RECENT DEVELOPMENT IN THE APPLICATION OF KALINA CYCLE FOR GEOTHERMAL PLANTS

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Key words: geothermal plants, Kalina cycle, thermodynamic efficiency

Abstract: It is the aim of this paper to review the basic characteristics of Kalina cycle and to describe its application in the special field of geothermal plants; comparisons are made both with conventional and non conventional applications in typical cases.

1. INTRODUCTION

The characteristics of Kalina cycle have been described in many papers .For the special case of geothermal applications see e.g. (Kalina *et al.* 1989,1994) and (Leibowitz *et al.* 1990). Basically the cycle, which represents a special simplified case of the more general Kalina cycle (Kalina, Tribus 1992), aims at a very large increase of the efficiency (while keeping costs basically at the same level of other geothermal applications) of the plant. Besides there are other fields (typically low enthalpy fields) where it is practically impossible to have reasonable efficiency without using this or similar type of applications. It should also be mentioned that the use of a water ammonia mixture allows the total flow of the fluid to remain within reasonable limits (typically in the 100 to 200 kj/(Kg/s) of working fluid) limiting the pumping parasitics , with beneficial effects on the total net efficiency Another interesting feature of Kalina cycle is the total absence of vacuum sections, which represents a typical problem for geothermal applications.

2. DESCRIPTION OF KALINA CYCLE

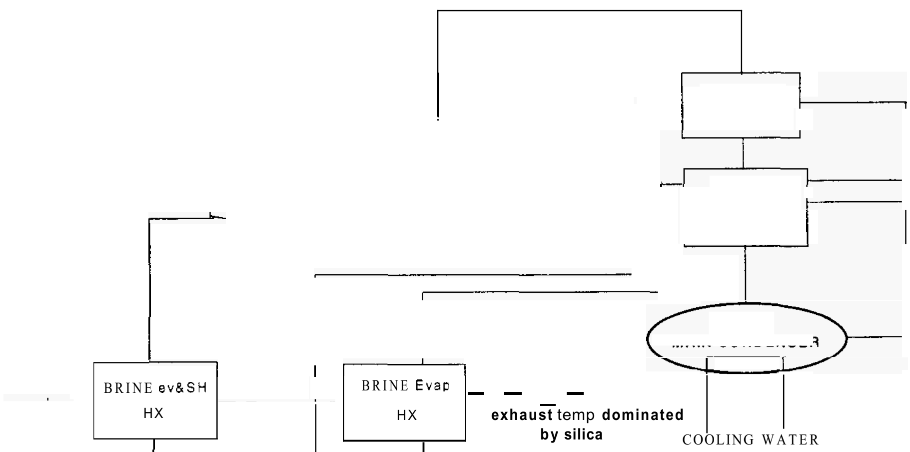
The fundamentals of the Kalina cycle have been already presented (Kalina *et al* 1989,1994) and they will not be repeated here.
A schematic representation of the Kalina cycle system 11 is shown in Fig. 1.

Basically the characteristics of the Kalina cycle system 11are as follows:

Ammonia fraction	0.80 to 0.90
Inlet pressure (bar)	25 to 40
Outlet pressure (bar)	7 to 10
Turbine outlet humidity (%)	1 to4

The main advantages are :

- the high exergetic efficiency (which is of course decisive in the case of low enthalpy fields), which is in turn tied to the characteristics of the good match in evaporation and effective recuperation
- the absence of vacuum sections
  the comparatively high power density in terms of kW of production per Kg/s of working fluid, which then minimizes the auxiliaries consumption. By contrast similar cycles have a power density less than 70 KW/(Kg/s) as opposed to the 100 to 200 in this case (the usual geothermal plants have of course a larger density, generally in the 500 KW/(Kg/s) range); obviously the auxiliary consumption is a function of the total working fluid flow rate and hence of the power density
- the limited temperature (in a geothermal plant never larger than about 230 "C, with maximum temperatures about 160 to 200 "C in most of the cases) makes the solution of some problems (e.g. the tightness, which is important for this type of fluids, as well for other similar plants) quite easy (see Kalina and Leibowitz, 1994).



BASIC KALINA CYCLE FOR GEOTHERMAL APPLICATIONS
Figure 1

- the turbine, which is employed , is very similar to a conventional **IP** turbine, possibly with three to four stages while not of a 'costumized ' design the turbine is able to benefit of the overall research and development in the steam turbine field, to achieve a very high efficiency
- the critical item is generally the surface of the heat exchangers HX (in particular the first brine-mixture HX); in this connection it should also be mentioned that the LMTD value must be calculated taking into account the peculiarities of the temperature profile in a binary mixture, typical profile is shown in Fig. 2

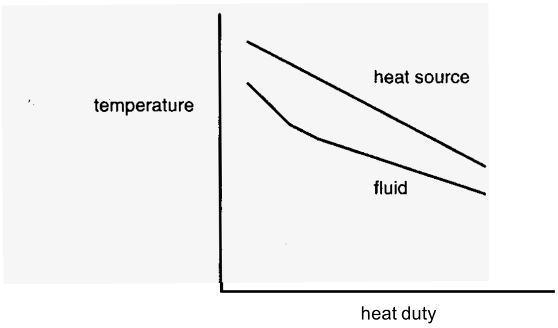


Figure 2

At any given time the composition of KCS 11 is always constant . The composition may vary from hot day to cold day operation eg winter vs summer

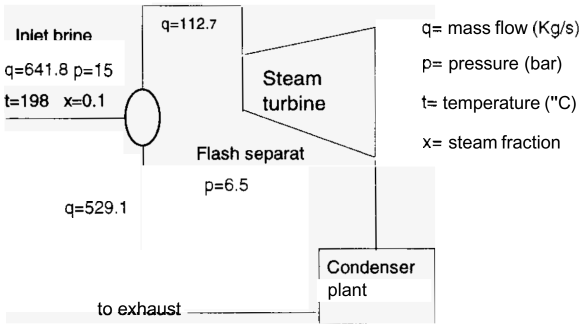
Steam inlet pressure	6.5 bar
Steam inlet temperature	saturated
NCG content (weight)	1.5 %
Air wet bulb temperature	20 °C

The typical data for GRAPE plants, in good agreement with actual tests on the present generation of plants, are as follows (Lazzeri *et al.* 1994, 1995):

Table 3.2
GRAPE 55
Reference consumption with steam ejectors

Turbine steam consumption	1105.66 Kg/s
Ejector steam consumption	5.06 Kg/s
Steam rate (turbine)	6.916 Kg/kWwhr
Steam rate (total)	7.247 Kg/KWwhr

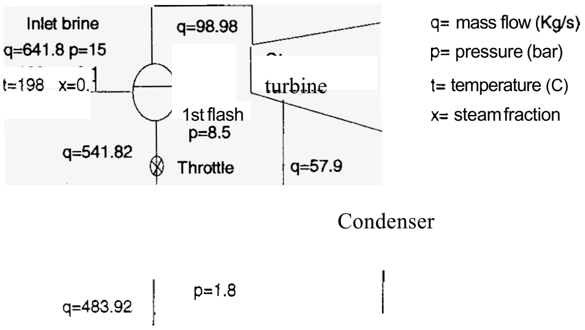
The typical scheme for a geothermal plant with GRAPE technology, in its simple configuration (i.e. without second flash.), is shown in Fig. 3.



GRAPE 55 (simple configuration)

Figure 3

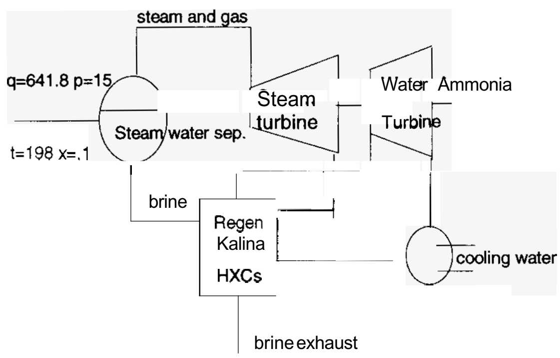
A possible increase of efficiency may be obtained by means of a second flash (silica precipitation being generally the main problem for this type of application); the corresponding schema is shown in Fig. 4.



GRAPE 55 configuration with double flash

Figure 4

The corresponding scheme for the applicable hybrid Kalina cycle referred to as system KCS 17 , is shown in Fig. 5; note that the discharge temperature for the brine is somewhat lower in this case than in the double flash case, due to the fact that no concentration of the silica is present in this case, as no steam separation is performed. In Fig. 5 the actual regenerative portion of the Kalina cycle is of the same type as encountered in section 2.



Schematics of a hybrid Kalina cycle
Figure 5

The comparison of power for this case is shown in the following table:

Table 3.3
GRAPE - Kalina comparison in terms of power at constant inlet conditions (Gross power)

Conventional GRAPE (Mw)	55.0
Double Flash GRAPE (Mw)	73.2
Kalina Hybrid (Mw)	86.7

The basic data in terms of global efficiency and exergetic efficiency are shown in the following table 3.4; the basic data are taken from Fig. 3 in terms of reference temperatures.
The theoretical efficiency is based on brine inlet temperature and ambient temperature.
The computation of the exergy and hence of the corresponding 2nd law efficiency is as stipulated in appendix **A,** where the details are also presented and which may be responsible for some apparent peculiarity in the data . It should also be noted that due to the particular definition of the theoretical efficiency the terms are heterogeneous

Table 3.4
Efficiency of the Kalina cycle hybrid solution

Theoretical efficiency (Carnot)	136.52 %
— Actual efficiencv	114.78%
— 2nd law efficiency	60.7 %

It should also be noted that a more complex Kalina cycle configuration (basically using the fully regenerative bottoming cycle with ammonia fraction change) would yield a power in excess of 90 Mw.On the other hand most of the auxiliary consumption in GRAPE comes from the vacuum system ; different schemes have been examined by Lazzeri *et al.* (1994), yielding an equivalent energetic value between 500 and 1500 kW (depending on the solution, a compressor being generally the most efficient , although cost effective only for fields with very large proportions of NCG). In the case of Kalina cycle the main parasitic loss is generally the pumping power of the liquid. The estimated pumping power is about 1.5 Mw (i.e. not too far from the classical GRAPE value); However other auxiliaries should also be considered (say the cooling system etc.) A discussion of the problem is made by Kalina and Leibowitz (1992) for a similar plant; the total auxiliaries consumption can be estimated in 4 to 5 Mw (quite lesser than similar plants with organic fluids where the power for the auxiliaries is about double).

4. A low enthalpy field application

From the energetic point of view the low enthalpy field is certainly the most favorable application of the Kalina technology for geothermal fields ; the case in table 4.1 (actually present in a resource in central Italy) is studied in some detail.

Table 4.1
Data for the low enthalpy field

Mass flow	200 t/hr
Pressure	13 bar
Temperature	180 °C
Reinjection temperature	70 °C
Dry bulb temperature	25 °C to 15 °C
Cooling	Air condenser

The type of cycle is very similar to the one in figure 1.

The basic characteristics of the cycle, as well as the reference power, are presented in table 4.2.

Table 4.2
Reference data for the cycle
(with dry bulb temperature 25 "C)

I/O pressures (bar)	24.1 19.58
Ammonia fraction	0.8315
Mass flow (Kg/s)	25.96
Gross power (Mw)	3.6
Auxiliaries (Mw)	0.450

In analyzing the results the surface requirements of the heat exchangers is very important.
Consequently the correlation between power and the heat exchanger surface is studied in some detail; typical results are presented in Fig. 6 in terms of net power **Vs** the surface of the first brine ammonia HEX, which is generally the most critical. It accounts for the final evaporative and all superheat duty It should also be mentioned that the HEX represent a large portion of the total cost, hence the importance in the analysis.

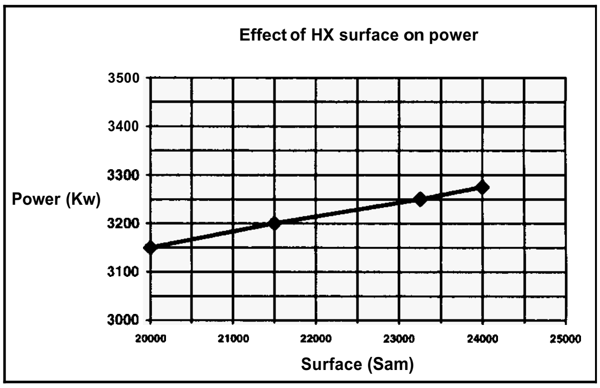


Figure 6

If the temperature of air drops to 15 °C then the power is characterized as shown in the following table:

Table 4.3
Gross power at 15°C dry bulb temperature

Gross power (KW)	3850
Auxiliaries (KW	1425

Again the basic efficiency values are shown in table 4.5.

Carnot efficiency(2nd law)	36.42 %
Actual efficiency	10.04%
2nd law efficiency	47.98%

5. CONCLUSIONS

From the precedent analyses the following conclusion can be drawn:

a) the increase in power (or efficiency) in the plant is indeed very large as compared to the state of the art technology such as the one present in GRAPE technology,
b) In particular the second law efficiency as shown in table **3.4** appears to be quite remarkable,
c) in the case of the low enthalpy field too, the data presented in table **4,5** appears to be quite reasonable and acceptable.

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Appendix A: Exergy calculations

The following nomenclature is used :
Th = source temperature
Ts = sinktemperature
x = steam fraction in the brain
Dh = vaporization heat at the source pressure
q = brine mass flow
cp = specific heat of the brine
Q = total heat input
E = total exergy input
W = mechanical work
et = theoretical efficiency
e1 = actual efficiency
e2 = 2nd law efficiency

$$Q = [cp * (Th - Ts) + x * Dh] * q$$
$$E = Q - cp * Ts * Ln(Th / Ts) - x * Dh * Ts / Th$$
$$e = 1 - Ts / Th$$
$$e1 = W / Q$$
$$e2 = W / E$$

Please note that the given formulation does not take into account the reinjection temperature of the brine, as it is sometimes done ; in the latter case the 2nd law efficiency is obviously slightly higher. Note also that the definition of the theoretical efficiency is based on Carnot formulation only and then does not have **a** precise physical meaning beyond the definition itself