New Thermodynamic Cycles and Power Systems for Geothermal Applications

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A new generation of binary power systems designed to utilize available geothermal resources offers enhanced efficiency and reduced costs as compared with previously existing technology. To evaluate these new systems, it is necessary to consider the nature and effects of efficiency in geothermal power systems.

The Role of Efficiency in Geothermal Power:

The development of power systems utilizing heat from geothermal sources has, in recent years, been concentrated mostly upon the utilization of liquid dominated geothermal sources with moderate or low initial temperatures of geofluid. With such source, the geofluid cannot effectively be used directly as a working fluid, and instead binary power systems must be used.

The lower the temperatures of such resources, the more geofluid needs to be utilized by the power system in order to produce a given amount of power. As a result, the cost of geofluid production is increased. This also leads to an increase in the costs of the rest of the power system, needed to utilize the greater amount of geofluid. Since the quantity of geofluid required to produce a given amount of power can be reduced by using a more efficient power system, the lower the initial temperature of geofluid, the greater is the importance of the efficiency of the power system designed to utilize these resources.

The increase in the efficiency of a power system can be achieved only by the reduction of thermodynamic losses in the thermodynamic cycle used to convert thermal energy into mechanical power. Conceptually, all thermodynamic losses can be divided into three categories;

a) *Technological thermodynamic losses*; losses caused by inefficiency of even state-of-the-art components used to build a system. These reflect the limits of current technological ability to create these components.

b) *Economic thermodynamic losses*; losses caused by such things as temperature differences in heat exchangers or lower than best available efficiency in the components selected for the system. Such losses are deemed "economic" because they are based on suboptimal choices in equipment made to save money.

c) *Structural thermodynamic losses*; losses caused by the arrangement and innate structure of the system. Such losses are implicit in the design of the system, and cannot be lowered regardless of the quality of components chosen for the construction of the system. An example of *structural thermodynamic loss* can be seen in a Rankine cycle system where boiling occurs at a constant temperature, whereas the geofluid heat source releases heat at variable temperatures. Thus, even if the temperature difference at the pinch point were to be zero (an impossibility), there would still be a substantial thermodynamic loss.

Increasing the efficiency of a power system by reducing the *technological or economic thermodynamic losses*, tends to increase the capital cost of the system. A reduction of *technological thermodynamic losses* requires substantial research and development costs to develop the improved components. Reductions of *economic thermodynamic losses* increase cost due to the selection of the most expensive available components, as well as the inevitable higher cost of larger heat exchangers.

However, if an increase in efficiency comes from reduction of *structural thermodynamic losses*, i.e. by introducing a new system with lower innate structural thermodynamic losses, then it is possible to attain a simultaneous increase in efficiency without an increase in capital costs. Moreover, in such a case, the increase in efficiency, instead of leading to increased capital costs, actually leads to a reduction of capital costs since the production of a given unit of power output needs a lesser quantity of heat to be processed. Thus, not only is less geothermal resource required per given unit of output, but, since less heat needs to be processed, the overall surface of the required heat exchangers (which are a major expense) is reduced as well.

Currently Available Technology for Geothermal Power Applications

Till recently, the most commonly used binary power system for geothermal application has been Organic Rankine Cycle systems, or ORC systems. Initially, single pressure ORCs were used, but more recently double pressure ORCs, with increased efficiency, have been introduced.

A higher efficiency alternative to an ORC is a multi-component, variable composition working fluid cycle, also known as a Kalina cycle. The first generation of Kalina cycles applicable to geothermal heat sources consisted of two systems, designated KCS-11 and KCS-34. KCS-11 was designed for the higher end of the temperature range of geothermal resources. KCS-34 was designed for lower temperature geothermal resources.

Kalex LLC has developed three new Kalina cycle power systems based on the concept of the reduction of structural losses and designed for the utilization of moderate and low temperature (primarily geothermal) heat sources. These systems, designed to utilize low temperature heat sources, have been designated SG-2a, SG-2d and SG-4d.

System SG-2a is designed for the utilization of low temperature heat sources, with an initial temperature of up to 310° F. (155° C.) System SG-2d is designed for the utilization of a wide range of heat sources, with initial temperatures of geofluid up to 400° F. (205° C.) *(It should be noted that, at an initial temperature of geofluid above 310° F., system SG-2a's operation degenerates so as to be identical to SG-2d).* System SG-4d is designed to operate with a range of initial temperatures from 310° F. to 400° F. However SG-4d is both more efficient and more complex than system SG-2d. System SG-2a and SG-2d have been described in prior publications (ref. 1, 2). System SG-4d, which was designed more recently, is described in detail in its patent documentation (ref. 3). The scope of this article does not allow for the reprinting of the detailed description of these systems. However conceptual flow diagrams of these systems are presented in Figure 1 (SG-2a), Figure 2 (SG-2d) and Figure 3 (SG-4d).

These three systems are all based on the principle of a "cycle within a cycle." Each system is comprised of two cycles, each using the same turbine; an external cycle and an internal cycle. Heat rejection from the internal cycle is utilized as an additional heat source for the low temperature portion of the external cycle. An example of this sort of structure can be seen in system SG-4d (see Figure 3). In system SG-4d, the

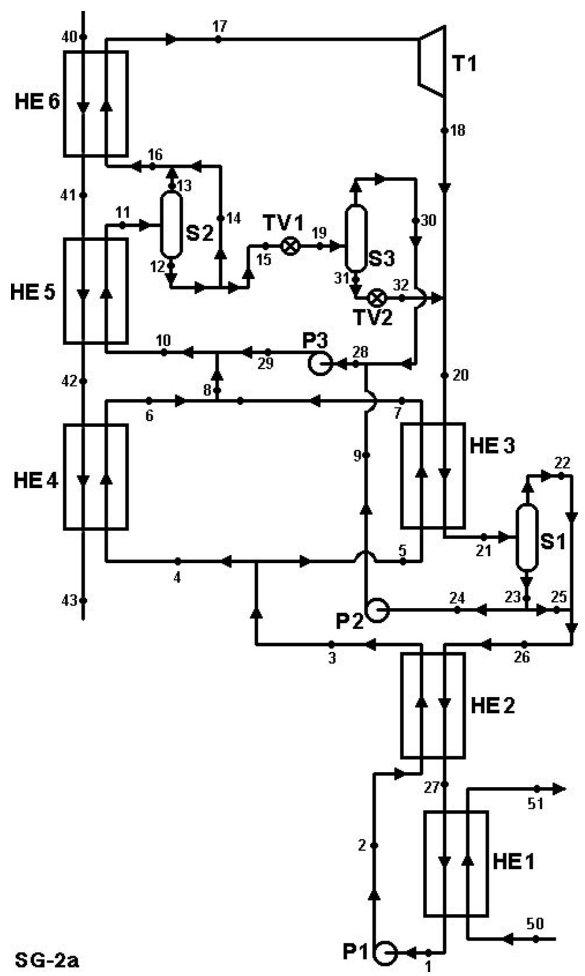

Figure 1. SG-2a.

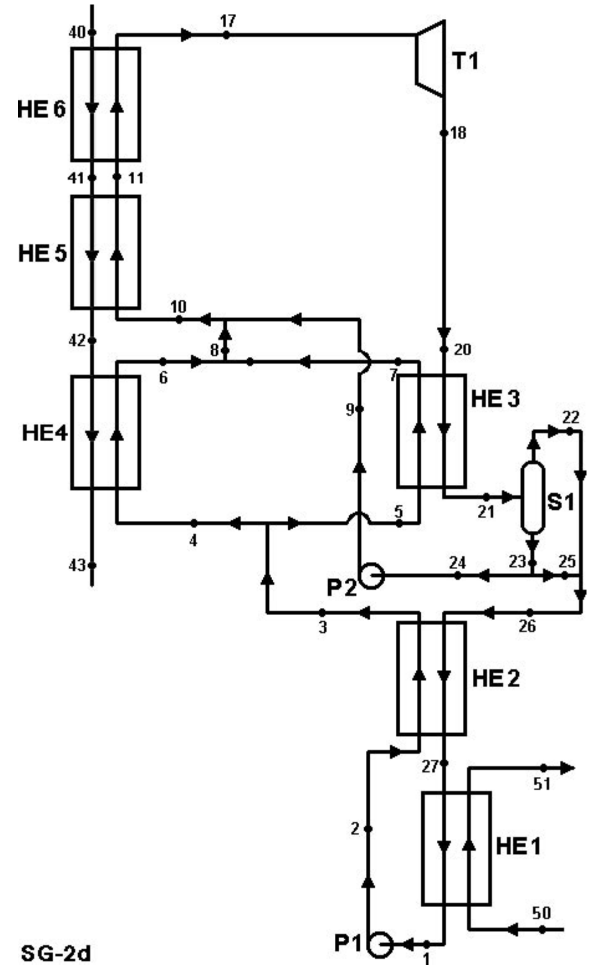

Figure 2. SG-2d.

working fluid of the internal cycle, which is a fully condensed liquid at point 24, is pumped by a recirculating pump, P2, and is then preheated in heat exchanger HE8. Thereafter the preheated working fluid, with parameters as at point 9, is mixed with partially vaporized working of the external cycle, having parameters as at point 14. As a result of this mixing, a substantial portion of the working fluid of the internal cycle is desorbed, i.e., is converted into vapor. Thereafter the mixed stream is fully vaporized, superheated and expanded in the turbine. After expansion, the mixed stream is partially condensed in a recuperative boiler / condenser HE3, releasing heat which is used for the vaporization of working fluid of the external cycle. Then the mixed working fluid is sent into a gravity separator, where the working fluid of the internal cycle is separated with parameters as at point 24. As a result of this structure, the flow rate of working fluid through the turbine is substantially higher than the flow rate of the working fluid through the condenser. This results in a substantial in the efficiency of the system.

One of the important advantages of the variable composition of the working fluid is that it allows the system to adapt to ambient temperature. This is a feature that cannot be replicated in systems with a non-variable working fluid, such as KCS-11 or any Rankine cycle. Any of the SG systems can be

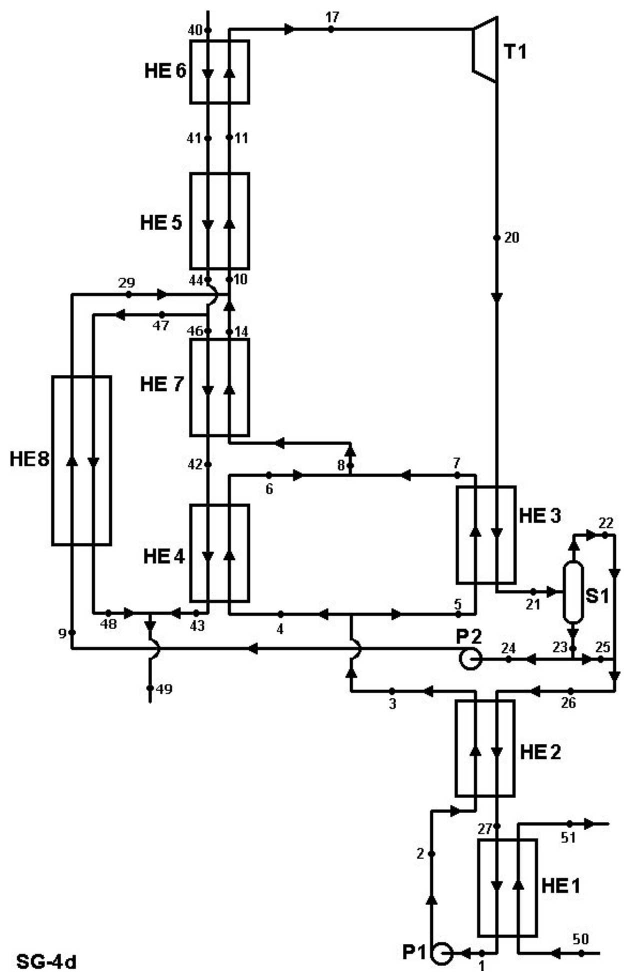

Figure 3. SG-4d.

adjusted to react to changes in ambient temperature by changing ratio of liquid to vapor when the basic working solution is reconstituted after leaving Separator 1 (S1); (for details, see any of the SG series flow diagrams.) This adjustment can be made automatically in any of the SG systems, without any interruption of normal operations of the system.

The SG systems, like previous Kalina cycle systems, are designed to operate with a mixture of water and ammonia, but if needed a mixture of organic compounds can be used as well.

It is instructive to compare the performances of different binary systems. There are two criteria of comparison; the thermal efficiency of the systems and their specific power output. The efficacy of any particular power system depends not only on its thermal efficiency but also on its ability to utilize the thermal energy of the stream of geofluid. Therefore, the most accurate means of evaluating the comparative performance of geothermal power systems is to compare their specific power output, i.e., the net power output per unit (by weight) of geofluid flow.

Specific power output takes into account all facets of the actual operational performance of a power system; for instance, it is possible for a given power system with a high specific power output to produce more power from a given heat source than another power system with a higher efficiency but a lower specific power output. Thus it is the specific power output, even more than thermal efficiency, that shows the clearest criteria of effectiveness for geothermal power systems. The specific power output depends on both the initial temperature of the geofluid, and on the final outlet temperature of the geofluid.

The outlet temperature of geofluid is usually limited by the mineralization of the geofluid, or by other considerations, (such as the further use of the geofluid for heating), which are extrinsic to the structure of the power system per se. This limited outlet temperature is hereafter referred to as “LOT.”

On the other hand, each power system has its own optimal outlet temperature of geofluid (hereafter, “OOT.”) At this optimal outlet temperature the specific power output reaches its maximum. If the actual outlet temperature is lower or higher than the OOT, the specific power output will be reduced. In cases where the LOT is lower than the OOT, the geofluid should still be cooled down only to the OOT; there is no advantage, and in fact there is a disadvantage, in cooling it further. On the other hand, where the LOT is higher than the OOT, there is no recourse but to cool the geofluid down only to the LOT, and accept the reduction in specific power output.

The performances of different binary power systems utilizing the same flow rate of geofluid (1,000,000 lb/hour) and subject to the same ambient conditions (air temperature of 59° F. and initial cooling water temperature of 51.7° F,) were calculated assuming the same set of technological constraints (turbine efficiency, pinch point temperature differences, etc.) The results are presented in Table 1, overleaf. A comparison of these system's thermal efficiencies is presented in Table 2, overleaf. These comparisons were calculated based on the NIST Reference Fluid Thermodynamic and Transport Properties Database.

As can be seen from this data, the SG series of systems outperform both the 1st generation Kalina cycle systems, and to an even greater degree, the ORC systems. It should be noted that

Table 1. Specific Output in Kilowatts per 1,000,000 pounds / hour flow rate.

IT	LOT	Kalex SG-4d	Kalex SG-2a	Kalex SG-2d	KCS-11	KCS-34	Double Pressure ORC	Single Pressure ORC
380 °F	168 °F	**11,417.52**	--	**11,324.12**	10,958.36	--	10,220.30	9,460.95
370 °F	168 °F	**10,702.04**	--	**10,632.34**	10,315.12	--	9,443.78	8,680.03
360 °F	168 °F	**10,000.45**	--	**9,957.68**	9,686.83	--	8,715.56	7,942.29
350 °F	168 °F	**9,313.88**	--	**9,300.92**	9,072.85	--	7,970.22	7,246.09
340 °F	168 °F	**8,656.80**	--	**8,648.81**	8,447.50	--	7,302.19	6,585.38
330 °F	164 °F	**8,040.20**	--	**8,002.73**	7,845.04	--	6,700.42	5,996.00
320 °F	160 °F	**7422.73**	--	**7,359.84**	7,244.47	--	6,107.82	5,415.42
310 °F	156 °F	--	**6,747.71**	**6,700.95**	6,647.06	--	5,547.15	4,856.33
300 °F	152 °F	--	**6,183.29**	**6,001.58**	5,885.47	--	5,022.59	4,333.26
290 °F	148 °F	--	**5,632.91**	**5,328.28**	5,024.31	--	4,506.75	3,844.53
280 °F	144 °F	--	**5,085.72**	**4,718.83**	4,146.18	4,546.38	4,030.00	3,387.56
270 °F	140 °F	--	**4,568.27**	**4,168.17**	3,264.37	4,124.12	--	2,963.94
260 °F	136 °F	--	**4,080.68**	**3,577.43**	2,392.32	3,713.95	--	2,570.74
250 °F	132 °F	--	**3,621.64**	**3,203.08**	--	3,319.11	--	--

Table 2. Thermal Efficiency Comparison Table.

IT	LOT	Kalex SG-4d	Kalex SG-2a	Kalex SG-2d	KCS-11	KCS-34	Double Pressure ORC	Single Pressure ORC
380 °F	168 °F	**18.31**	**--**	**18.13**	17.22	--	16.06	14.87
370 °F	168 °F	**17.80**	**--**	**17.82**	17.04	--	15.60	14.34
360 °F	168 °F	**17.45**	**--**	**17.52**	16.87	--	15.17	13.83
350 °F	168 °F	**17.13**	**--**	**17.20**	16.69	--	14.66	13.33
340 °F	168 °F	**16.88**	**--**	**16.86**	16.47	--	14.23	12.84
330 °F	164 °F	**16.27**	**--**	**16.19**	15.88	--	13.56	12.13
320 °F	160 °F	**15.62**	**--**	**15.48**	15.24	--	12.84	11.39
310 °F	156 °F	**--**	**14.86**	**14.66**	14.55	--	12.14	10.91
300 °F	152 °F	**--**	**14.10**	**13.68**	13.42	--	11.45	10.44
290 °F	148 °F	**--**	**13.41**	**12.68**	11.96	--	11.03	9.98
280 °F	144 °F	**--**	**12.66**	**11.74**	10.32	12.43	10.25	9.54
270 °F	140 °F	**--**	**11.91**	**10.86**	8.51	11.95	--	9.11
260 °F	136 °F	**--**	**11.16**	**10.48**	6.54	11.43	--	8.70
250 °F	132 °F	**--**	**10.42**	**9.88**	--	10.70	--	--

because it is not a variable composition working fluid system, and cannot adjust to changes in ambient temperature, KCS-11's actual average annual performance is substantially worse than the optimal performance at fixed ambient conditions, which given in the data presented here.

In summary, the new generation of Kalina cycle systems, using the cycle-within-a-cycle concept, offer superior efficiency and economic viability for the utilization of available geothermal resources. In particular, these systems offer the possibility of utilizing geothermal resources that have previously been unviable.

References

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Abbreviations in Tables

IT is Inlet Temperature.
LOT is Limited Outlet Temperature.
KCS-11 and **KCS-34** are examples of the 1st generation of Kalina cycle systems.
ORC is Organic Rankine Cycle.