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Application of the Kalina Cycle Technology to Geothermal Power Generation

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Abstract

The Kalina cycle technology is ideally suited for low-temperature, liquid-dominated sources that are now being served by binary Rankine cycle plants. The technology focuses on structural changes to the design, high degrees of recuperation, and the use of working fluid mixtures. As a result, output is often 50 percent greater than that of a comparable Rankine cycle plant.

A 5MW plant design is presented, giving performance, thermodynamic state points, and heat exchanger duty curves. Preliminary sizing of the plant's heat exchangers are presented as the initial step in establishing plant cost. Extrapolation to and comparison with the Heber ORC plant is also presented.

A hybrid flash/Kalina plant is shown for higher temperatures.

Introduction

For geothermal source temperatures normally too low for flash steam designs (somewhere around 350°F), economics favor the use of an organic Rankine cycle, often referred to as the binary cycle. The additional cost of heat exchangers in the binary cycle is offset by the reduction in brine consumption per kW generated.

While the binary cycle's thermodynamic efficiency (kW/lb/hr of brine) is superior to the flash steam cycle at lower temperatures, there are inherent structural losses within the binary cycle that keep its efficiency substantially lower than that achievable (based on thermodynamic Second Law principles). More advanced binary designs, such as the supercritical plant built at Heber,(1) have attempted to improve performance by operating with mixtures at supercritical pressures to reduce the mismatch between the brine and cycle working fluid. Still, Heber's design only reaches approximately 50 percent(2) of its Second Law potential.

There is another design approach for binary plants. This new approach embodies a methodology often referred to as the Kalina Cycle technology. It is not a single design but rather a family of new designs applicable over a wide range of temperatures and uses.(3,4)

These designs normally feature a highly recuperative cycle using a mixture of two fluids having substantially different boiling temperatures, typically water and ammonia. Other pairs are possible as well. Often the composition of the working fluid changes throughout the cycle. Recuperation is achieved by judicious selection of the mixture composition and usually a need to change composition from one part of the cycle to another, e.g. boiler vs. condenser. Operating pressures are kept subcritical as a maximum and above atmospheric as a minimum.

In the design that follows, a geothermal plant is shown to operate at a Second Law efficiency near 70 percent. This is approximately 40 percent better than the Heber binary design.

5 MW Kalina Cycle System 12 (KCS12)

Based on a brine inlet temperature of 367°F, a flowrate of 440,000 lb/hr, and reinjection temperature of 170°F, the design of a 5MW KCS12 plant is established and presented in Figure 1. The accompanying heat and mass balance state points are presented in Table 1.

The selection of the working fluid composition is crucial to this design. It was chosen at .83 (by weight of NH_3/H_2O) so that the dew point temperature at the turbine exit (point 36, 90.9 psia) is higher than the bubble point of the oncoming fluid entering the evaporator (point 21, 432.4 psia). This results in a high degree of recuperation, i.e. all liquid preheat and 33 percent of the vaporization duty in heat exchangers HE-2 and HE-4, respectively, is achieved recuperatively. The cycle design is shown in temperature enthalpy coordinates in Figure 2.

Heat acquisition to the working fluid occurs between points 21 and 30. A substantial portion of this heat is provided by the turbine exhaust. The heat between points 36 and 38 is used to vaporize a portion of the working fluid between points 66 and 60. The heat in the turbine exhaust between points 38 and 29 is used to preheat the oncoming

KCS12 Conceptual Flow Diagram

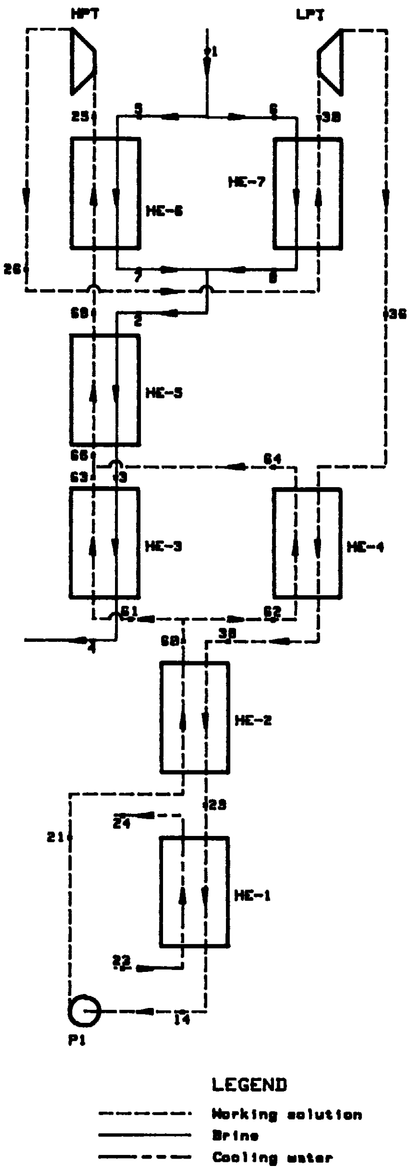


Figure 1

liquid from point 21 to point 60. In total, the heat transferred to the plant is 850.0 Btu/lb of working fluid. Of this, 323.6 Btu/lb, or 38 percent, is provided by direct recuperation.

The plant's operation is straightforward. Brine at point 1 is split into two streams, 5 and 6, where it enters the superheater and reheater, respectively. The streams recombine at point 2 and pass through a vaporizer/superheater, HE-5, and then vaporizer HE-3. At the outlet of HE-3, the brine has been cooled to its minimum temperature of 170°F, where it is reinjected back to ground at point 4.

On the process side, the working fluid leaves the condenser, HE-1, is pumped to the evaporator pressure of 432 psia, and then passes through the preheater HE-2 and evaporators HE-3 and HE-5. The working fluid is superheated to 352°F at point 25, is expanded through the high-pressure turbine down to 232 psia at point 26, and is then reheated to 352°F at point 30. From there, it is expanded in the low-pressure turbine to 90.9 psia at point 36, having a temperature of 222.2°F (near saturation). The heat remaining in the exhaust is used recuperatively in HE-4 and HE-2 to vaporize and preheat the oncoming liquid. At point 29, having fulfilled its recuperation mission, the working fluid is fully condensed through HE-1.

TABLE 1

Thermodynamic State Points

Point	Pressure (psia)	Composition	Temperature °F	Enthalpy (Btu/lb)	Flow/ Flow 25
1	--	Brine	367.00	--	2.6269
2	--	Brine	333.96	--	2.6269
3	--	Brine	222.26	--	2.6269
4	--	Brine	170.22	--	2.6269
5	--	Brine	367.00	--	.9851
6	--	Brine	367.00	--	1.6418
7	--	Brine	333.96	--	.9851
8	--	Brine	333.96	--	1.6418
9	--	Brine	170.00	--	2.6269
14	89.30	0.8305	60.00	-20.33	1.0000
21	432.44	0.8305	60.00	-18.78	1.0000
23	--	Water	53.00	--	16.8761
24	--	Water	78.07	--	16.8761
25	402.44	0.8305	352.00	776.80	1.0000
26	232.20	0.8305	273.78	736.73	1.0000
29	89.60	0.8305	121.93	402.82	1.0000
30	227.20	0.8305	352.00	792.06	1.0000
36	90.90	0.8305	222.26	726.46	1.0000
38	89.90	0.8305	170.00	519.86	1.0000
60	422.44	0.8305	165.00	98.25	1.0000
61	422.44	0.8305	165.00	98.25	.4029
62	422.44	0.8305	165.00	98.25	.5971
63	412.44	0.8305	217.26	444.29	.4029
64	412.44	0.8305	217.26	444.29	.5971
66	412.44	0.8305	217.26	444.29	1.0000
68	407.44	0.8305	307.75	743.60	1.0000

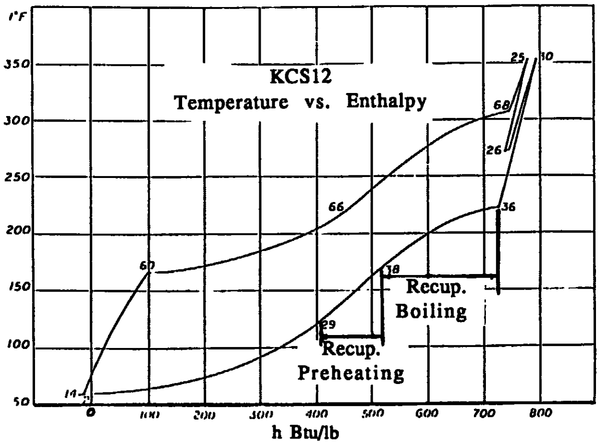


FIGURE 2

Performance

Using a brine flowrate of 440,000 lb/hr on a 60°F day (53°F cooling water), the plant's net output (not including brine pumping or reinjection power) is 4961 kW. The plant's thermal (First Law) and thermodynamic (Second Law) efficiencies are 19.2 percent and 69.7 percent, respectively. This corresponds to 88.7 lb/kWh of brine consumption. A summary of the plant's performance is presented in Table 2.

TABLE 2

5MW KCS12 Performance Summary
(53F Cooling Water)

Geothermal Fluid Weight Flow	440,000 lbs/hr
Working Fluid Weight Flow at 25	167,500 lbs/hr
Heat Input From Brine	528 Btu/lb
Turbine New Output	5056 kW
Pump Power	95 kW
Net Power Output	4961 kW
NET THERMAL EFFICIENCY	19.2%
Second Law Efficiency Limit	27.5%
Second Law Efficiency	69.7%
Specific Brine Consumption	88.7 lb/kWh

KCS12 vs. Supercritical Binary

The 5MW KCS12 design was extrapolated to 70MW gross output and its performance was compared to that of the Heber plant$^{(2)}$. Slight adjustments were made to assess performance at the same source temperature and cooling water temperature, 367°F and 65°F, respectively. The comparison is presented in Table 3.

TABLE 3

KCS12 vs. Supercritical Binary ORC

	KCS12	Supercritical ORC	Dual Flash
Gross Power Output (kW)	70,000	70,000	70,000
Power Cycle Output (kW)	68,500	59,200	70,000
Net Power Output (kW)	57,490	46,600	63,300
Heat Source Temperature (F)	367	367	367
Cooling Water Temperature (F)	65	65	65
Brine Flow Rate (mm lb/hr)	6.6 x 106	7.4 x 10	10.9 x 10
Cooling Water Flow (mm lb/hr)	45.5 x 10	67.1 x 10	68.6 x 10
Cooling Water Pump Power (kW)	2,030	3,000	3,070
Working Fluid Flow (mm lb/hr)'	2.7 x 10	7.65 x 10	1.34 x 10
Working Fluid Pump Power (kW)	1,460	10,800	--
Brine Pump Power (kW)	5,150	7,600	2,630
Miscellaneous Parasitics (kW)	2,370	2,000	1,000
Boiler Duty (mm Btu/hr)	1349 x 10	1546 x 10	--
Power Cycle Efficiency (%)	17.3	13.1	--
Plant Efficiency (%)	14.5	10.3	--
Specific Brine Flow (lb/hr-kW)	114.8	158.7	172.3

On a net basis, the output of KCS12 is 40 percent better than the supercritical ORC. This is evident in a comparison of the plant's thermal (First Law) efficiency and specific brine flow (lb/kWh). A significant portion of the improvement is due to seven-fold difference in working fluid pumping losses, 10.8MW vs. 1.46MW. This is directly attributable to the difference in working fluid flow rate (7.7 million lb/hr vs. 2.7 million lb/hr) and pump pressure rise (500 psia vs. 330 psia).

Hybrid Flash Steam/KCS12

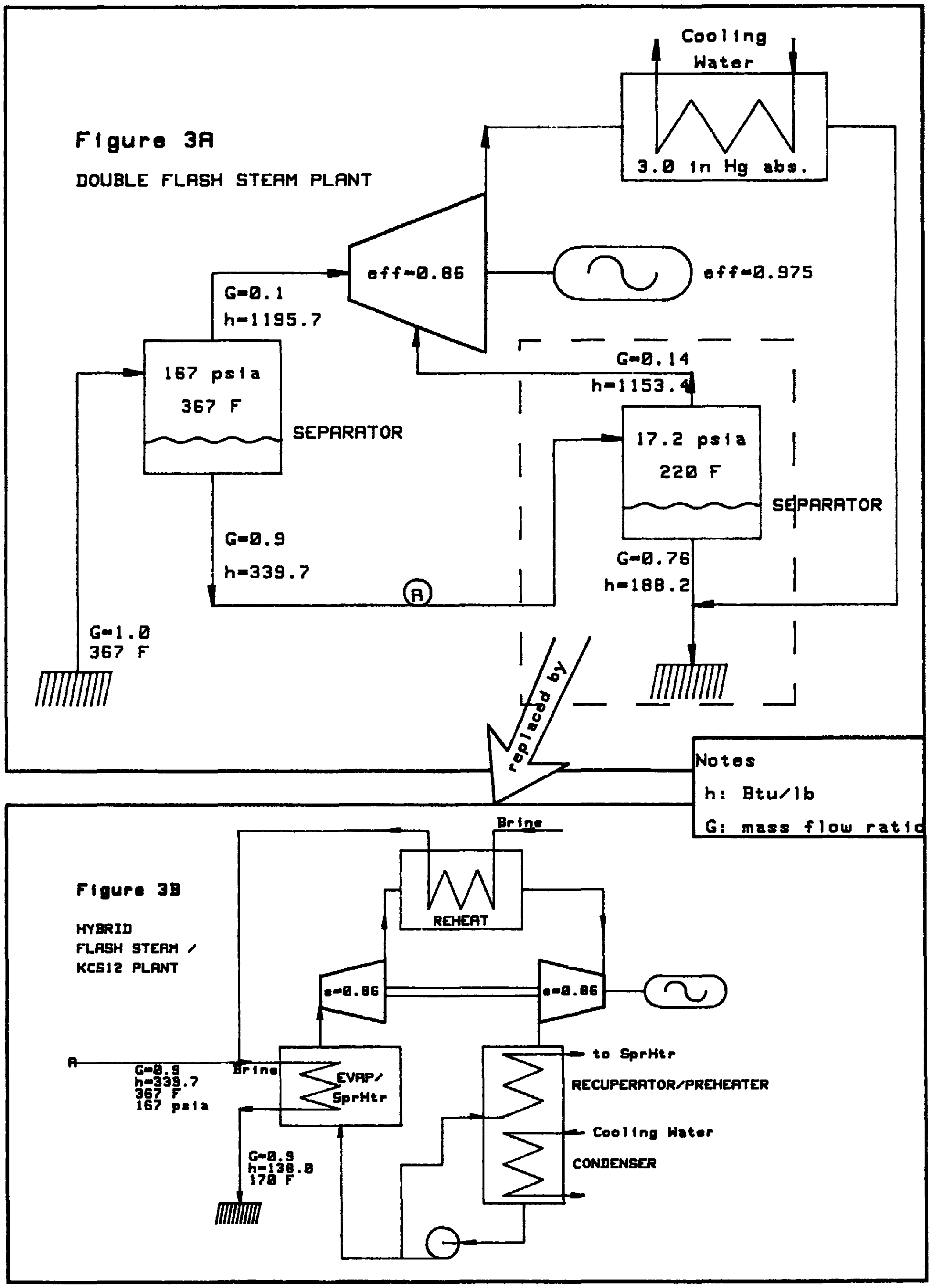
For higher temperature sources, where double flash steam is more economic than binary, the KCS12 plant may be integrated with the flash steam plant to produce a hybrid plant that is more economical than either the flash or KCS12 designs would be by themselves.

In a double flash plant, some portion, typically 5 to 20 percent, of the brine flashes to steam during its delivery from the well bore to the power plant. This steam is then passed through a separator and expanded directly in a turbine down to condensing pressure. The unflashed fluid is then throttled (flashed) to generate an additional amount of steam, typically half the amount initially entering the plant. The steam from the second flash is admitted to the low-pressure section of the turbine where it, too, expands down to condensing pressure. The remaining unflashed liquid, approximately 70 to 80 percent of that entering the plant, is reinjected back to ground. Typically, flash plants with source temperatures of 350°F to 400°F require 120 to 200 lb/kWh of brine consumption. See Figure 3A.

As an alternative, the KCS12 plant is substituted for the second flash process as shown in Figure 3B. In so doing, the destruction of thermodynamic availability (exergy) by throttling down to low pressure in the second flash tank and subsequent rejection of the hot liquid brine is substantially reduced.

For the purpose of comparison, it is assumed that the brine enters the hybrid plant at 367°F with a quality of 10 percent. The 10 percent vapor is expanded to condensing pressure in the usual steam plant manner. The 90 percent unflashed brine is then delivered to the KCS12 evaporator at 367°F. As was shown in Table 2, this design consumes 88.7 lb/kWh of brine. Considering only 0.9 of the brine is used in the KCS12 portion, the actual consumption per unit of brine entering the plant is 98.5 lb/kWh.

On the other hand, if the 367°F brine is flashed in a second step at 17.2 psia/ 220°F, an additional 14 percent of steam is produced (based on geofluid entering Flash No. 1). Condensing down to 3 inches Hg absolute at a theoretical steam rate of 21.49 lb/kWh' yields .00546 kW per lb/hr of geofluid. This corresponds to 183.2 lb/kWh. The net effect of substituting KCS12 for the second flash state is a reduction in brine consumption from 183.2 lb/kWh to 98.5 lb/kWh.



Heat Exchanger Surface Estimate

The premium paid to achieve the higher output of KCS12 is heat exchanger surface. To assess this premium, surface areas were calculated using empirical heat transfer correlations of two-phase mixtures in a model developed by Exergy specifically for water/ammonia mixtures.

Geometry for each heat exchanger was initially estimated. Based on the assumed configuration, the pressure drops on the shell and tube sides were calculated and compared with those allowable. When the pressure drops complied with design values, the surface areas were calculated for these geometries. A summary of the heat exchangers is presented in Table 4. The heat duty vs. temperature profile for each of the heat exchangers is presented in Figures 4 through 10. Because the profiles are often curved, typical of mixtures, the model divides the duty into ten sections for accurate measurement of the mean temperature differences.

In all, there are 41,400 ft^2 of surface area required for the 4.96MW plant, of which 27,700 ft^2 are for heat acquisition and recuperation. All exchangers are conventional shell and tube and, because all are in contact with liquid on one side or both, all tubes are unfinned. The material for each is plain carbon steel. According to (5), the cost of the heat acquisition/recuperation surface is $339,000 based on $12/$ft^2$ for material and 50 man hours per 10,000 ft^2 for installation. Based on 4700 kW of KCS12 output, the specific cost of the additional surface is $72/kW.

TABLE 4

KCS12 Heat Exchanger Summary

Heat Exchanger	Pressure Drop (psi) Shell	Tube	Duty (million Btu/hr)	U (Btu/ hr-sq.ft.-°F)	Area (sq.ft.)
1 - Condenser	-0.05	12.3	71.3	370	13,700
2 - Liquid Preheater	0.06	2.1	19.2	260	3,350
3 - Vaporizer 1	0.63	4.9	25.3	460	4,600
4 - Recuperative Vaporizer	0.24	4.4	36.8	430	6,400
5 - Vaporizer 2	1.08	4.3	48.4	420	8,150
6 - Superheater	2.21	0.7	5.7	110	2,750
7 - Reheater	3.87	-6.1	9.5	120	2,450
					41,400

Conditions

Brine flow = 440E3 lb/hr
Brine inlet = 367°F
Brine outlet = 170°F
Cooling water = 65°F

In a double flash plant, where a total installed cost of $2,000/kW is assumed, the cost of the resource is typically 25 percent of the total plant, or $500/kW(6). This, of course, varies with the depth of the well bore. At a 33 percent reduction in specific brine flow (115 vs. 172 lb/kWh), the resource size can be reduced by one-third, with a commensurate savings of $167/kW. The result is a net savings of $95/kW for KCS12. Although this is far short of a comprehensive economic analysis, it does suggest that the additional heat exchange surface is more than offset by the savings in the development of the resource.

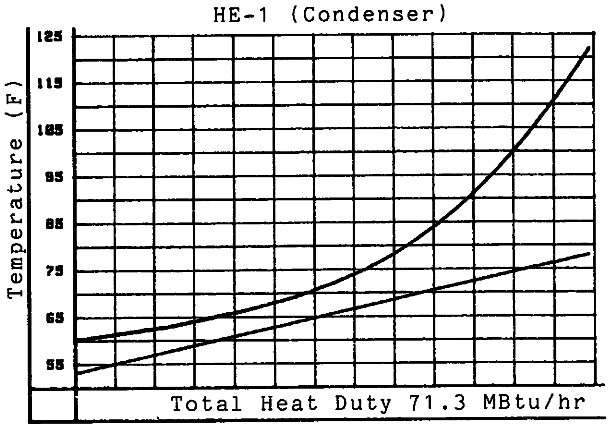


FIGURE 4

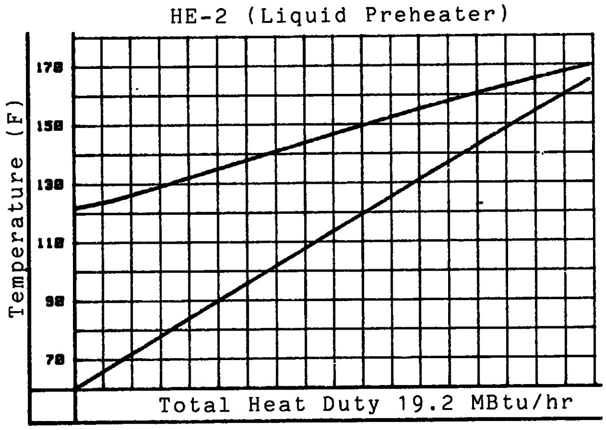


FIGURE 5

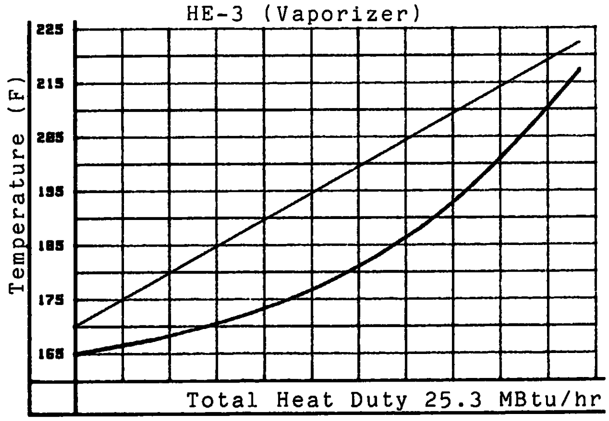


FIGURE 6

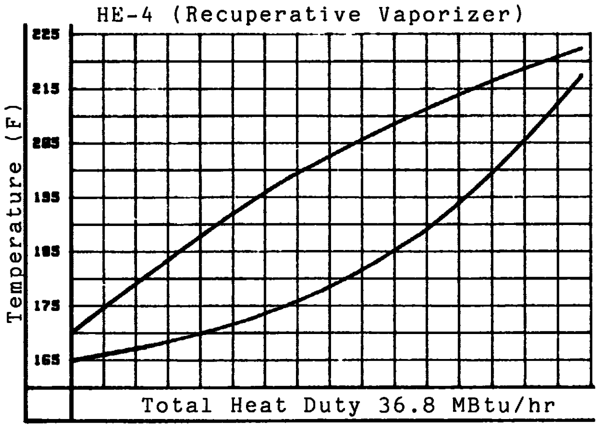


FIGURE 7

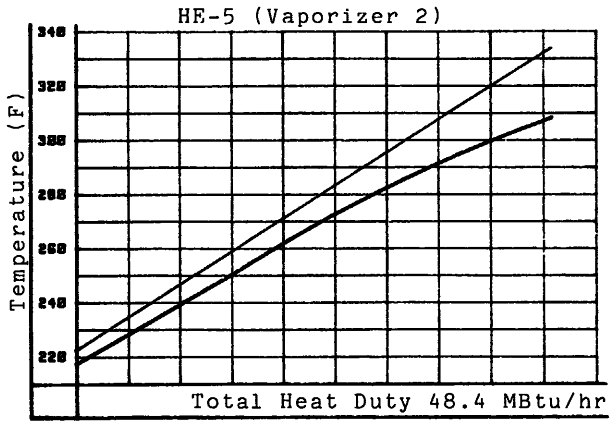


FIGURE 8

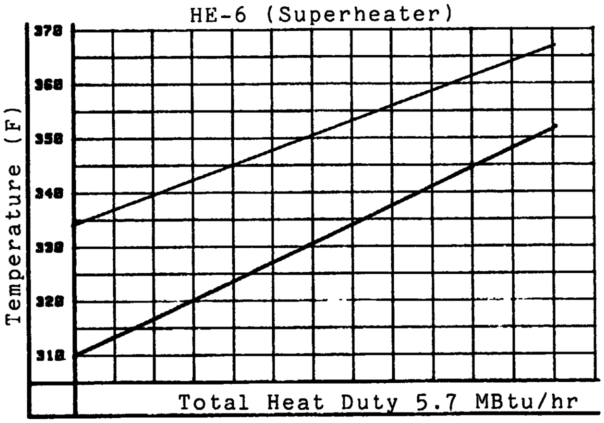


FIGURE 9

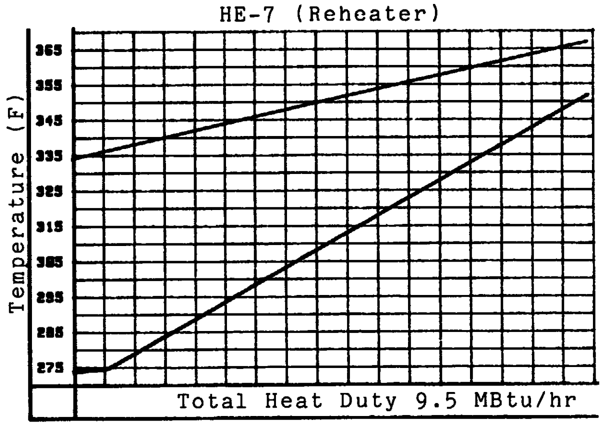


FIGURE 10

Turbine Selection

The turbine design for a water/ammonia cycle differs significantly from one specified for an organic Rankine (binary) cycle. The molecular weight of ammonia (17.03) is almost identical to that of water (18). As a result, the ammonia/water turbine's blading, passage heights and diameters are the same as that specified for conventional steam turbines. On the other hand, ORC turbines operating with hydrocarbons such as isobutane (C_4H_{10}) or chloro-fluorocarbon refrigerants, e.g. R113, R114, are substantially different in geometry due to their much higher molecular weight than ammonia or water. The molecular weight has direct bearing on the sonic velocity which, in turn, dictates the relationship between the fluid speed to blade speed. Further, these hydrocarbon fluids have relatively low enthalpy drops compared to ammonia/water and therefore need to circulate a much greater volume of fluid for the same power output. Thus, the ORC turbine's size is much larger than an ammonia/water turbine. This is also why pumping parasitic losses are much lower with ammonia/ water.

Finally, while the KCS12 turbine enjoys the convenience of using conventional steam turbine design and manufacturing practice, it does not suffer the downside that penalizes condensing applications such as with flash plants. Rather, the KCS12 turbine's discharge of 95 psia totally eliminates the need for the expensive, large volume condensing stages. Low exhaust kinetic leaving losses are incurred. The exhaust is also dry, meaning that no wetness losses or erosion damage occurs.

It is envisioned that the 5MW turbine for the KCS12 plant will be an axial, back-pressure design consisting of three or four high-pressure and a similar quantity of low-pressure stages rotating on a common shaft at approximately 7500 rpm. As output and volume flow increase, the shaft speed will decrease to synchronous speed (3600 rpm or 1800 rpm) where no gear reducer is required.

Material Selection

A comprehensive chemical stability and corrosion test program was conducted(7) to identify materials that are suitable for ammonia/water duty. Plain carbon steel (A106B) and T22 alloy (2.25 Cr, 1 Mo) were evaluated at 200°F and 500°F, respectively, for an exposure period of 720 hours. No evidence of decomposition was found, and corrosion levels less than .0002 inches (0.2 mils) per year were measured. Based on this, all heat exchangers shown in KCS12 are specified with A106B plain carbon steel.

Conclusions

The application of the Kalina Cycle technology for low-temperature geothermal sources provides significant improvement in output over conventional binary ORC and flash steam designs. Preliminary cost estimates based on heat exchange surface requirements indicate that the premium paid for additional surface is more than offset by the reduction in resource requirements and balance of plant.

The KCS12 turbine specification is of standard back-pressure steam design. No vacuum condensing stages are required. Standard equipment and materials are used throughout the plant.

From the standpoint of process design, equipment and material selection, the KCS12 design contains virtually no technological risk. Overall, it contains less risk than the supercritical binary ORC approach.

References

(1) *Heber Geothermal Binary Demonstration Plant: Design, Construction and Early Startup,* Electric Power Research Institute, October 1987, AP-5146.

(2) See Ref. 1, p. 4-56.

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