Application of Recent Developments in Kalina Cycle Technology to the Utilization of High Temperature Geothermal Sources

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ABSTRACT

The application of Kalex Kalina Cycle power systems for low temperature geothermal sources was presented at the 2006 GRC annual meeting in San Diego (1). This paper shows the applicability of current Kalina Cycle power systems to high temperature geothermal sources.

This paper reviews the design of a typical, conventional high temperature geothermal power plant and examines alternatives for generating power utilizing high temperature geothermal sources using new technology developed and patented by Kalex, LLC. This technology, which relies on the "Kalina Cycle" power cycle, offers the potential for increased power generation, lower cost, lower maintenance, and reduced well-field degradation.

Conventional High Temperature Geothermal Power Systems

The earliest use of geothermal resources for power generation involved the use of high temperature geothermal sources. Such sources, with an initial temperature of between 380 and 500 °F, produced geofluid in the form of steam, or more frequently, in the form of a liquid-steam mixture. Conventional utilization of such resources involves the use of dual flash power systems, in which steam is used as the working fluid of the power cycle. A conceptual flow diagram of a typical dual flash system (DFS) is given in Figure 1.

Analyzing the operation of a Dual Flash system, the work potential of the steam should be considered separately from the work potential of the liquid.

The utilization of the energy potential of the steam in a DFS is substantially efficient but is limited by the wetness of the steam towards the end of expansion process. This wetness must not exceed a fixed limit defined by the turbine's design, usually 10%. A further limitation is the pressure of condensation. The lower the pressure in the condenser the greater the output of the turbine. It is, however, difficult to maintain a pressure of less than 1 psia at the exit from the condenser. Considering the inevitable loss of pressure inside the condenser, the exit pressure in actual application will generally be 3 psia or higher.

This in turn limits the possible pressure at point 100. If the pressure at point 100 is overly high, then at the exit from the second turbine, at the point where wetness reaches 10%, the pressure

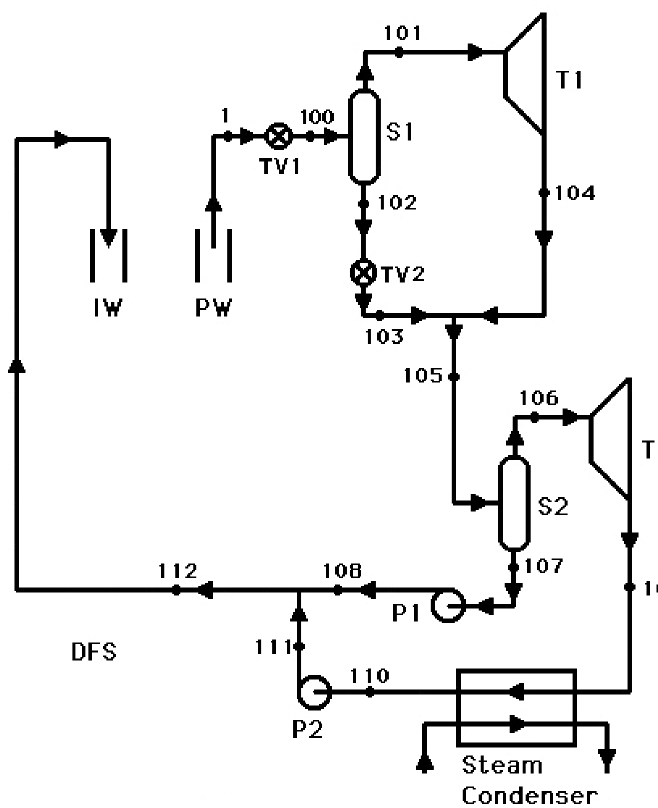

Figure 1. Conceptual flow diagram of a tyypical dual flash system (DFS).

will be higher than 3 psi. As a result, a substantial portion of the energy potential of the steam will be lost.

Therefore, if the initial pressure of the geofluid at point 1 is too high, the geofluid needs to pass through a throttle valve (TV1) in order to obtain the desired pressure at point 100.

The utilization of the energy potential of liquid in a DFS is extremely inefficient. A substantial portion of the energy potential of the liquid is lost in throttle value TV2. This does produce some additional quantity of steam, but the exergy losses in this process are high.

As can be seen from the description of the DFS, above, stream 107 is reinjected at a relatively elevated temperature and its heat potential is not utilized. Operators of several dual flash geothermal systems have added an organic Rankine Cycle (ORC) a bottoming binary cycle utilizing the lost potential of the liquid to produce additional power. A conceptual flow diagram of a system including a bottoming binary cycle is given in Figure 2.

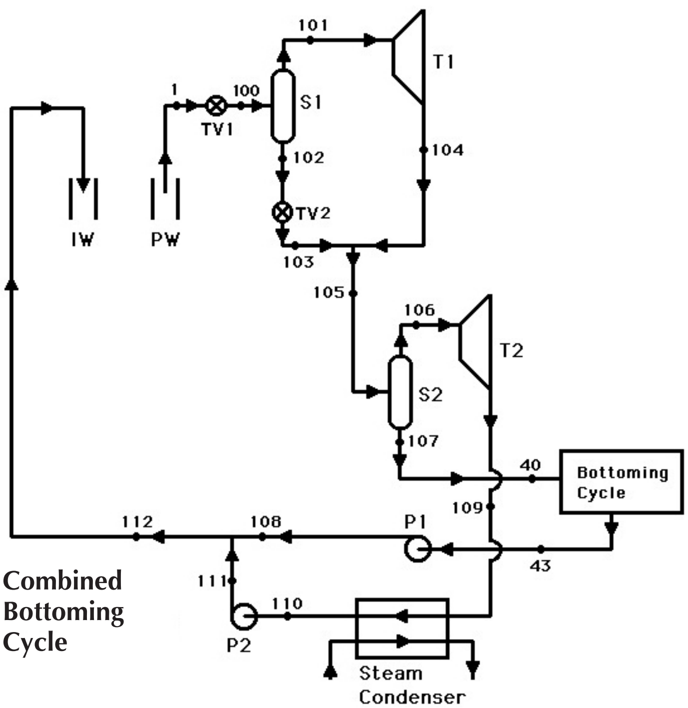

Figure 2. Conceptual flow diagram of a system including a bottoming binary cycle.

The total heat potential of stream 107 depends on the initial quality of the geofluid at point 100. When stream 100 contains a substantial quantity of liquid, the weight-flow rate of stream 107 is relatively high and the additional power generated by a bottoming cycle can be substantial. However, when the quality of the geofluid at point 100 is high (mostly steam) the flow rate at point 107 is small and the additional power that can be generated by a bottoming cycle is likewise small.

Application of the Kalina Cycle in High Temperature Geothermal Power Systems

It is possible to use a Kalina cycle designed for low temperature geothermal applications as such a bottoming cycle. This will increase the power produced by the bottoming binary cycle as compared to using an organic Rankine cycle, but if the overall heat potential of stream 107 is relatively small, the increase will not be very large as compared to the overall power produced by the dual flash cycle.

Kalex has developed two alternate approaches to utilizing this sort of high temperature geothermal resource. These approaches are designated "parallel combined cycle" and "direct utilization in a mid-temperature power system."

The first of these, the parallel combined cycle, is based on the separate utilization of steam and liquid by two different systems operating in parallel, presented in Figure 3.

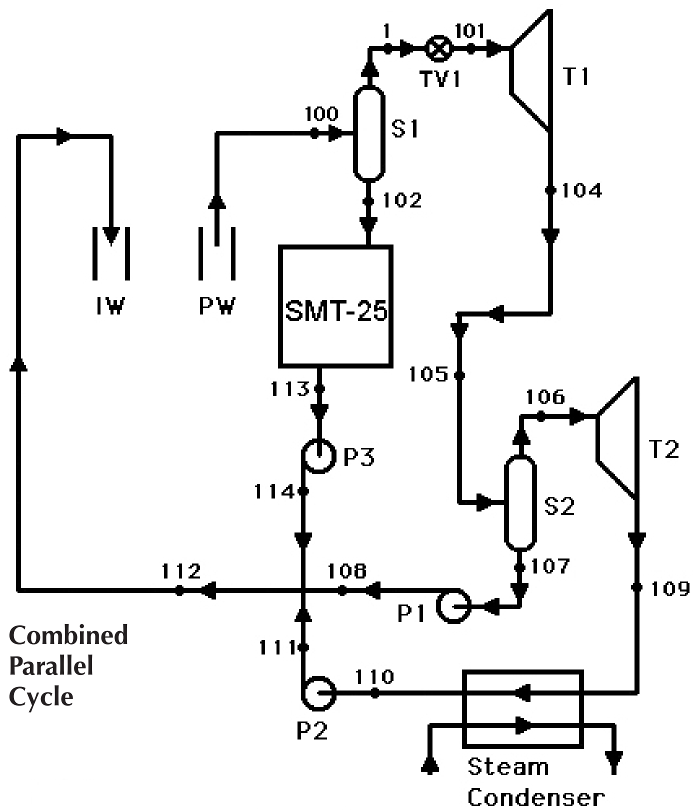

Figure 3. Separate utilization of steam and liquid by two different systems operating in parallel.

Vapor, separated in flash tank, S1, with parameters as at point 101, is utilized in a dual flash systems (DFS) as described above.

Liquid from S1 is utilized as a heat source for a Kalex mid temperature power system, designated SMT-25. This utilization of the energy potential of the liquid is substantially more efficient than in a traditional DFS.

(In general, when looking at applicability of Kalex systems, high temperature geothermal sources are considered part of the "mid temperature" range of heat sources and are best served by Kalex mid-temperature systems, designated SMT systems.)

The second approach is the direct utilization of the entire stream of geofluid as a heat source for system SMT-25.

As both of these approaches utilize SMT-25, it is described in detail, below. A conceptual flow diagram of system SMT-25 is presented in Figure 4.

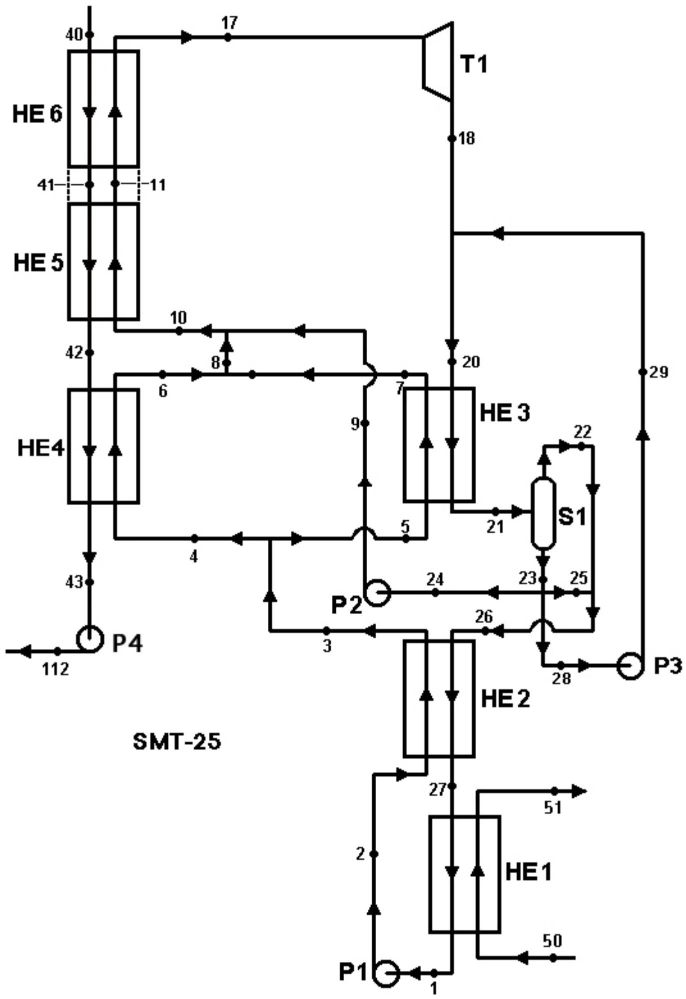

Figure 4. A conceptual flow diagram of system SMT-25

The system operates as follows: Geofluid taken from the wellhead with parameters as at point 40. (This point corresponds to point 1 in the diagram of the DFS.) The geofluid is sent into heat exchanger HE6 where it partially condensed, obtaining parameters as at point 41. Thereafter stream 41 is sent into heat exchanger HE5, where it is fully condensed and subcooled, obtaining parameters as at point 42. Stream 42 is then sent into heat exchanger HE4, where it is further subcooled, obtained parameters as at point 43. Geofluid with parameters as at point 43 is then pumped by a pump, P4, to a required pressure, obtaining parameters as at point 112, and is then sent out of the system to the reinjection well.

Fully condensed working fluid, with parameters as at point 1 is pumped to a desired high pressure by pump P1, and obtains parameters as at point 2. Thereafter, the stream with parameters as at point 2 passes through heat exchanger HE2, where it is pre-heated by a returning stream of working fluid (26-27, see below) obtaining parameters as at point 3, corresponding to the boiling point of stream 3. Stream 3 is then divided into two substreams, having parameters as at points 4 and 5 respectively. Stream 4 then passes through a heat exchanger, HE4, where it is partially vaporized in counterflow by a stream of geofluid (42-43) obtaining parameters as at point 6. Meanwhile stream 5 passes through a heat exchanger, HE3, where it is likewise partially vaporized, in counterflow with a returning condensing stream of working fluid (20-21) and obtains parameters as at point 7. Thereafter streams 6 and 7 are combined forming stream 8. Stream 8 is then mixed with a stream of lean liquid having parameters as at point 9 (see below) forming a stream with parameters as at point 10.

The stream with parameters as at point 10 passes through heat exchangers HE5 and HE6 is counterflow with the stream of geofluid (40-41-42, see above) and obtains parameters as at point 17. Stream 17 is then sent into a turbine, T1, where it is expanded, producing work, and obtains parameters as at point 18.

The stream at point 18 can be is a state of wet or superheated vapor. In the case that point 18 corresponds to a state of superheated vapor, stream 18 is de-superheated by mixing it with a stream of lean liquid with parameters as at point 29, obtaining parameters as at point 20. In the case that point 18 corresponds to a state of dry saturated or wet vapor, the stream with parameters as at point 29 does not exist, and the parameters of point 18 and point 20 are identical.

The stream with parameters as at point 20 passes through HE3, where it is partially condensed, providing heat for process 5-7 (see above) and obtaining parameters as at point 21. It then enters into a separator, S1. In separator S1, stream 21 is separated into two substreams: a stream of saturated vapor with parameters as at point 22 and a stream of saturated liquid with parameters as at point 23.

Stream 23 is then divided into two or three substreams, with parameters as at point 24, 25 and 28. In the case that stream 29 does not exist (see above) then stream 28 likewise does not exist. If stream 29 does exist, then stream 28 is sent into a pump, P3, where it is pumped to a pressure equal to the pressure at point 18, and obtains parameters as at point 29.

The stream with parameters as at point 24 is pumped by pump P2, to a pressure equal to the pressure at point 8, obtaining parameters as at point 9 (see above).

Meanwhile, stream 25 is combined with a stream of vapor with parameters as at point 22, forming a stream of working fluid with parameters as at point 26. The composition of stream 26 is the same as the composition at point 1. The stream with parameters as at point 26 then passes through HE2, where it is partially condensed, releasing heat for process 2-3 (see above) and obtains parameters as at point 27. Stream 27 is then sent into the final condenser, HE1, where it is fully condensed in counterflow by stream of coolant 50-51, (water or air,) and obtains parameters as at point 1 (see above).

Technologically, if the geofluid to be used in SMT-25 is a mixture and vapor, it is preferable to separate the liquid from the vapor, and to utilize these two streams in two separate heat exchangers, working in parallel or consecutively.

System SMT-25 is similar to system SG-2d, but because it is used for a much higher temperature heat source, the methodology of computation is substantially different.

Comparison of Power Generation Outputs

A computation of the performance of all the approaches discussed here is given in Table 1, overleaf. Table 1 covers the following:

--Dual Flash System (DFS)
--DFS with Organic Rankine bottoming cycle (DFS/ORC)
--DFS with a Kalex SG-2a bottoming cycle (DFS/SG-2a)
--DFS in parallel with SMT-25 (DFS+SMT-25)
--SMT-25.

Table 1. A computation of the performance of all the approaches.

	DFS	DFS/ORC		DFS/SG-2a		DFS+SMT-25		SMT-25	
Quality of Geofluid	Net Output (kW)	Net Output (kW)	% Output Increase	Net Output (kW)	% Output Increase	Net Output (kW)	% Output Increase	Net Output (kW)	% Output Increase
0.15	7910.27	8882.15	12.29	9502.47	20.13	10846.29	37.12	10532.24	33.15
0.30	12843.64	13667.36	6.41	14193.10	10.51	15261.53	18.83	14261.45	14.93
0.45	17777.00	18452.55	3.80	18883.73	6.23	19676.78	10.69	19050.64	7.16
0.60	22710.37	23237.75	2.23	23574.36	3.80	24092.02	6.08	23366.53	2.89
0.80	29288.19	29618.02	1.13	29828.54	1.84	29979.02	2.36	29050.64	-0.82
1.00	35866.01	35998.28	0.37	36082.71	0.60	35866.01	0.00	34915.31	-2.72

All computations have been performed for geofluid having an initial temperature of 400 °F. (204.44 °C.) with different qualities of initial geofluid ranging from 0.15 to 1.0.

The weight flow rate for all computations is 500,000 lb/hour (62.9989 kg/sec).

The temperature of cooling water was assumed to be 51.7 °F. (10.78 °C.), corresponding to ISO conditions.

Note that relative performance of all variants that include binary cycles will be reduced if the temperature of coolant is higher.

It should be noted that the data presented in Table 1 are preliminary data. The computations do not take into account the additional power consumption of a DFS system needed to maintain a vacuum in the condenser. Also, the reduction of turbine efficiency due to wetness is not taken into account in the data presented in Table 1.

(In the case where the initial temperature and pressure of the geofluid at point 1 [point 40 in SMT-25] is overly high and the geofluid is therefore throttled in TV1, the ratio of performance of a DFS and of SMT-25 is none the less approximately the same as shown in Table 1).

As shown in Table 1, the most efficient system possible is a parallel installation of a DFS and SMT-25.

The use of SG-2a as a bottoming cycle with a DFS is substantially more efficient that the use of an ORC as a bottoming cycle, but is less efficient that the use of SMT-25 in parallel with the DFS.

In general, where geofluid quality is very high, (quality of .80 or higher) the incremental increase in output from the addition of a binary cycle to a DFS is quite small and not likely to be economically justifiable

The use of SMT-25 on its own, with no DFS, has slightly lower efficiency than the DFS + SMT-25 parallel system, but has the advantage of much lower costs since the SMT-25 uses only a single turbine, whereas DFS uses two turbines and both the parallel DFS + SMT-25 and the DFS + bottoming cycles use three turbines. The cost savings possible due to smaller number of turbines will substantially exceed any extra installation costs due to the need for heat exchangers in the SMT-25 system.

Additional Considerations

Direct use of geothermal fluids in DFS expansion cycles has several drawbacks that are not apparent from the assessment of net power generation. These drawbacks, which are associated with the low temperatures and pressures obtained by the geofluid, are reduced or eliminated by using an SMT-25 system.

The first drawback of the DFS system is the need for frequent maintenance to clean the turbine and condenser surfaces. Geofluids almost invariably include dissolved solids. As the fluid is cooled, the saturation point of the water is reached and the excess solids are deposited on equipment surfaces. It is necessary to shut down the power cycle to open and clean the equipment. By using a closed loop cycle of clean ammonia-water mixture, SMT-25 removes any potential for deposition of mineral solids on the turbine or in the condenser. In addition, because the exit temperature of the geofluid is much higher in SMT-25 than in the condenser of the DFS, solids deposition through the heat exchangers is substantially reduced, which should result in greater availability of the power plant.

It should be noted that, even with very high quality geofluid (pure steam or almost pure steam) where a DFS system has superior theoretical efficiency compared to SMT-25, the greater availability of an SMT-25 cycle over a DFS means that over the course of an actual operating year the output from an SMT-25 system will be greater than the output from a DFS.

The second drawback of the DFS system is the very low pressure in the condenser required to obtain complete expansion of the vapor through the turbine. SMT-25 condenses the geofluid at elevated pressure, leading to a substantially reduced power requirement for the reinjection pumps. In some cases, it may be possible to use the well-field production pumps to provide enough pressure to reinject the geofluid with no further pumps, using only the exit pressure of the SMT-25 system. This would eliminate both the initial cost and the ongoing maintenance expense associated with the reinjection pumps.

The third drawback is the need to remove and dispose of incondensible gases. Geofluids usually contain impurities in the form of incondensible gases, typically including carbon dioxide, hydrogen sulfide, or sulfur oxides. The removal of these incondensibles, which are often highly corrosive, requires the installation of vacuum pumps or compressors. (The power requirements for these systems have not been deducted from the net power estimates shown in Table 1.) In an SMT-25 system, however, complete condensation of geofluid occurs at elevated pressures typically requiring no more than a 25 psi pressure drop from the system inlet. Consequently, a simple, and far less costly, separator can remove incondensibles. This removal occurs at a much higher pressure than for the DFS systems, resulting in lower cost and power requirements for reinjection equipment, if any is required. If the system pressure provided by the production pumps is adequate, there may be no need for separate reinjection equipment.

The fourth drawback of DFS systems is that reinjection of cold geothermal fluid typically results in gradual degradation of the geothermal well field. SMT-25 returns the geofluid at a higher average temperature than does the DFS system, which will reduce the rate of degradation.

An additional consideration is the system's complexity. The dual flash system requires either two turbines or a turbine with intermediate withdrawal and reintroduction of the steam. Dual flash systems with bottoming cycles require a third turbine along with the equipment and maintenance associated with the auxiliary power cycle. The SMT-25 system by itself has only a single turbine. The presence of liquid at the turbine exit provides the potential for impact of the liquid on the turbine blades, resulting in higher rates of erosion and increased maintenance costs. In addition, the presence of liquid through a turbine stage reduces the efficiency of the stage, typically by about 1 percentage point for each percentage increase in the average wetness through the stage. The SMT-25 turbine operates with a lower wetness at the turbine exit, which is results in lower maintenance requirements, reduced cost, and higher turbine efficiency.

Conclusion

Based on the material presented, the following general conclusions can be reached. At very high quality levels (80% and above), dual flash systems provide excellent use of the energy of the source. Nevertheless, the SMT-25 system provides comparable power output without the exposure of turbine internals to the geothermal brine, with only a single turbine instead of two, with greater availability, with higher reinjection temperature for the geothermal brine, and with lower parasitic losses for capturing and returning incondensable gases.

With lower quality geofluid, the Kalex systems provide significant improvements over either the DFS system or the DFS with a conventional ORC bottoming cycle. In terms of maximum energy recovery, the best choice is a DFS system for the vapor component of the geofluid and a parallel SMT-25 system for the liquid component. For a modest penalty in power output, the SMT-25 system used alone would eliminate the need for the DFS train altogether, including two turbines, a vacuum condenser, high pressure reinjection pumps, and equipment for capturing and returning incondensable gases.

References

Kalina, A. (2006, September) *New Thermodynamical Cycles and Power Systems for Geothermal Applications*. Paper presented at GRC-2006, San Diego, California. USA.