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ADVANCES IN BINARY ORGANIC RANKINE CYCLE TECHNOLOGY

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ABSTRACT

The Organic Rankine Cycle (ORC) is used to produce energy from low enthalpy resources. This technology is applicable to geothermal power plants where the ORC may be more efficient and cost effective than a steam cycle for low temperature sources. The binary cycle has been used when the flashing of brine to produce steam is not practical. However, the thermal efficiency realized from low temperature heat sources is inherently low, so that the installed equipment costs per kW capacity are relatively high. Given the trend to lower energy capital costs, manufacturers are faced with the challenge to improve efficiency and lower power equipment costs. Ormat has made some significant improvements to the binary cycle which have led to improved economics and the ability to achieve higher power plant outputs from a given resource and have helped broaden the use of binary cycles from traditional low enthalpy sources to higher enthalpy sources. The advances focus primarily on improved component efficiencies and on better utilization of the heat source.

INTRODUCTION

For low enthalpy resources, the binary Organic Rankine Cycle is often utilized to convert the resource heat to electrical power. The hot brine or geothermal steam is used as the heating source for a secondary (organic) fluid, which is the working fluid of the Rankine cycle. Ormat Energy Converters (OEC) employ such a cycle and a typical schematic is shown as Figure 1. Geothermal brine passes through a heat exchanger to vaporize the organic fluid and is then injected back into the geothermal reservoir. The organic vapor produced in the vaporizer expands through a turbine, which is coupled to a generator. The exhaust vapor from the turbine is subsequently condensed in either a water-cooled or air-cooled condenser and is then returned to the vaporizer by the motive fluid pump to complete the cycle.

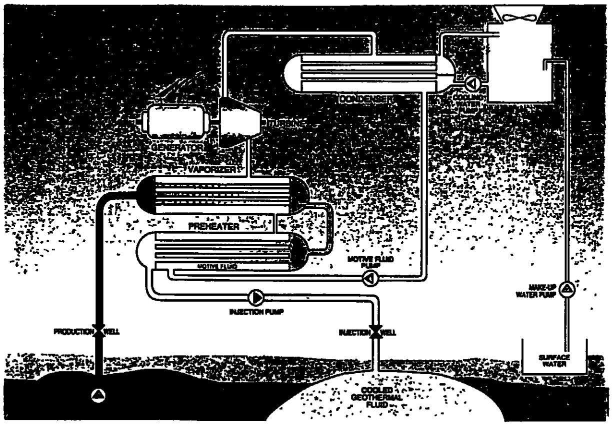

Figure 1. Water Cooled Binary Geothermal Power Plant

In the early 80's the cascade concept was developed [1] to increase the power output from a given brine resource by increasing the thermal cycle efficiency. Instead of arranging the OEC units in parallel, the units are cascaded at various levels of brine temperature. Essentially this cycle extracts more heat from the brine source by cooling the brine to a lower optimum temperature than obtained for a non-cascaded (parallel) arrangement. At the Ormesa I power plant in Southern California, a three level arrangement was employed resulting in increased efficiency, or power output gain, of about 10% over that achievable with a parallel arrangement of the OEC units. The brine utilization rate of this 330°F resource was 168 lbs/kW-hr.

In the mid 80's Ormat introduced the Integrated Two Level Unit (ITLU) as a means of lowering the complexity and cost of the plant. Initially Ormesa IH and several other projects (e.g. Stillwater and Soda Lake in Nevada) were designed with ITLU'S which eliminated the need for long brine headers and numerous valves which exist in the OR-I design.

In all of the above arrangements, a modular approach was employed so that high plant capacity factors of 98% and above were achievable. As the binary cycle has gained greater acceptance as reliable power, advancements have been pursued to further increase brine utilization. Furthermore, the technology has also been expanded to higher enthalpy sources including geothermal two-phase and steam resources.

BINARY CYCLE FOR MODERATE ENTHALPY RESOURCES

For moderate enthalpy two phase resources where the steam quality is between 10 to 30%, the organic Rankine cycle is an efficient and cost effective means of producing power. Furthermore, when the geothermal fluid has a high non-condensable gas (NCG) content, the ORC can obtain even higher efficiency than a flash steam cycle with condensing steam turbines.

A typical example of this technology is the recently commissioned power plant in the Azores Islands consisting of two 3.0 MW OEC units. A schematic diagram of the cycle in which the total two-phase flow is utilized as the heat source is shown in Figure 2. Separated steam containing NCG is introduced in the vaporizer heat exchanger to vaporize the organic fluid. The geothermal condensate at the vaporizer exit is then mixed with the hot separated brine to provide the preheating medium of the organic fluid.

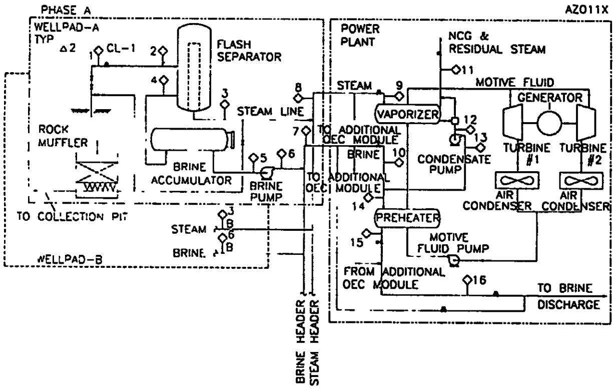

Figure 2. Two-Phase Flow Diagram - Azores Plant

In the ideal case the steam latent heat would exactly equal the heat of vaporization of the organic fluid. This "perfect" match of heat transfer between the geothermal fluid and the secondary organic fluid represents the maximum thermodynamic efficiency for this cycle.

In the case of the Azores resource, the ideal thermodynamic match was not possible due primarily to a limit on the resource exit temperature which was imposed to avoid potential silica precipitation. In order to improve the utilization of the resource two solutions were developed: (a) brine dilution with the condensate and (b) recuperation of internal heat otherwise lost to the cooling sink (i.e. air).

Since the onset of silica precipitation is related to its concentration in the brine, dilution of the brine with the condensate effectively lowers the precipitation temperature at which silica crystallizes. The silica concentration in the separated brine is about 500 ppm and the brine makes up about 73% of the total resource flow. Thus by diluting the brine with the condensate the minimum allowable exit temperature was lowered to 90°C, which is 30°C lower than allowed if only brine was cooled. This lower temperature added 3.5 MW heat to the cycle representing 20% of the total heat input.

The second solution to better utilize the resource was the addition of a recuperator heat exchanger between the organic turbine and the air-cooled condenser. Since the organic fluid has a retrograde dew point, or saturation curve, when plotted on a temperature-entropy (T-S) diagram (see Figure 3), the organic vapor tends to superheat, or become drier, when the vapor is expanded through the turbine. The recuperator is used to recover the superheated vapor for preheating of the organic liquid prior to further heating in the economizer or pre-heater. The heat exchanger is of relatively low cost since there are no corrosion or material problems associated with organic fluids. For this case the recuperator was designed to recover about 7% of the total heat input.

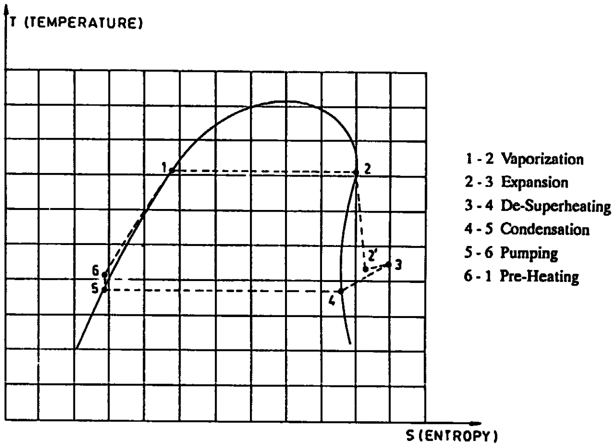

Figure 3. Temperature Entropy (T-S) Diagram of the Organic Rankine Cycle

Figure 4 shows the temperature-heat (T-Q) diagram for the Azores power plant for the base case and for the improved cycle (brine dilution and recuperator). In both of the above improvements the added heat is of low quality (i.e. lowest temperature heat in the cycle). However, it is important to note that this heat is utilized at the same overall thermal efficiency as the rest of the heat. In other words, because geothermal steam is used for boiling of the organic fluid, the boiling temperature and cycle efficiency remain unchanged as additional heat is added. For the Azores power plant the above improvements accounted for a 27% increase in power output.

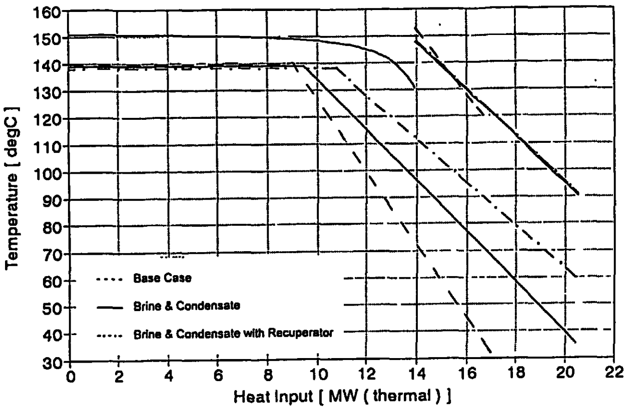

Figure 4. Temperature - Heat (T-Q) Diagram - Azores Plant

IMPROVED COMPONENT EFFICIENCIES

In addition to improving upon the thermodynamic cycle characteristic to increase output, attention must also be directed at improving component efficiencies. Much of the available energy in the cycle is indeed lost in irreversible processes such as heat exchanger temperature differences and pumping and turbine isentropic efficiencies. As an example consider the Ormesa I plant design which had a 330°F resource and 75°F cooling water temperatures. The ideal Rankine cycle efficiency which accounts for the organic fluid characteristics and heat exchanger irreversibilities is 18.6%. Finally, when accounting for turbine, pump and generator efficiencies as well as other auxiliary requirements, one finds that the net thermal efficiency (based on equipment gross power) is only about 12%, at such a low overall efficiency it is clear that component efficiencies are extremely significant.

Turbine isentropic efficiency is one of the major inefficiencies in the system. Ormat undertook a major development program to introduce larger size (3.5 MW) turbines (Frame 18) with higher efficiency in their latest projects. The larger size is desirable to keep the number of modules to a reasonable figure while also realizing cost effectiveness (fewer generators, MCC's, and controls). Furthermore, the new Frame 18 turbines are synchronous with the generator speed so that a gear box is not required. This not only improves efficiency but also eliminates a major rotating component which reduces cost and improves maintainability. Even though these turbines are designed for a much higher rating, there was no compromise on life or reliability since disk and blade stresses were kept to previous design levels. Furthermore, while the previous built turbines were generally of supersonic blading design, the new turbines are subsonic throughout, which improves off-design performance. Since turbine back pressure is strongly dependent upon ambient conditions (cooling water or air temperature) seasonal performance may vary considerably. The new turbine design greatly improves the annual energy production (kW-hr) due to better off-design performance.

A development project to improve the water cooled condenser performance was also very successful. Through extensive field and test data much information was gathered regarding the performance characteristics of the tube-and-shell heat exchangers. Combined with analytical support models several important modifications were made to the condenser design to improve the shell side condensation of the organic vapor. Also a new and unique shell side NCG gathering and removal system was designed to avoid the negative blanketing effects of NCG on the tubes. These advances resulted in a 30 to 40% increase of the shellside heat transfer coefficient. Accordingly, the LMTD (mean logarithmic temperature difference) and approach temperatures were significantly reduced which results in a lower condensation temperature and increased power output.

The recent Second Imperial Geothermal Heber power plant in California uses a binary cycle with pumped brine at 330°F and incorporates the Frame 18 turbines and new water cooled condensers discussed above. The plant consists of six (6) ITLU's and is designed for a brine flow of 6 M lbs/hr (Figure 5). At 68°F cooling water temperature, the OEC's expected net output is 41.25 MW so that the brine utilization rate is only 145 lbs/kW-hr which is about 16% better than the Ormesa I design.

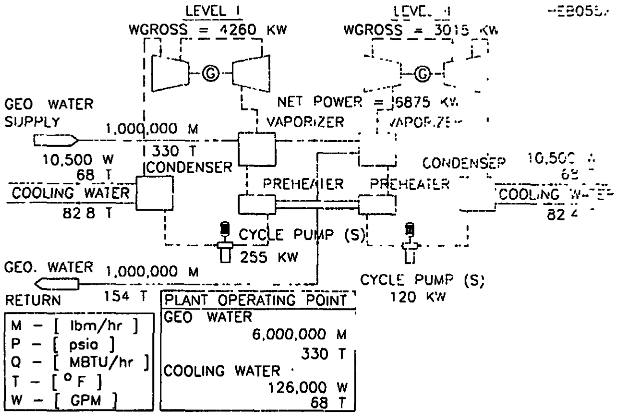

Figure 5. Heat & Mass Balance Diagram - Heber Plant

SUMMARY

- The use of higher efficiency components and better heat utilization has made the Ormat Power Plant equipment much more cost-effective.
- Installed costs in $/kW are no more costly than in 86' in nominal $'s. This is a 32% real reduction in price over an 8 year period.
- ORC Combined Cycle Plants are gaining acceptance in higher enthalpy resources.
- ORC technology can be effectively used as a bottoming unit to increase the efficiency of power plants using back pressure turbines.