COMPARISON OF DIRECT CONTACT AND KETTLE REBOILERS TO REDUCE NON-CONDENSABLES IN GEOTHERMAL STEAM

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ABSTRACT

The economics of energy recovery from high-gas-content geothermal steam is generally improved if the gas content of the steam can be reduced before it is admitted to the power recovery turbines. This gas rejection has normally been accomplished by heat exchange where the energy of the high-gas-content steam is used to generate a lower pressure but lower gas content motive steam. The exchange of heat can be carried out using standard surface heat (indirect contact) exchange devices or by direct contact between the geothermal steam and a cooler water stream. This paper presents a comparison of the two types of heat exchange and shows that direct contact heat exchange is more cost effective than surface heat exchange for a resource steam containing 20 weight percent gas.

INTRODUCTION

Water-dominated geothermal resources frequently contain significant quantities of dissolved gases such as CO_2, H_2S, H_2, and CH_4. When the geothermal water is flashed in the wellhead separator, these non-condensable gases (NCGs) concentrate in the steam. Depending on the resource, the concentration of the non-condensables can vary from less than 0.5 to greater than 25 weight percent of the steam (Makansi, 1989). When the steam is fed directly to a condensing turbine as illustrated in the "No Reboiler" alternative shown in Figure 1, the non-condensable gases seriously impair the power generation performance. Power is consumed in extracting the non-condensables from the vacuum condenser and compressing them to atmospheric pressure. In addition, the non-condensables impair the performance of the condenser, leading to the need for a larger condenser.

Because the non-condensables are generally corrosive, construction of the turbine, condenser, and condenser venting system may also be more costly. It may also be necessary to remove hydrogen sulfide,

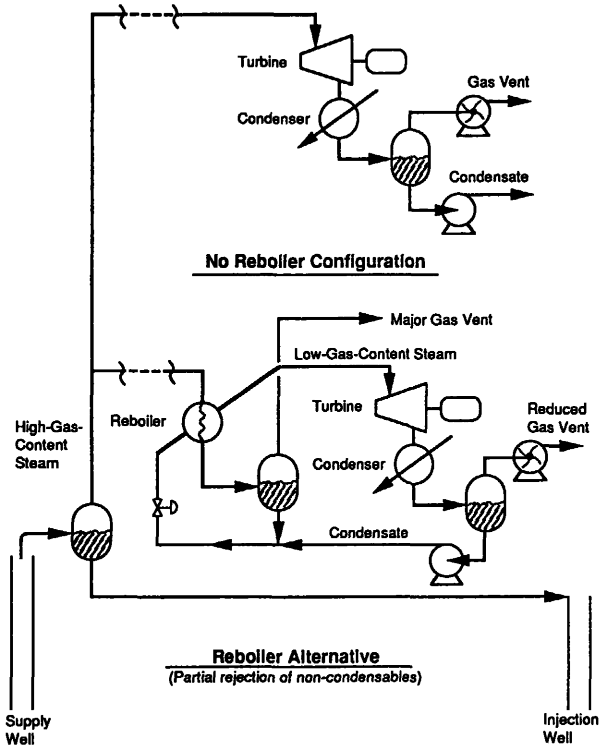

Figure 1. Gas rejection processes

frequently present in geothermal gas, to avoid unacceptable emissions.

For steam sources with high concentrations of non-condensable gases, total or partial rejection of gases from the steam before expansion through the power turbine has generally been shown to improve the efficiency of net energy recovery (Allegrini et al., 1989). Suggested rejection processes generally make use of a reboiler (as shown in Figure 1) to generate a separate, lower pressure steam of reduced gas content.

Suitable heat exchange devices (reboilers) are illustrated in Figure 2. They include: A. Direct Contact heat exchangers [such as the Bechtel geothermal reboiler (Awerbuch et al., 1985)] in which water is first heated by contact with the geothermal steam and then flashed at a lower pressure to yield motive steam of reduced gas content, and B. Indirect Contact heat exchangers (such as kettle reboilers) in which condensing geothermal steam is used to generate motive steam of reduced gas content.

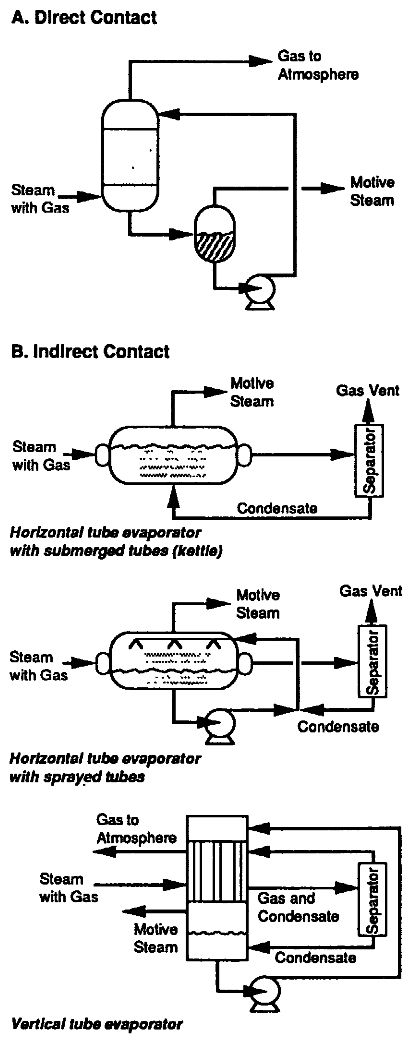

Figure 2. Direct contact and indirect contact heat exchangers

PREVIOUS EVALUATION WORK

Allegrini et al. (1989) performed a thermodynamic comparison of a direct contact reboiler for reduction in gas content of the motive steam with five non-reboiler schemes that did not reject non-condensable gases. The study assumed a high-gas-content geothermal resource similar to the illustrative resource used in this study. The schemes were:

1. A single-stage brine flash with the flash steam expanded in a back-pressure turbine.
2. A single-stage flash as in (1) above, but with the steam expanded in a condensing turbine and non-condensables extracted by a centrifugal compressor.
3. A two-stage flash with the high-pressure flash steam expanded in a back-pressure turbine, and the steam produced by flashing the residual brine expanded in a condensing turbine.
4. A two-stage flash as in (3) above, but with the high- and low-pressure steams expanded in condensing turbines, and non-condensables extracted with a compressor.
5. A three-stage flash in which the first-stage high-gas-content steam is expanded in a back-pressure turbine. The steam produced by flashing residual brine in two stages is expanded in two condensing turbines.

These five schemes were compared with a modification of scheme 5 which employed a direct contact reboiler to recover heat from the first-stage (wellhead) flash steam. The residual gas was vented from the reboiler. The hot water produced by the reboiler was then flashed in two stages, and the flash steams combined with the corresponding pressure steams produced by the second and third stages of brine flash. The two levels of low-gas-content steam were then expanded in condensing turbines, and the non-condensable gases were removed from the condenser by a centrifugal compressor.

The reboiler scheme developed the highest net power for the hot brine resource employed.

By discharging a large proportion of the non-condensables at the elevated pressure of the reboiler, the scheme also provided the potential for decreasing hydrogen sulfide emission through reinjection of the high-pressure vent gas with the spent brine.

DIRECT AND INDIRECT CONTACT REBOILER PROCESSES

This study compares the direct contact reboiler with an indirect contact (kettle) reboiler in the process schemes illustrated in Figure 3. For each reboiler, the first-stage (wellhead) flash pressure selected is 130 psia. The steam from this flash contains the bulk of the non-condensable gas at a concentration of 20 percent weight. Heat is recovered from the steam to produce two steam flows of successively lower pressure but of lower gas content. These flows are combined with steam from two successive stages of brine flash. The higher pressure steam (72 psia) and the lower pressure steam (32 psia) are

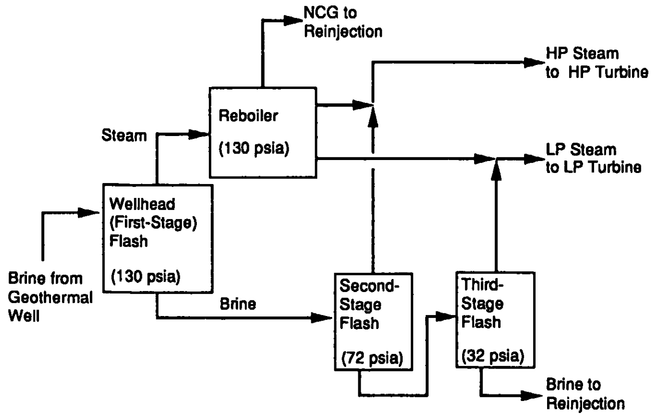

Figure 3. Reboiler process flow schematic

expanded to 1 psia through individual condensing turbines. The net power produced is about 30 MWe for both reboiler types.

Direct Contact Reboiler

The equipment configuration for the direct contact reboiler is shown in Figure 4 and keyed to the stream flows shown in Table 1. The high-gas-content steam (130 psia) is scrubbed by a cooler stream of water which absorbs the latent heat of the condensing steam while absorbing only a small quantity of its non-condensable gas. The heated water leaving the reboiler bottom is then reduced in pressure (72 psia) to produce steam. The bulk of the flashed water (at 304°F) is returned to the lower section of the reboiler. The remaining water is then flashed at still lower pressure (32 psia) and then returned to the top of the reboiler. Packing or trays are used in the reboiler to provide multistage contact.

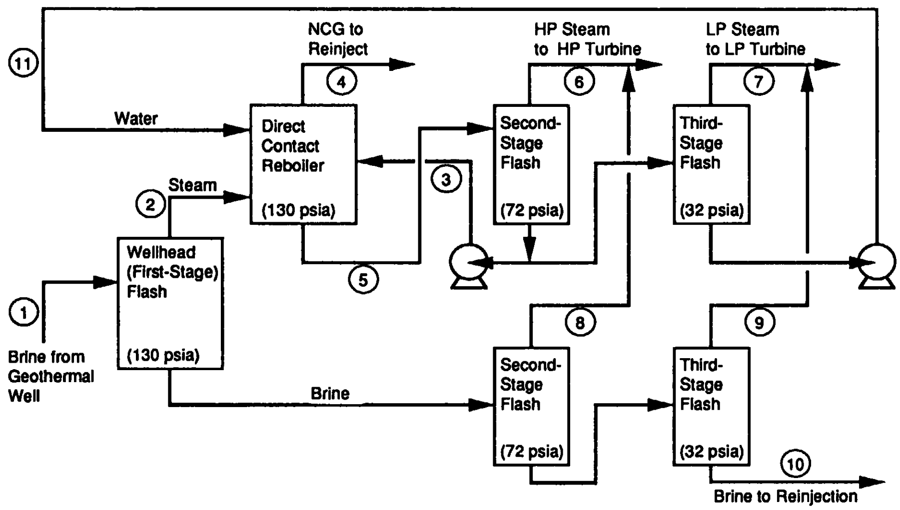

Figure 4. Direct contact reboiler flow schematic

Table 1. Direct contact reboiler stream flow rates

	Stream Flow Rates, lb/hr										
Component	Brine from well (1)	Well-head flash steam (2)	Reboiler HP recirc. water (3)	Non-condens. gases (4)	Reboiler bottoms (5)	Reboiler HP steam (6)	Reboiler LP steam (7)	2nd stage brine steam (8)	3rd stage brine steam (9)	Spent brine (10)	Reboiler LP recirc. water (11)
H_2O	3,130,000	300,338	3,940,000	11,765	5,640,000	208,408	86,874	117,386	157,482	2,560,000	1,480,000
CO_2	68,273	67,400	38	64,705	2,733	2,681	14	873	15	-	-
H_2S	2,560	2,333	12	2,100	260	240	5	158	47	-	-
Total	3,200,833	370,071	3,940,050	78,570	5,642,993	211,329	86,893	118,417	157,544	2,560,000	1,480,000
Temp., °F	410	340	304	262	330	304	253	304	253	253	253

Indirect Contact Reboiler

As an alternative to the direct contact of steam and water described above, heat may be transferred by a tubular heat exchanger.

Three indirect contact reboilers - the vertical tube evaporator (VTE), horizontal tube evaporator (HTE), and kettle reboilers - are illustrated in Figure 2. The kettle reboiler was selected for this study because of its extensive use in the chemical industry and inherently rugged construction. The VTE reboiler was not selected because of a tendency of its tubes to collapse under a high pressure differential across the tube wall (Awerbuch et al., 1984). The HTE reboiler has not been used in the geothermal industry.

The equipment and configuration for the kettle reboiler are shown in Figure 5 and keyed to the stream flows in Table 2. The high-gas-content steam is condensed in the tube side of two reboilers arranged in series.

Condensate recovered from the partial condensation in the first boiler is returned to its shell side and boiled. Condensate recovered from the second reboiler is returned to its shell side and boiled at still lower pressure. Vapors from the second reboiler constitute the gas removed from geothermal steam.

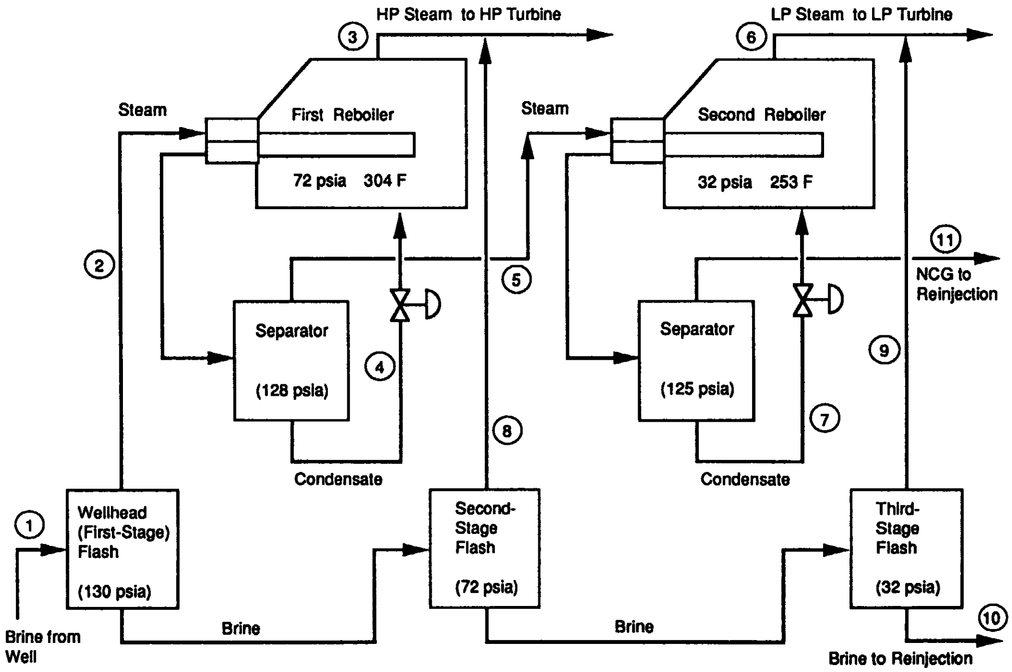

Figure 5. Kettle reboiler flow schematic

Table 2. Kettle reboiler stream flow rates

Component	Stream Flow Rates, lb/hr										
	Brine from well (1)	Well-head flash steam (2)	First reboiler steam (3)	First reboiler cond. (4)	Steam to second reboiler (5)	Second reboiler steam (6)	Second reboiler cond. (7)	2nd stage brine steam (8)	3rd stage brine steam (9)	Spent brine (10)	Non-condens. gases (11)
H_2O	3,130,000	300,338	190,166	188,342	111,996	97,166	94,088	117,386	157,482	2,560,000	17,907
CO_2	68,273	67,400	124	124	67,277	190	190	873	15	-	67,087
H_2S	2,560	2,333	4	4	2,329	7	7	30	1	-	2,322
Total	3,200,833	370,071	190,294	188,470	181,602	97,363	94,285	118,289	157,498	2,560,000	87,316
Temp., °F	410	340	304	330	330	253	280	330	253	253	262

COMPARISON OF DIRECT CONTACT AND KETTLE REBOILERS

The key performance factors for the two reboilers are compared in Table 3. Their significant differences are discussed in the following paragraphs.

Non-condensable Gases Removal

As shown in Table 3, the kettle reboiler achieves a higher rejection rate of gas than does the direct contact reboiler (98 percent versus 94 percent). This is because the latent heat of the condensing geothermal steam is recovered in the direct contact reboiler as the sensible heat of a very large recirculating water stream, and in the kettle reboiler as the latent heat of vaporization of water feed to the shell of each reboiler. The large recirculating water flow in the direct contact reboiler dissolves more non-condensables than does the kettle reboiler feed water, and these dissolved gases are released into the high pressure flash steam.

Power Production

Gross power production is compared for the two reboiler configurations in Table 3. Net power produced by the direct contact reboiler case reflects the use of a centrifugal compressor for removing gases from the direct contact reboiler condensers and the large power consumption of the water recirculation pumps. The kettle reboiler uses steam jets to maintain condenser vacuum (permissible with the lower gas quantity)* and has a lower pumping requirement. The net power for the two designs is, however, nearly identical (29.2 MWe versus 29.4 MWe).

*Steam ejectors are cheap and, because they do not have any moving parts, require very little maintenance. However, steam ejectors use more steam than the equivalent horsepower used by a centrifugal compressor. Therefore, centrifugal compressors, instead of steam ejectors, may be preferred for some high-gas-content geothermal applications (see, for example, Hamano, 1983). Although compressors are comparatively expensive and require maintenance, Tucker et al. (1985) have shown that if the amount of non-condensables exceeds 2,000 lb/hr, the centrifugal compressors are more economical than steam ejectors. Thus, a centrifugal compressor was used for the direct contact reboiler (extraction rate of 4,000 lb/hr) and a steam ejector for the kettle reboiler (extraction rate of 1,200 lb/hr).

Table 3. Comparative performance of direct contact and kettle reboilers

	Direct Contact Reboiler	Kettle Reboiler
Water recirculation, lb/hr	5,420,000	283,000
High-pressure steam production, lb/hr	321,000	309,000
Low-pressure steam production, lb/hr	244,000	255,000
Non-condensables removed, lb/hr	65,000	69,000
Non-condensables to turbine, lb/hr	4,000	1,200
Non-condensables removed, %	94	98
Gross power production, MWe	30.6	30.0
Net power production, MWe	29.2	29.4

Estimated Capital Cost

Estimated capital costs for reboiler-affected portions of the facility are compared in Table 4. The installed capital cost of the direct contact reboiler is estimated at $3.36 million and the kettle reboiler, $4.54 million. These figures include the cost of the compressor and steam jet ejectors.

Table 4. Capital cost of direct contact and kettle reboilers, mid '88 dollars

Equipment (Quantity)	Direct Contact Reboiler Cost, $000's	Kettle Reboiler Cost, $000's
Reboiler (1) 16.5' bottom dia., 10.5' top dia. x 35' H, CS shell, 316L clad plus packing	273	–
1st stage kettle reboiler (4) 6,100 ft^2, duplex SS tube; CS shell	–	1,104
2nd stage kettle reboiler (2) 4,200 ft^2, duplex SS tubes, CS shell	–	397
2nd stage flash tank	129	91
3rd stage flash tank	59	68
400 hp condensate pump (3)	190	–
250 hp condensate pump (3)	160	–
10 hp startup water pump (1)	–	10
Compressor (differential)	175	–
Instruments, piping, insulation, electrical, concrete, and painting	571	947
Labor	510	410
Field distributables	434	348
Total field cost	2,501	3,375
Home office @12%	300	405
Contingency @ 20%	560	756
Totals	3,361	4,536

NOTE: The capital cost does not include brine flashing tanks, cooling tower, turbine, and generator.

Levelized Power Costs

The levelized cost of electricity attributable to the cost-estimated portion of the facility for the two processes was calculated based on the assumptions listed in Table 5. In terms of constant 1988 dollars, the cost attributable to the direct contact reboiler process is 2.82 mills per kWh and to the kettle reboiler process, 3.42 mills per kWh, about 20 percent higher.

For equivalent power production, both the capital cost and the levelized power cost differentials favor the direct contact reboiler.

Table 5. Financial assumptions for estimating levelized cost

Federal and state taxes	40%
Insurance and other taxes	1.5%
Book life	30 years
Tax life	15 years
Inflation rate	4%
Investment tax credit	0
Year of estimate	1988
Year of operation	1988

Projected Effects of Steam Gas Content

The stream flow rates shown in Tables 1 and 2 are based on a wellhead flash steam containing 20 weight percent non-condensables. In the case of the direct contact reboiler, an increase in gas content produces minimal change. The sizes of the direct contact reboiler and the water flash vessels are determined, for the most part, by the liquid flow rate, and not by the vapor flow rate. The amount of non-condensables dissolved in the water, the size of the compressor to extract non-condensables from the spray condenser, and size of the water recirculation pump would remain substantially unchanged.

In the case of the kettle reboiler, an increase in feed steam gas content decreases the overall heat transfer coefficient across the reboiler tubes. Consequently, a larger heat transfer surface is required for the same heat transfer rate.

For the above reasons, the direct contact reboiler will become relatively more attractive with increases in the non-condensable gas content of the resources. With a reduced-gas-content steam, the size and cost of the direct contact reboiler will not be reduced significantly because water circulation is a function of the heat transferred. The kettle reboiler will decrease in size as a result of improved heat transfer.

Projected Effects of Process Capacity

The scale of the process may also have an effect. At the scale considered here, parallel trains of kettle reboilers were needed, but only a single train was needed of the direct contact reboiler. A lower system capacity will thus tend to reduce the advantage of scale illustrated here for the direct contact reboiler.

CONCLUSIONS

Previous study (Allegrini et al., 1989) showed that reboiler processes providing non-condensable rejection from the motive steam have a significant advantage over configurations that do not provide gas rejection.

This study has shown that for large-scale projects based on a high-gas-content resource, the direct contact reboiler has significant capital cost and levelized cost of power advantages over the kettle (indirect contact) reboiler.

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