THE COMMERCIAL DEVELOPMENT OF THE KALINA CYCLE AND A 30 MEGAWATT DESIGN FOR WAIRAKEI

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SUMMARY - A major development in the field of thermodynamics in recent years is the Kalina cycle which uses an adjustable proportion working fluid mixture. Following its first successful implementation in a demonstration plant in the United States, three new power stations are being built or proposed for building in 1993-94. This promises to he the preferred option for geothermal power generation throughout the next century, because it can produce the highest power output per unit of heat input in comparison with alternative available power generating systems. A 30 megawatt design is proposed to utilise waste hot water discharged from the Wairakei steamfield.

1 Introduction

The Kalina Cycle has Been developed in the United States by Dr Kalina to improve the efficiency of the Rankine Cycle in the conversion of heat into work. It is particularly superior to conventional Rankine cycles when used with low grade heat sources, where the small temperature difference between the heat source and the heat sink results in very low Rankine cycle efficiency.

This paper describes the current status of development of Kalina cycle technology, its commercial development in the United States, and reviews the technical feasibility, likely performance and cost of applying the Kalina cycle at Wairakei to utilise waste geothermal fluid.

The theory of the Kalina cycle is given in Section 2, and the development of the world's first operating Kalina power station is described in Section 3. For commercial development, the Kalina cycle has been simplified, but without losing any of its innovative features. A version for geothermal use is described in Section 4 with a proposed design to make use of the waste separated geothermal water at Wairakei, amounting to 3500 tonnes per hour at 130°C. Commissioning, operation and maintenance is covered, and capital costs are discussed.

2 The Kalina Cycle Theory

The Kdina cycle was conceived by Dr Alex Kalina in 1980 for use in waste heat recovery and combined cycle power generation systems. The ideas were developed from the realisation that variable composition is an important aspect of a regenerative ammonia refrigeration cycle, and that a similar principle might be applied to improve the efficiency of the Rankine cycle in the conversion of heat into work. The development is documented in papers by Kalina and Tribus, reference [1].

In the Kalina cycle, a mixture of 70% ammonia and 30% water is used in a boiler to produce superheated vapour. The ammonia begins to boil off first, having the lower boiling point. As the ammonia boils off, the concentration of ammonia in the remaining mixture decreases, and the mixture's hoiling point increases. This results in a better match in the temperature profiles of the heat source and the hoiling fluid, and heat is transferred more effectively than it does in the conventional steam Rankine cycle. More of the available heat is used for vapour production, which leads to more power output from the turbine generator.

The 70% ammonia-water solution cannot be condensed at normal cooling water temperatures. Dr Kalina solved the problem by first cooling the gases in a recuperative heat exchanger and mixing the cooled vapour with a weak 37% ammonia-water mixture, increasing the concentration to 42% ammonia. Heat is given off when the strong ammonia solution is absorbed by the weak solution, and this heat can be used to preheat the working fluid entering the boiler. The following description is taken from a paper by H.M.Leibowitz and N.Zervos, [2], who developed the demonstration Kalina plant at Canoga Park, California. It can best be understood with reference to the schematic diagram of the plant, which is included here in Figure 1 by permission of Exergy Inc.

The heated weak mixture enters a flash tank where a distillation (separation) process occurs. Enriched ammonia vapour (97% ammonia) is produced, leaving behind a lean liquid of 37% ammonia concentration. The enriched vapour is sent to the high pressure condenser, partially condensed and then mixed with some of the 42% liquid to re-establish the 70% working solution. The 37% lean liquid at the bottom of the flash tank is used to dilute the 70% solution as described earlier. The 70% working solution is then completely condensed in the high pressure condenser and pumped to the boiler via the main feed pump.

The extra work output of the process results from the overexpansion of the vapour through the turbine by the difference in pressure between the high and low pressure condenser. The pressure difference is about 0.39 MPa (56 psi), and results in a 10-25% improvement over the Rankine steam cycle.

The process described above is unique to the Kalina cycle. No other binary cycle uses a combination of fluids which give off heat on condensation at a higher temperature than that of the boiler feed, allowing the heat to be reused. Combining this with the close

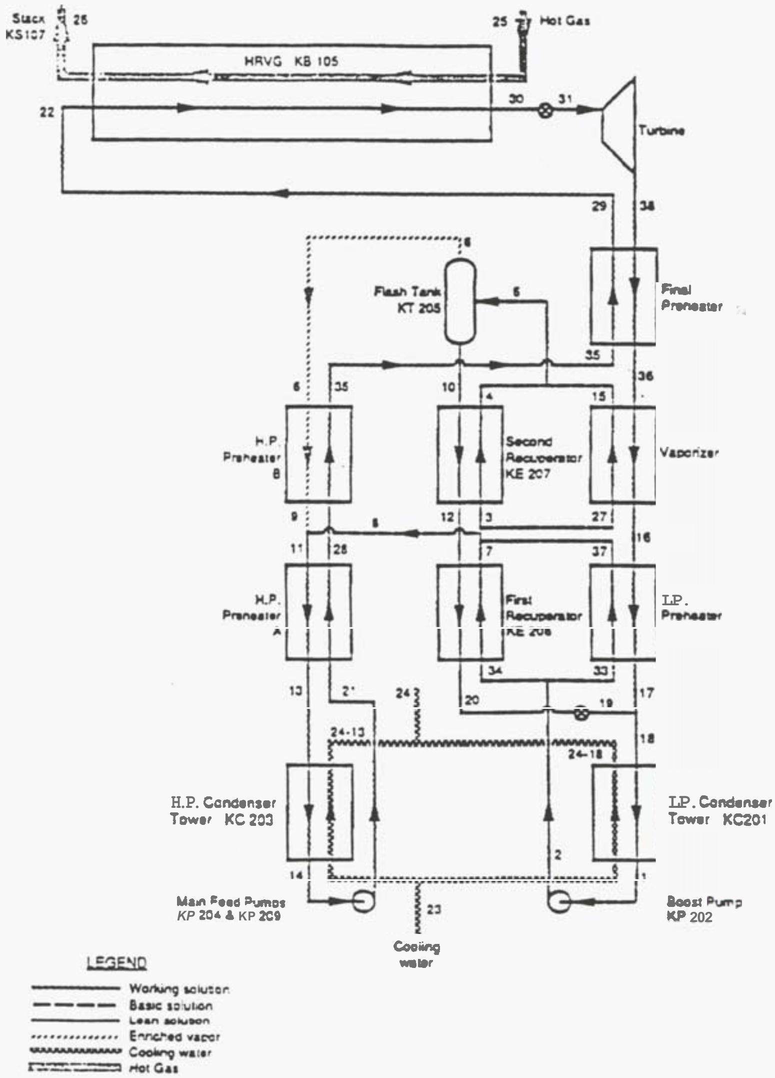

FIGURE 1 Flow Diagram of Canoga Park Kalina Plant

matching of the boiling temperature curve with the temperature curve of the heating medium, and the use of two condensers allowing overexpansion through the turbine, results in a cycle which has the highest possible efficiency, and which has the closest approach to the theoretical Carnot efficiency.

3 The Development of Kalina Technology

In 1986 Dr Kalina and others formed a company, now known as Exergy Inc, to develop the technology commercially. Negotiations were initiated with Rockwell international for the purpose of building the world's first Kalina power station at their rocket testing site at Canoga Park, near Los Angela, California. Detailed drawings and equipment specifications were completed during 1988 and 1989, and contracts for the construction were finalised in October 1990. Details of the design are given in a paper by Kalina and Leibowitz (1988), [3].

The power station finally began operating in December 1991. Sustained operation at that time was not possible because of the lack of a heat source. The power station uses waste heat from a gas-fired research facility on the Rockwell site, and the facility was closed down for maintenance from January to April 1992. Since that time the plant has operated for about 4000 hours, and no operating problems have come to light so far.

The success of the Canoga Park project was expected, and before commissioning was complete, the designs of further Kalina power plants were started. These were primarily for gas turbine bottoming cycles and geothermal power stations. The latter has been completed for plants ranging in size from 10 MW to 30 MW.

Exergy Inc. has concentrated on the commercialisation of bottoming cycles and geothermal power stations prior to coal fired plants. The coal plant design is more complex than the others, primarily due to its high heat acquisition temperature. It calls for substantially more regenerative boilers and more reheat than either the bottoming cycle or geothermal design requires. Research is continuing into the design of a retrofit system for existing coal and gas fired power stations.

Meanwhile the existing designs are suitable for New Zealand conditions, especially the 30MW design given in this paper, because the geothermal fluid temperature is relatively low.

Currently, negotiations are underway between Exergy and leading power equipment suppliers, and architectural and engineering companies, for licensing of the technology for geothermal applications. Marketing of the Kalina technology in Australia and New Zealand is being handled by Cape Range Ltd. in Perth, Australia.

3.1 Application to New Zealand

The Kalina Cycle is well suited to New Zealand because it makes more effective use of this country's geothermal resources, i.e., more kilowatts of power are produced per kilogram of brine pumped. Also, operating in a closed cycle reduces the amount of CO_2 or H_2S emissions compared to conventional flash technology. The New Zealand Energy Supply and Demand Forecast, 1991 [4], from the Energy Foundation shows a total geothermal resource of 100PJ. The Kalina cycle increases the energy conversion efficiency of geothermal electricity generating plant by up to 40%. This effectively increases the size of the country's geothermal resource to 140PJ, with a corresponding reduction of the amount of CO_2 and H_2S emitted, or waste heat discharged into the environment. The cycle works with low temperatures and pressures and it is ideal for generating power from low temperature sources and where the resource is mainly hot water. The waste hot water resource at Wairakei is an ideal source of heat for a Kalina power station. A relatively small plant can be built to obtain valuahle operating experience before large scale plants are needed at the beginning of the next century. A 30 MW design is presented here, together with budgetary costs, to 'show what is possible. It is hoped that ECNZ or other power developers will give it serious attention.

4 A Wairakei Geothermal Project

The Kaiina cycle has been under investigation by the author for a power station at Wairakei since 1990. At that time two versions with outputs of 7.4 MW and 9.4 MW were designed to use 1000 Toms per hour of the fluid, and the first discharged the fluid at a temperature of 85°C. The second discharged the fluid at 69°C. The reason for the two designs was because of uncertainty of the lowest allowable discharge temperature of the fluid before dissolved solids begin to precipitate out. There is confidence that there will be no precipitation in the reinjection well if the temperature is kept above 85°C, but it is also possible that the fluid temperature can safely he lowered to 69°C without precipitation occurring.

However since 1990, research into the precipitation of silica has been carried out, and a process is reported to be available which will enable the silica to be recovered from the geothermal fluid, without any loss of temperature of the fluid [5]. If this process can be acquired for use at Wairakei, then the higher output version of the Kalina cycle can be used with confidence. It may also be possible to obtain a further increase in output by taking the fluid temperature down to say 30°C.

The present design to produce 30 MW, uses the full amount of 3500 Tonnes per hour of waste water at 130°C, and it has been made possible by improvements and simplification of the Kalina design for geothermal use, since the completion of the Canoga Park project.

4.1 The Simplified Kdina Cycle

The original Kalina cycle versions of 7.4 MW and 9.4 MW used 1000 Tonnes per hour of the Wairakei waste geothermal fluid. The new 30 MW design uses the same temperatures and pressures throughout the cycle, and the sizes of all the vessels and tanks are approximately 3.5 times the originals.

A schematic diagram of the power plant is given in Figure 2. This differs from the Canoga Park diagram because a plant designed for use with low temperature geothermal fluid can be simplified considerably. This version of the Kalina cycle is described in a paper by Kdina and Leihowitz, (1989), [6]. The number of heat exchangers has been reduced to five, but in practice they can be stacked one upon the other in two columns. The plant uses a single stage conventional steam turbine. This is fitted with a mechanical face seal instead of the labyrinth type generally used in a steam turbine. The mechanical face seal is required to achieve the zero leakage specification for the ammonia working fluid.

The geothermal fluid enters the superheater HE-5 at 1, and then to the evaporator HE-3 at 3. At the outlet of HE-3, the fluid has been cooled to its minimum temperature of 76°C, and is discharged to the reinjection well at point 4.

The ammonia-water working fluid leaving the condenser HE-1 is pumped to the evaporator pressure of 2.94 MPa, and passes through the preheater HE-2 and evaporator HE-3. The working fluid is superheated to 124°C at point 30, is expanded through the turbine down to 0.77 MPa at point 36, having a temperature of 101"C (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.

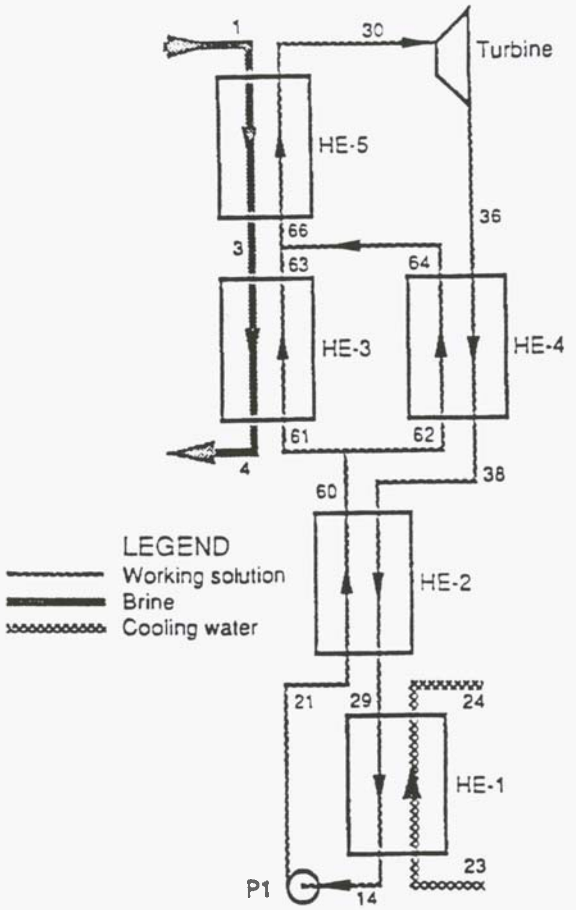

FIGURE 2 Flow Diagram for Wairakei Kalina Plant

4.2 Performance

With an input flowrate of 3500 tonnes per hour of geothermal fluid at 130°C, and a cooling water temperature of 12.7°C, the turhine net output is 30.0 MW. The thermodynamic (Second Law) efficiency is 58.9%. The overall thermal efficiency (First Law) is 13.6%. A summary of the performance is given in Table 2.

TABLE 2 Kalina Plant Performance Summary

Geothermal Fluid Weight Flow	3500 t/hr
Working Fluid Weight Flow at 25	700 t/hr
Discharge Temperature of Brine	76°C
Heat Input from Brine	1049 kJ/kg
Turbine Net Output	30.0 MW
Total Pump Power	3.74 MW
Net Power Output	26.26 MW
Net Thermal Efficiency	13.41%
Second Law Efficiency	58.88%
Specific Brine Consumption	135.3 kg/Kw

4.3 Kalina Plant Capital Cost

Capital costs for U.S. installations have been estimated by Calpine Corporation, a leading U.S. geothermal developer, and reported by Exergy, [7]. These costs were compared to that of a leading binary design which uses a hydrocarhon working fluid in one megawatt modules. The Kalina plant's installed cost per kilowatt was 40 percent lower than the hydrocarhon binary design. The main reasons for the Kaiina plant's cost advantage are given below:

1. Better thermodynamic match between the working fluid and brine heat source.

2. The Kalina plant's highly recuperative nature. Almost 40 percent of the heat transferred to the working fluid is done via the heat in the turbine exhaust.

3. Central station versus modular design.
   - higher turbine efficiency
   - economy of scale

4. Less expensive turhine. An ammonia/steam turhine uses the same design as a pure steam turhine. These are much more readily available than hydrocarbon turbines.

5. Heat exchangers are less expensive for ammonia/water. Ammonia/water heat transfer rates are higher than for hydrocarbons.

4.4 Operations and Maintenance

A Kalina cycle power station is only slightly more complex than a conventional steam power station, and its construction follows conventional lines. Ammonia is toxic and the vapour is corrosive, so particular care is taken to ensure complete sealing of the system. Special seals are fitted to all moving parts in contact with the ammonia, such as pumps and the turhine generator shaft. The seals must not include any copper or copper based alloys such as monel metal.

The assembled heat exchangers, pipework and pressure vessels are hydro tested and chemically cleaned and flushed. The Canoga Park plant in California was hot tested with steam only initially to confirm the operability and leak-free status of the process lines and the heat acquisition system. These check-outs were much easier to perform without ammonia present.

Air is purged from the system to prevent corrosion of the carbon steel piping and heat exchangers. The system is rinsed with deionised and deaerated water, which is circulated through absorbtion filters until 1 umho quality water is produced. Heat is supplied by the geothermal fluid feed until all the vessels reach about 0.172 MPa (25 psig), when the vents are opened to purge all trapped air. On cooling, the system is back-filled with nitrogen to prevent a vacuum.

The anhydrous ammonia supply at a pressure of 0.55 MPa is used to purge the nitrogen. The purged nitrogen and ammonia vapour is vented to a sparge tank, and following the purge, further ammonia vapour is added to the working fluid until the required ammonia/water composition is reached.

Temperatures and pressures at the inputs and outputs of all heat exchangers are continuously monitored to confirm the correct operating conditions. Composition of the working fluid at the turbine inlet and the temperature at the outlets of Heat Exchangers HE-3 and HE-4, points 63 and 64, are the key parameters for optimising the cycle. The complete solution of the cycle requires that the First and Second Laws of Thermodynamics are satisfied at every point. This requires careful attention to the presence of pinch points at every place in the cycle where there is a transition between liquid-vapour mixture and pure vapour or pure liquid. The flow rate is the independent variable, and the system is monitored by observing property values at selected locations.

The flow rates are controlled by matching the measured properties at various points in the cycle with calculated properties. A computer control system allows completely automatic control. The transient response is difficult to analyze, but results from Canoga Park do not show any particular problems with load changing.

Maintenance is a concern with any new design of power plant, and the Kalina cycle has attracted criticism that it will be difficult to maintain. These fears have so far been unfounded at the Canoga Park plant. Special precautions have been taken to prevent any expected maintenance problems, as follows:

a) Corrosion:

Ammonia reacts with copper based alloys so the components must be fabricated from iron and steel. At high temperatures, stainless steel must be used, but the operating temperatures of the design for Wairakei are not high enough to warrant the use of stainless steel in any part of the plant. Stainless steel may be used for certain vessels and tanks to eliminate the need for painting etc, but high temperature corrosion is not expected.

b) Nitriding:

Ammonia also reacts with steel under special circumstances. The nitriding process, in which steel is exposed to dry ammonia gas at temperatures of 500°C to 540°C, is used to give the steel a hard, wear resistant coating. However for nitriding to occur, the flow rate of ammonia must he kept very low to allow sufficient residence time for the chemical reaction to take place. The process is self limiting, and any water vapour present tends to inhibit the reaction. At the Canoga park plant, a special test section has been incorporated with coupons of different steel alloys to test for nitriding. These can be removed periodically for examination. After 4000 hours of operation, there is no evidence of nitriding occurring.

c) Decomposition:

At sufficiently high temperature, ammonia will decompose. The rate of decomposition during operation affects the need for makeup and the need for removal of noncondensible gases which are the products of decomposition. The presence of water vapour tends to suppress the reaction and, as with nitriding, reaction rate is crucial. Samples of vapour taken from the condenser at Canoga Park have shown negligible free hydrogen.

d) Ammonia Safety:

Ammonia is toxic but its presence is easily detected by smell. It is easily absorbed in water, and substantial experience with large refrigeration systems exists. With proper precautions this does not appear to be a significant limitation.

Safety requirements for the storage of anhydrous ammonia are dealt with by the Inspector of Explosives, Occupational Health and Safety, and are covered by sections 92 to 103 of the Dangerous Goods (Class 2 - Gases) Regulations 1980.

5 A Comparison with Other Technologies

The design of Kalina plant presented in this report has been compared with four other competitive binary plants. All the plants are designed to use 3500 tonnes per hour of the waste water at 130°C. The higher power output Kalina plant has been designed to cool the waste water to 76°C, but otherwise the input conditions for all the plants are the same.

The results are given in Table 4.

The Kalina plant makes much more use of the available heat than the competitive plants. This is because heat is recovered by the recuperator before the working fluid passes to the condenser. This also results in smaller condensers and less cooling water per megawatt generated.

TABLE 4 Binary Plant Comparisons

Plant	Source Temp°C	Discharge Temp°C	Flowrate tonnes/hr	Cooling Water Flow T_{in} T_{out} t/hr	Power MWe
(1)	130	85	3325	evaporative	16.8
(2)	130	85	3360	11515 17 29	14.5
(3)	130	91	3570	12740 15 25	14.7
(4)	130	98	4620	air cooled	14.0
(5) Kalina	130	76	3500	18224 13 22	30.0

6 Conclusions

The Wairakei site is an ideal site for the building of the first Kalina power station in New Zealand. The energy source is already available for exploitation. Resource consents and other formalities can he completed with minimum delays compared with totally new developments. The site requires the minimum of preparation, good road access and grid connection are already available.

Although alternative schemes for use of the geothermal waste may he cheaper, no other scheme offers such a high power output as the Kdina cycle. The Kalina cycle is going to he the preferred option for thermal power generation throughout the next century, and early experience with the technology would he a great advantage to any power developer at the present time to develop a lead in cheap power generation. There is the opportunity at Wairakei for an entry level scheme which is not too expensive, and an appreciable amount of power will he generated from a resource which is already there.

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