^*. \quad (13)$$

This gives rise to a definition of a figure of merit

$$F = \eta_h / \eta_{fg}^*, \quad (14)$$

the value of which has to be greater than unity if the hybrid system is to prove superior to the two separate state-of-the-art systems. Substituting for η_h and η_{fg}^* we obtain

$$F = \dot{W}_h / (\dot{W}_f^* + \dot{W}_g^*) \quad (15)$$

In some cases, it may be more important to assess the efficiency with which one of the two resources is being utilized in a hybrid plant when the other is assumed to be utilized at its state-of-the-art level. For this purpose we define two additional figures of merit: the fossil figure of merit

$$F_f = (\dot{W}_h - \dot{W}_g^{**}) / \dot{W}_f^{**} , \quad (16)$$

and the geothermal figure of merit

$$F_g = (\dot{W}_h - \dot{W}_f^{**}) / \dot{W}_g^{**} . \quad (17)$$

The first of these two figures determines whether the fossil fuel is better utilized in the hybrid plant than in a separate, state-of-the-art, fossil plant; the second one applies to the geothermal resource.

ANALYSIS

In order to demonstrate the potential advantage of hybrid fossil geothermal power plants we consider specific examples of the geothermal-preheat system. In Ref. (2) we have demonstrated that, for a hybrid power plant of the geothermal-preheat type to be advantageous, the geothermal feedwater preheater should be introduced only in systems that are not much different from the state-of-the-art steam power plants. These plants make use of both the reheat principle and the regenerative feedwater heating principle. They may operate at either sub- or supercritical pressures and have a maximum superheat temperature seldom exceeding 540°C. Therefore we have chosen to graft the geothermal preheating principle onto two cycles, a subcritical cycle with a single reheat and a supercritical cycle with double reheat, both with seven feedwater heaters. The fixed cycle parameters for the two cases are given in Table 1. No attempt has been made to optimize the bleed and reheat pressures beyond the application of the recognized rules of thumb (6).

Table 1. Fixed cycle parameters

	<u>Subcritical</u>	<u>Supercritical</u>
Initial steam temperature, °C	540	540
Initial steam pressure, MPa	16.5	24.0
Number of reheat stages	1	2
Reheat temperature, °C	540	540
First reheat pressure, MPa	3.9	5.9
Second reheat pressure, MPa	—	2.0
Condenser pressure, kPa	5.5	5.5
Turbine isentropic efficiencies		
High pressure	0.82	0.82
Intermediate pressure	0.86	0.86
Low pressure	0.82	0.85
Dryness fraction at exhaust	0.95	0.98
Number of feedwater heaters	7	7
Pressure loss in heat exchangers	10%	10%
Terminal temperature difference in		
feedwater heaters, °C	2	2
Pump efficiency	0.8	0.8
Cycle efficiency, η_c	0.43	0.45
Steam generator efficiency, η_{SG}	0.9	0.9
Fossil fuel utilization factor;		
$\eta_f^* = \eta_c \times \eta_{SG}$	0.39	0.40

In order to study the effect of including the geothermal preheater in the feed loop on the choice of the bleed conditions we have analyzed a case in which all but one of the feedwater heaters have been replaced by a geothermal preheater, allowing the bleed pressure to float. In all cases, it was assumed that the first bleed pressure coincides with the first reheat pressure. This assumption agrees with the accepted practice in steam turbine technology. Naturally, a single feedwater heater combined with a geothermal preheater represents a practical arrangement only if the geofluid temperature is reasonably high ($T_g > 200^\circ\text{C}$), otherwise the cycle performance will suffer in comparison with a cycle containing several feedwater heaters complementing the geothermal preheater.

The properties of steam needed for these calculations were obtained from the computer program WASP (8) which is based on the fundamental equation of Keenan, et al (9). The results of this thermodynamic optimization study reveal that the figure of merit exhibits a very flat maximum over a wide range of pressure ratio, as can be seen in Fig. 2. The figure of merit, F , remains practically constant when the bleed pressure changes from 0.15 to 0.25 of the initial steam pressure. It is recalled that the conventional rule calls for a reheat pressure of 0.2 - 0.25 the initial pressure (6). We thus adopted the simple rule for the choice of bleed and reheat pressures in the geothermally preheated systems.

Having chosen the cycle parameters in the manner outlined above, we proceeded to calculate the figures of merit for geofluid temperatures covering the range extending to 250°C . In all cases it was assumed that (i) the geofluid is pure water, (ii) the geothermal utilization factor, η_g^* , is 0.6, and (iii) a temperature difference of 10°C is maintained in the geothermal preheater. The results are shown in Figs. 3 and 4 for the subcritical cycle

and the supercritical cycle, respectively. It is noted that nearly 60% more work can be produced from a geofluid at 200°C used for preheating the feedwater in a supercritical hybrid plant than could be produced from the same geofluid if utilized in a conventional, state-of-the-art, geothermal power plant ($\eta_g^* = 0.6$). This marked improvement is achieved while utilizing the fossil fuel at its state-of-the-art level ($\eta_f^* = 0.4$). Alternatively, the results may be interpreted as showing that about 4% more work can be produced from the fossil fuel than can be produced from the same amount of fuel if it were burned in a conventional supercritical steam power plant ($\eta_f^* = 0.4$) while maintaining a level of geothermal energy utilization equal to that achievable in state-of-the-art geothermal power plants ($\eta_g^* = 0.6$).

HYBRID UTILIZATION OF FINITE RESOURCES

The analysis of the previous section was carried out without considering the relative magnitude of the geothermal and the fossil resources. In general, a hybrid power plant will not utilize the two resources at the same rate. This characteristic of hybrid plants will not be of significance as a design and selection consideration provided the two resources are inexhaustible. However, when one or both of the resources are finite, the relative rate at which the two resources are depleted becomes a significant design parameter. For this reason we introduce a work amplification factor

$$\psi = \dot{W}_h / \dot{W}_g^* , \quad (18)$$

which expresses the ratio of the outputs of a hybrid plant and a purely-geothermal plant utilizing the same geofluid. It is worth noting that the four parameters, F , F_f , F_g and ψ are related by the two equations

$$F = \psi / (1 + \psi - F_g) , \quad (19)$$

and

$$F_f = (\psi - 1) / (\psi - F_g) \quad . \quad (20)$$

In choosing between a number of possible hybrid arrangements (i.e., geothermal-preheat versus fossil-superheat systems (4)), one has to decide which figure of merit is appropriate for the comparison. The nature of eqs. (19) and (20) indicates that one hybrid system may have a higher F_g than another but, at the same time, have a lower F_f . This is shown in Fig. 5 which depicts the relationship implied by eq. (20).

The ambiguity associated with choosing an appropriate figure of merit can be removed by considering the relative size of the two resources. For this purpose, we define a resource ratio

$$R = W_G^* / W_F^* \quad (21)$$

in which W_G^* designates the amount of work that can be extracted from the geothermal resource by means of state-of-the-art geothermal power plants and W_F^* is its fossil counterpart, over the respective lifetimes of the resources. If $R < 1$ then the geothermal resource will be depleted much earlier than the fossil fuel resource. In this case the appropriate figure of merit is F_g which determines the effectiveness of a given hybrid system in utilizing the depletable geothermal resource. Contrariwise, the fossil figure of merit, F_f , becomes the appropriate one if $R \gg 1$. It is more likely that the first case, $R < 1$, will prevail in this country for the near future; however, there may be situations in which R is of order unity. In these situations, the utilization strategy, characterized here by the parameter ψ , will determine which of the two resources will be depleted first.

A given hybrid system will deplete the geothermal and fossil resources in the ratio

$$r = W_g^* F_f / (W_h - W_g^*) \quad . \quad (22)$$

In terms of the work amplification factor, ψ , and the figures of merit, F_f and F_g , the depletion ratio, r , reduces to

$$r = F_f (\psi - 1) = 1 / (\psi - F_g) \quad . \quad (23)$$

We introduce the relative depletion parameter

$$\Delta = r/R = F_f / R(\psi - 1) = 1 / R(\psi - F_g) \quad . \quad (24)$$

The value of this depletion parameter determines which of the two resources will be depleted first; the geothermal resource will be depleted first if $\Delta > 1$, and vice versa. Simultaneous depletion of the two resources will occur if $\Delta = 1$.

When the depletion parameter, Δ , is greater than unity, the total depletion of the geothermal resource will result in only partial depletion of the fossil resource. This partial depletion amounts to

$$W_F^D = W_G^* / r = (\psi - 1) W_G^* / F_f \quad . \quad (25)$$

After the geothermal resource has been exhausted, the remainder of the fossil resource will be assumed to be utilized conventionally, i.e., with $F_f = 1$. This will yield an amount of work

$$W_F^R = W_F^* - W_F^D = W_F^* - (\psi - 1) W_G^* / F_f \quad . \quad (26)$$

An overall figure of merit, F_o , that takes into account the finite nature of the resources is defined by

$$F_o = (W_G^* + W_F^H + W_F^R) / (W_G^* + W_F^*) \quad , \quad (27)$$

in which W_F^H is the fossil contribution corresponding to the complete depletion of the geothermal resource by the hybrid system. That is,

$$W_F^H = (\psi - 1) W_G^* \quad (28)$$

Substituting for W_F^H and W_F^R we obtain

$$F_O = 1 + R (F_g - 1)/(1+R); \quad \Delta > 1 \quad (29)$$

In a similar manner we find that for $\Delta < 1$ the overall figure of merit is

$$F_O = 1 + (F_f - 1)/(1+R); \quad \Delta < 1 \quad (30)$$

It is interesting to note that the overall figure of merit for a given resource ratio, depends only on F_g when $\Delta > 1$, and only on F_f when $\Delta < 1$, as would be expected.

Table 2 contains a comparison among three hybrid systems for a resource ratio $R = 0.1$. The first system is an example of the geothermal-preheat system analyzed here. The values of ψ , F_g and F_f correspond to a geofluid temperature of 200°C in Fig. 4. The second system is the two-stage, fossil-superheat system of Ref. (4) optimized for a geofluid temperature of 200°C. The third system is similar to the second system except that it comprises a gas-turbine topping loop. This system is still under investigation; however, a description of it is given in Ref. (3).

Table 2. Comparison among three hybrid systems for a resource ratio $R = 0.1$

<u>System</u>	<u>ψ</u>	<u>F_g</u>	<u>F_f</u>	<u>Δ</u>	<u>F_O</u>
1	16.9	1.61	1.04	0.65	1.036
2	1.4	1.08	1.26	31.25	1.007
3	2.1	1.28	1.34	12.20	1.025

It is clear from this comparison that although the first system has a lower F_f than the other two systems, its overall utilization of the two resources

(F_0) is superior. Naturally this is valid only for the specific resource ratio considered. Other situations can be envisaged in which one of the other two systems is superior as demonstrated for the same three systems in Fig. 6. For example, the second system (the fossil superheat system) is superior to the first (the geothermal preheat system) when the resource ratio, R , is greater than about 0.5. The third system is superior to the other two for any value of R greater than about 0.15. In all cases, a given system is at its best if the resource ratio is such that $\Delta = 1$.

DESIGN AND ECONOMIC CONSIDERATIONS

Since hot geofluids cannot be transported without excessive losses (or expense) over distances exceeding one or two kilometers, a hybrid power plant has to be constructed at or very near the geothermal site. Subsequently the fossil fuel has to be transported to the geothermal site. It is understood, therefore, that the economic feasibility of hybrid fossil-geothermal power plants will be determined mainly by the distance between the the two resources. It is likely that this factor will also affect the choice of the appropriate hybrid arrangement for a specific site. A detailed site-specific economic study of hybrid fossil geothermal power plants has been conducted by the Pacific Sierra Research Corporation (10) under the direction of the municipality of the City of Burbank in California. This study dealt only with the geothermal preheat system. It was shown that a plant of this type constructed at Roosevelt Hot Springs in Utah can produce electricity at a 10% saving in comparison with a proposed coal-fired plant located at the coal mine (10). Furthermore, the hybrid plant may become even more attractive if the hot geofluids can be used for coal processing and cleaning to remove some of the sulfur and other potentially harmful effluents.

The choice of the appropriate hybrid utilization strategy will depend, among other factors, on the resource ratio, R . This ratio depends on the relative availability of geothermal energy and fossil energy. Once the geothermal resources, suitable for hybrid utilization, have been identified, it is a simple matter to calculate the quantity of fossil fuel needed to meet the demand for electric power. This calculates, approximately, the resource ratio, R , which can be used, in the manner outlined in the previous section, to select the most suitable arrangement among a number of feasible hybrid systems.

Finally it is worth noting that all the components of a hybrid plant are conventional; they have been tried and tested extensively in the process and power industries. The realization of the proposed hybrid arrangement can thus be achieved with a minimum extrapolation of existing technology.

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Figure 1. The geothermal-preheat system

C Condenser

D Deaerator

FWH Feedwater Heater

GHX Geothermal Heat Exchanger

SG Steam Generator

HPT High-Pressure Turbine

IPT Intermediate-Pressure Turbine

LPT Low-Pressure Turbine

RH Reheat

Figure 2. The optimum bleed-reheat pressure ratio

Figure 3. The figures of merit for a subcritical cycle

Figure 4. The figures of merit for a supercritical cycle

Figure 5. The relationship between the figures of merit

Figure 6. The overall figure of merit for finite resources