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APPLYING KALINA CYCLE TECHNOLOGY TO HIGH ENTHALPY GEOTHERMAL RESOURCES

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Abstract

A new conversion system has been designed for high enthalpy streams where mixed phase (vapor/liquid) flow exists at the wellhead. It is designated Kalina Cycle System 13 (KCS13). The working fluid is flash steam and an 80% ammonia-water mixture.

KCS13 consists of binary and flash processes combined in an integrated manner to improve thermodynamic availability (exergy) and brine utilization compared to existing flash steam designs. Generation costs are reduced by lowering unit capital and operating costs.

Vapor and liquid streams from the resource are initially separated, partially processed, then mixed together to provide optimum heat acquisition to the ammonia-water working fluid. Details of the process flow, heat-mass balance and preliminary equipment specifications are provided for a 46 MW plant.

INTRODUCTION

Geothermal power plants using high temperature/enthalpy resources, typically 180C (356F) and higher, are configured almost exclusively as flash or dry steam systems. Normally, binary technology is not employed until the resource becomes liquid dominated at 170C (338F), or lower. Single flash systems have become the standard, primarily because they are more simple, easy to operate, and low in capital cost. However, this design is not without its drawbacks. For one, single flash units are thermodynamically inefficient. Too much useful energy is discarded during brine injection. They also suffer from forced outages and high O&M expense as a consequence of the corrosive behavior of the flashed steam and equipment damage due to solids carryover, particularly in the turbine.

Dual flash systems have been developed to improve plant output (and economic performance) where resource chemistry permits. The second flash process increases the solids concentration in the liquid phase, while simultaneously lowering the solubility limit by decreasing the brine temperature. Often the initial solids content of the brine is too high to install the second flash, lest scaling occurs in the injection piping.

Further improvement in thermodynamic and economic performance of high enthalpy sources should include utilization of the useful energy (often referred to as exergy) in the unflashed liquid. One way to accomplish this is to add a binary "bottoming" plant under the flash plant. The authors presented an example of this approach at the 1989 GRC meeting.[1] This design suffered only in that the flash/binary combined cycle is actually two separate plants, i.e., two turbines, two condensers, two sets of piping, etc. A more optimum configuration would be a flash/binary design integrated into a single plant. This design had not yet been developed ......until now.

The subject of this paper, Kalina Cycle System 13 (KCS13), is a novel approach to addressing high temperature/enthalpy sources. It represents a substantial improvement over flash systems while using conventional flash and binary system equipment. KCS13 evolved directly from Kalina Cycle Systems 11 and 12 developed for liquid dominated binary applications. Its features and performance are presented for review by the geothermal power community.

KCS13 DESIGN

A process flow schematic and heat/mass balance for KSC13 are given in Figure 1 and Table 1, respectively, for a 46 MWe net, plant. It is air-cooled based on 10C ambient.

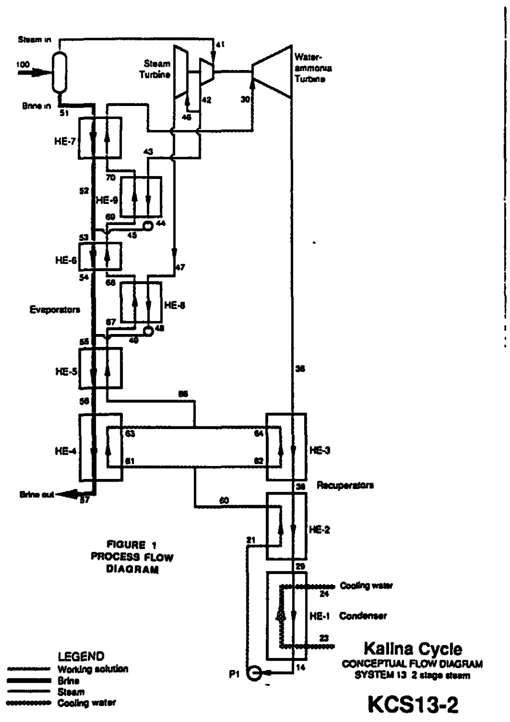


FIGURE 1
PROCESS FLOW DIAGRAM

TABLE 1
KCS13-2
HEAT/MASS BALANCE

#	P bar	X	T °C	H kJ/kg	G/G30	Flow kg/s	Phase
14	6.22	.7792	18.89	-63.16	1	188.657	SatLiquid
21	29.58	.7792	19.40	-59.26	1	188.657	Liq 106°
23	•	Air	10.56	10.54	39.9823	7542.937	
24	•	Air	33.45	34.03	39.9823	7542.937	
29	6.51	.7792	56.05	867.94	1	188.657	Wet .3835
30	26.48	.7792	189.87	1920.56	1	188.657	Vap 52°
36	6.60	.7792	110.91	1696.34	1	188.657	Wet .0374
38	6.53	.7792	80.00	1139.47	1	188.657	Wet .2691
40	6.60	.7792	113.64	1781.75	1	188.657	SatVapor
41	14.97	Steam	198.20	2791.44	.1739	32.815	SatVapor
42	5.29	Steam	153.98	2623.97	.1695	31.985	Wet .0603
43	5.29	Steam	153.98	2623.97	.1017	19.191	Wet .0603
44	5.29	Steam	154.01	649.16	.1017	19.191	SatLiquid
45	14.97	Steam	154.01	649.68	.1017	19.191	Liq 80°
46	5.29	Steam	153.98	2623.97	.0678	12.794	Wet .0603
47	2.88	Steam	132.13	2528.24	.0678	12.794	Wet .0898
48	2.88	Steam	132.16	555.12	.0678	12.794	SatLiquid
49	14.97	Steam	132.16	555.89	.0678	12.794	Liq 119°
51	•	Brine	198.20	846.42	1.5244	287.595	
52	•	Brine	154.01	657.71	1.5244	287.595	
53	•	Brine	154.01	657.71	1.6262	306.786	
54	•	Brine	132.16	564.39	1.6262	306.786	
55	•	Brine	132.16	564.39	1.6940	319.580	
56	•	Brine	110.91	473.64	1.6940	319.580	
57	•	Brine	80.00	341.64	1.6940	319.580	
60	28.89	.7792	77.22	212.26	1	188.657	SatLiquid
61	28.20	.7792	108.13	992.73	.2865	54.048	Wet .4006
62	28.20	.7792	108.13	992.73	.7135	134.609	Wet .4006
66	28.20	.7792	108.13	992.70	1	188.657	Wet .4007
67	28.00	.7792	119.66	1146.43	1	188.657	Wet .3215
68	27.51	.7792	129.38	1280.24	1	188.657	Wet .258
69	27.31	.7792	139.86	1431.99	1	188.657	Wet .1892
70	26.83	.7792	151.23	1632.88	1	188.657	Wet .0975

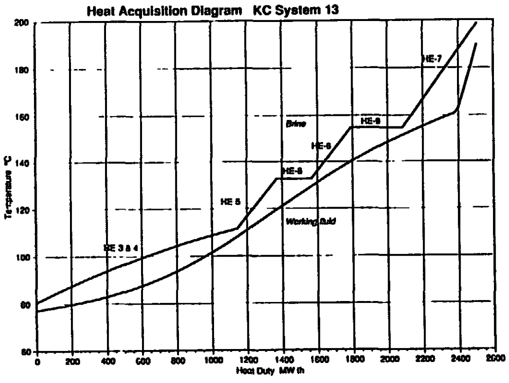
From Figure 1, it is apparent that the flash process and binary portion are integrated into a single plant. Heat supplied to the binary process comes from the liquid brine and the steam turbine's extraction and exhaust. This cascade approach creates an excellent thermodynamic match between the heat source and binary working fluid. See Figure 2.

Typical of all Kalina-type systems, the working fluid in the binary portion is an ammonia-water mixture. For this application an 78% mixture (.78 ammonia, .22 water) is specified. The composition of the mixture does not change during the cycle, but does from hot to cold day operation. It also changes to accommodate part load and off-design operation.

Another feature of the design is its highly recuperative capability. In addition to liquid preheating there is substantial vaporization that is accomplished recuperatively. Approximately 42% of the heat required by the ammonia-water working fluid is provided recuperatively. Recuperative vaporization is not found in hydrocarbon Rankine cycles currently offered by binary plant developers.

FIGURE 2

Heat Acquisition Diagram KC System 13



KCS13 PERFORMANCE

The KCS13 plant described in Table 1 and Figure 1 produces 46.4 MWe net based on 320 kg/s of fluid entering the plant. Its performance is measured in three ways:

Brine consumption, Wh/kg	40.22
Thermal efficiency (First Law), %	20.75
Thermodynamic or exergetic efficiency (Second Law), %	67.6

The brine reaches the wellhead at a 15.0 bar 198°C with an enthalpy of 1039kJ/kg. This corresponds to approximately 18% of vapor content. Without any additional throttling the fluid is sent to a gravity separator. The vapor portion, 32.8 kg/s, is expanded through an axial steam turbine to produce 6.7 MW. Brine leaving the separator is used to produce 188.7kg/s of superheated ammonia water at 26.5 bar, 190°C. The mixture is 77.9% ammonia. The exhaust steam is condensed in the binary evaporator to augment the generation of ammonia-water working fluid. Ammonia-water superheated vapor is expanded through an axial vapor turbine to generate 42.2 MWe. It leaves nearly dry saturated (2.7 % wet) at 6.5 bar and is used recuperatively to evaporate and preheat oncoming aqua from the condenser hotwell. The plant's gross output, measured at the generator terminal, is 47.8 MW. Cooling fans and feed pump losses amount to 1,404 kW or 2.9% of output.

Brine leaves the plant and is injected back to the resource at 80°C. Of course, this temperature is very dependent on the solids content of the brine. It should be noted that the condensed steam is mixed with the hot brine during the binary evaporation process. This has the effect of diluting the concentration of solids, mitigating the onset of scaling.

PROCESS DESCRIPTION

Two phase fluid (wet vapor) enters the plant at point 100. Without throttling any further, the liquid and vapor phases are separated. The flashed portion is expanded through a back pressure steam turbine. Depending on the mass fraction of vapor entering the plant, the steam turbine may or may not require extraction. In this example the mass fraction is high, close to 20%, so extraction is specified at point 42. At 10%, vapor fraction it is not necessary. The extracted steam is condensed in HE-9 to vaporize the binary working fluid. Likewise, the exhaust steam at point 47 condenses in HE-7 to vaporize ammonia-water in a lower cascade. See Figure 2. After the steam is condensed, it is pumped to higher pressure and injected into the brine stream at points 53 and 55.

On the brine side, the heat released from the brine is used to superheat the ammonia-water in HE-7 and then used sequentially to vaporize the working fluid in HE-4, 5, and 6. The brine is injected back to the reservoir at point 57. The plant is designed so that point 57 is approximately the same as the working fluid's bubble point, i.e., where boiling begins. Consequently, the brine is only used for vaporization duty. All liquid preheat and some vaporization is accomplished in the recuperative condensers, HE-2 and HE-3. The final water or air-cooled condenser completely condenses the working fluid in HE-1.

COMPARISON WITH FLASH TECHNOLOGY

Plant performance was calculated for single and double flash units operating at the same condition specified for KSC13. See Table 2. KCS13 output is 64% and 29% greater than single and double flash, respectively.

In the single flash design, the brine is throttled from 15 bar to 6.5 bar. The flashed vapor, representing 17.5 percent of the fluid entering the wellhead, is expanded down to 0.1 bar to generate 28.4 MW, net.

The additional flash at 2.1 bar produces another 8 percent vapor fraction of the brine entering the second flash to increase the net plant output to 36.0 MW.

TABLE 2
FLASH DESIGNS

SINGLE FLASH

	Well-head	Flash Exit Vapor	Flash Exit Liquid	Condenser
Pressure, bar	15	6.5	6.5	0.1
Temperature, °C	198.2	162	162	
Enthalpy, kJ/kg	1039.4	2758.8	681.34	2255.92
Flowrate, kg/s	320.41	56.35	264.06	56.35

DOUBLE FLASH

	Well-head	Flash 1 Exit Vapor	Flash 1 Exit Liquid	Flash 2 Exit Vapor	Flash 2 Exit Liquid	Condenser
Pressure, bar	15	6.5	6.5	2.1	2.1	0.1
Temperature, °C	198.2	162	162	121.1	121.1	
Enthalpy, kJ/kg	1039.4	2758.8	681.34	1164.0	508.23	
Flowrate, kg/s	320.41	56.35	264.06	21.15	284.38	77.50

PERFORMANCE COMPARISON

	KCS13	Single Flash	Double Flash
Output, MW	46.4	28.35	36.0
Brine Consumption Wh/kg	40.22	24.58	31.21
Improvement, %		63.6	28.8

PLANT COST

Qualitatively, the output advantage of KCS13 over flash systems should improve economic performance as well. The additional heat exchanger cost in KCS13 is offset by:

1. The explicit value of the additional power produced by KCS13.

2. Lower resource development costs of KCS13 in direct proportion to output improvement.

3. Lower absolute turbine cost with KCS13 due to the reduction in the number of stages of expansion and elimination of all condensing stages.

4. Lower O&M costs of KCS13 due to:

   a. lower non-condensible gas removal
   b. no vacuum system requirement
   c. lower H_2S treatment
   d. lower solids carryover into turbine
   e. no turbine erosion, corrosion damage.

A detailed, quantitative cost comparison of KCS13 and flash technology will be the subject of a future paper.

PLANT DESIGN

TURBINES

Both the ammonia-water and steam turbine are conventional multi-stage axial designs available from numerous steam turbine manufacturers worldwide. The ammonia vapor turbine, having a modest expansion ratio of 4.0, requires only 3-4 stages. Further, the high back pressure of 6.5 bar keeps the last stage bucket height relatively short. These two features reduce the turbine cost substantially below comparable hydrocarbon turbines and lower than condensing steam turbines where the last stage buckets are quite long.

From a performance consideration, the ammonia-water vapor turbine is optimally configured. The expansion ratio is low so only a few stages are required. The absolute inlet and exhaust pressure are modest, so blade heights are neither too short nor too long. Leaving losses are low because the exit specific volume is relatively low. Wetness losses are minimal because the exhaust is virtually dry. The blade speed and fluid speed are well matched so gear box (speed reduction) requirements vary from low to none, the latter at outputs of 30 MW and higher. It is estimated that the turbine's isentropic efficiency will be in the upper 80's (percent).

Materials of construction are the same as those used for steam operation. Commercial proposals have been received from turbine suppliers with 12 chrome stainless steel specified as the rotor and bucket material. Other than a strict prohibition against the use of any copper-bearing alloys, there are no material issues in the turbine.

The seal requirement is slightly different than for steam operation. To insure that no ammonia leaks to the atmosphere as fugitive emissions, it is necessary to install either a mechanical seal or labyrinth seal in conjunction with a gland fluid condenser and stripper. See Figure 3. Working fluid that has leaked past the glands is directed to an exhaust compressor. A slight vacuum is maintained near the outboard gland to insure that no working fluid leaks to the atmosphere. A small quantity of air is pulled into the gland leak-off through the exhaust compressor.

The working fluid and air mixture are sent into a sparge tank where the ammonia-water vapor is absorbed into a very lean liquid. Air, as a non-condensible, is vented overboard. The aqua ammonia liquid is then passed through an oxygen scavenge, then to a stripper, forming a rich vapor and lean liquid. The enriched vapor is sent to the condenser while the dilute aqua is cooled and returned to the sparge tank.

The steam turbine, which accounts for approximately 14% of the plant's output, has an expansion ratio of 2.83, exhausting at a pressure of 5.3 bar. It requires no more than two or three stages.

HEAT EXCHANGERS

The heat exchangers specified for KCS13 can all be fabricated by vendors who now supply standard commercial equipment to the power and process industries. All units are of the shell and tube variety and are made from carbon steel. The only departure from usual power plant practice is the orientation of the condensing units which are necessarily vertical.

There are three categories of heat exchangers; brine evaporators, steam evaporators and condensers.

- **Brine Evaporators**

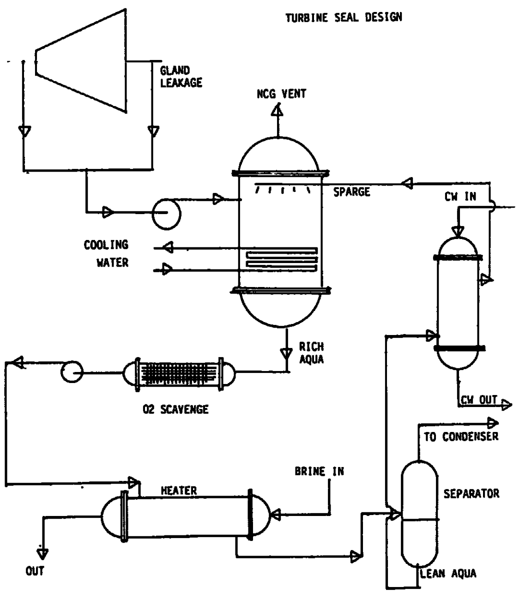
These units consist of HE-4, 5, 6, and 7 and are functionally identical to the evaporators now in use in hydrocarbon binary plants. The units are horizontal with the brine flowing inside the tubes. Ammonia-water flows in the shell in a counterflow direction. The evaporated portion uses bare tubes, while the superheater, HE-7, is finned.

- **Steam Evaporators**

Steam is condensed inside the tubes to evaporate and superheat the ammonia-water working fluid. The units are set vertically so condensing occurs as a falling film in a counterflow arrangement to promote maximum heat transfer.

FIGURE 3

TURBINE SEAL DESIGN



- **Condensers**

There are three condensing heat exchangers: HE-1, 2 and 3. In all cases, condensing of the ammonia-water vapor occurs in the shell. The units are vertically oriented using a straight tube bundle. Condensation and evaporation occur as pure counterflow.

- **Air cooling**

When water is not available and air coolers are specified, there is a potentially large savings that KCS13 achieves over pure component (hydrocarbon or steam) systems. Because the ammonia-water vapor condenses over a wide temperature range (37C in the heat balance shown in Table 1), the cooling bundles are stacked higher to accommodate a greater allowable air temperature rise (approximately 23C). See Figure 4. In the KCS11 geothermal binary project at Steamboat, there are four passes of tubes per unit, while for the isobutane plant adjacent to it where condensing is virtually isothermal, the coolers have two passes of tubes per unit. The result is almost halving the number of condenser units for the same plant output.

PLANT COST

A detailed cost analysis of KCS13 has not yet been conducted. It will be presented in a future paper.

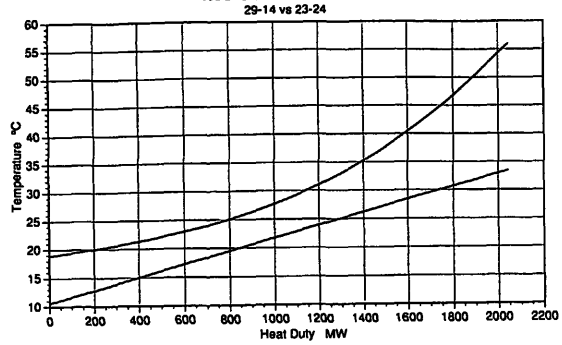
AMMONIA SAFETY

Anhydrous ammonia vapor is toxic to humans at concentrations in the range of 1,000 ppm[3] and greater. Fortunately, its pungent odor is perceptible at concentrations of 5-10 ppm, so detection of the smallest leaks is possible. Liquid spills are rendered harmless by diluting with water to form aqua ammonia. Ammonia solubility in water is very high. Lean solutions of aqua ammonia (20% or less) are shipped in non-pressurized containers as fertilizer and feedstock and household cleansers. Similarly, vapors are readily absorbed into water. It is common practice to direct all reliefs and vents to a sparge tank where contact with water immediately absorbs the vapor, reducing its pressure (by 100:1 volume change) and concentration form dilute aqua. In fact, the 3 MW Kalina Cycle demonstration plant[4] is designed with a vent system precisely in the manner just described. After 3000 hours of operation and numerous plant upsets, the vent system continues to operate flawlessly.

On the other hand, ASHRAE recommends that mechanical ammonia-based refrigeration systems be designed to discharge pressure-relief devices to the atmosphere.[5] The International Institute of Ammonia Refrigeration (IIAR) specifies that the point of discharge be outside the building, not less than 15 feet above ground level, not less than 7 feet above the highest structure on the building and not less than 20 feet from any window or ventilation opening.[6]

Atmospheric discharge is recommended because ammonia is lighter than air, making it easy to vent safely. The IIAR explains: "Ammonia is biodegradable and when released readily combines with water and carbon dioxide to form harmless compounds. Other reactions in the atmosphere involve pollutants such as acids which are neutralized by the combined action of ammonia and water. These characteristics make it an ecologically safe industrial substance when handled and released properly."

FIGURE 4
KCS13 Condenser HE-1
29-14 vs 23-24



- **Fire Hazard**

Ammonia is considered non-flammable by the U.S. Department of Transportation.[3] In the presence of a flame or spark at about 1200F, ammonia vapor will ignite, but only within the limited range of 16-25% of ammonia in air, by volume. The heat generated by combustion is insufficient to maintain a flame which, therefore, will extinguish upon ignition source removal. At the 3 MW demonstration plant, fire sprinklers were installed over the turbine generator and gearbox bearings. The Ventura County Fire Department was concerned only with a lube oil fire, not an ammonia vapor fire. Consequently, none of the electrical equipment or instruments require explosion-proof boxes. Also, ammonia buoyancy in air eliminates the need to keep a constant positive pressure inside of buildings housing operating personnel.

Ammonia Handling and Mitigation Equipment

Based on excellent results from operation of the 3 MW demonstration plant, the following procedures and equipment are suggested for KCS13 geothermal plant operation:

1. Install a remotely activated fog nozzle near the anhydrous ammonia storage tank. In the event of a spill, the nozzle may be activated from the control building to dilute and "knockdown" the vapors created by the liquid leak. Additionally, a one meter high cement curb should be built around the storage tank.

2. Stationary fire hose stations should be installed at designated locations around the plant where there are large inventories of aqua ammonia and/or at equipment where spills are more likely to occur. These include the plant's heat exchangers, main feed pump, and so on.

3. All plant drains should be collected in a large reservoir to avoid releasing high pH level fluids to local water sources.

4. Respirators are essential for working in close proximity to high concentration aqua. It is good practice to have masks with charcoal filters and masks with bottles (SCBA) on hand depending on the ammonia environment.

5. Automatic ammonia leak detectors (down to 50 ppm) should be installed to alert operating and security personnel.

AMMONIA COST

Industrial grade anhydrous ammonia, purchased by the tanker load (6500 gallons), sells for approximately $.50/gallon.

CONCLUSION

1. KCS13 provides substantially more output per unit of resource than current flash steam designs.

2. Plant equipment costs are expected to be low (per unit of installed capacity) because they are of standard, commercial origin. Materials consist of commonly used low cost alloys, i.e., carbon steel heat exchangers, chrome steel turbines.

3. Plant operation is expected to be safe, reliable and free of fugitive emissions owing to the well established procedures for using ammonia in the process and refrigeration industries.

ACKNOWLEDGMENTS

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