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Organic Rankine Cycle Configurations

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ABSTRACT

In the last two decades the binary power plant, utilizing the Organic Rankine Cycle (ORC), has become a preferred means of exploiting low to moderate enthalpy geothermal resources. It has been widely used to utilize the brine in existing single flash plants and in many other applications as an efficient and reliable way of employing a geothermal resource, in the form of brine only or brine and low pressure steam coming from a separator. Over the years the basic ORC has been improved and modified to better adapt the cycle to various conditions of the heat source.

In this paper we will describe some advanced versions of the Organic Rankine Cycle and will demonstrate its means of providing an efficient conversion cycle adapted to specific thermal and chemical properties of geothermal fluid sources.

Examples of implementation in different power plants include the power plants in the Azores, Iceland and the plant being constructed in Landau by Geo X GmbH of Ludwigshafen.

1. INTRODUCTION

The process of designing a geothermal power plant can be considered as one of matching and optimization of the entire system. The matching process must take into consideration the characteristics of the geothermal fluid and selection of the optimum power conversion cycle, as well as other factors such as system simplicity, low maintenance requirements, and reservoir and environmental considerations. The availability and plant factor of the operating power plant is at least as important as the plant efficiency A very high efficiency conversion cycle will not do its job if the power plant is too complicated to maintain, too expensive to construct or too harmful to the environment. A conversion cycle that prevents injection of all or most of the geofluid along with the concomitant pressure support may negatively impact the sustainability of the reservoir and as a result will not be economically viable in the long term. The advantages and benefits of Organic Rankine Cycle power plants in terms of their high reliability operation, reservoir sustainability and environmental friendliness has been well demonstrated during more than twenty years of successful operation around the world. The power conversion cycles described in this paper are some examples of optimizing and maximizing the power output from different geothermal resources, while maintaining the simplicity and high reliability of the ORC equipment [1] [3].

The cycles described in this paper utilize geothermal heat sources containing steam and brine, where the enthalpy is relatively low. No thermodynamic cycle provides a “total” solution to all low enthalpy cases, but rather can provide a working tool to the plant designer to enable selection of the proper answer for optimization for the specific site conditions.

The intention of this paper is to describe several innovative processes in geothermal power plants using ORC, some of which have recently been developed and patented by Ormat, and which provide good solutions for the utilization of geothermal resources with certain characteristics.

2. COMPARISON BETWEEN THERMODYNAMIC CYCLES [2]

The second law of thermodynamics determines the limitations of performance of a power generation process. Exergy is a useful tool to define the maximum theoretical power output for a given heat source, and at a given environmental temperature. The exergy and the exergetic efficiency provide a useful tool for comparison between cycles. The exergetic efficiency is the ratio of the plant output to the maximum theoretical output at the plant conditions.

The exergy is defined by the following expression:

$e = h - h_o - T_o(S - S_o)$ (DiPippo – 1984)

where:

e is the specific exergy

h is the enthalpy

T is the temperature

and S is the specific entropy.

The subscript o refers to the ambient (dead state) temperature.

For a fluid flowing at a certain mass flow rate, multiplying the specific exergy by the mass flow rate results in the *maximum power output* theoretically obtainable from the given fluid for the given surroundings.

The real power generated by the power plant is always lower than the maximum theoretical value as defined above as a result of losses or irreversibilities in the cycle and the power plant. The main losses are due to the fact that the input heat to the system is limited in temperature, i.e. the heating fluid cannot be cooled down to the ambient temperature. One more major irreversibility in a binary power plant process is the difference in the temperature and enthalpy between the heating fluid and the secondary (working) fluid. An efficient process is one with a minimum such enthalpy difference. The enthalpy difference between the cooling media and the working fluid in the cold section of the process (condenser) is another form of loss. In addition to the above, there are mechanical and electrical losses which reduce the net generated output, as compared to maximum available exergy.

The overall exergetic efficiency of a power plant is defined as the ratio between the plant net power and the exergy of the hot source, as follows:

$$h_{ex} = \frac{W_{net}}{m \cdot e}$$

Where:

h_{ex} = overall exergetic efficiency

m = the heat source fluid mass flow

W_{net} = Net power generated by the plant

The irreversibility of a binary process on the hot side, namely the temperature difference between the heating fluid and the working fluid, is very nicely demonstrated on a Q/T (Heat rejected from the heating fluid vs. Temperature) diagram. Figure 1 is a typical Q/T diagram showing a liquid-type heat source heating the working fluid in a simple ORC containing a preheater and vaporizer. The marked parts between the two curves represents the irreversibility (losses) of the conversion process. It is clear from this figure that the similarity in shape of the two curves and the proximity between them are good indications of the process efficiency. [4]

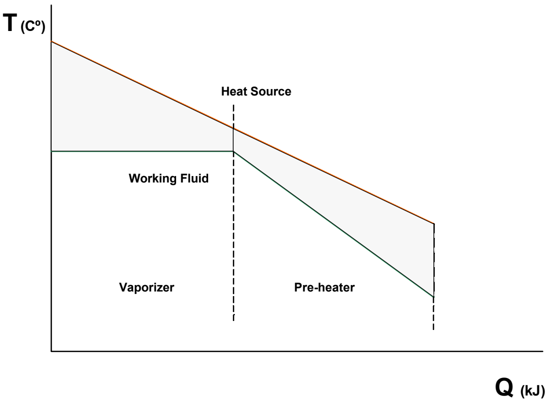

Figure 1

3. TWO-PHASE GEOTHERMAL POWER PLANT

In the majority of geothermal fields worldwide, the geothermal fluid is separated in an above ground separator into a stream of steam and a stream of brine.

In a low to moderate enthalpy resource the steam quality is 10 to 30% as a function of fluid enthalpy and separation pressure. The two streams can very efficiently be utilized in a "Two-Phase ORC Unit", as shown in Figure 2. Separated steam (usually with some percentage of Non-Condensible Gases or NCGs) is introduced in the vaporizer to vaporize the organic fluid.

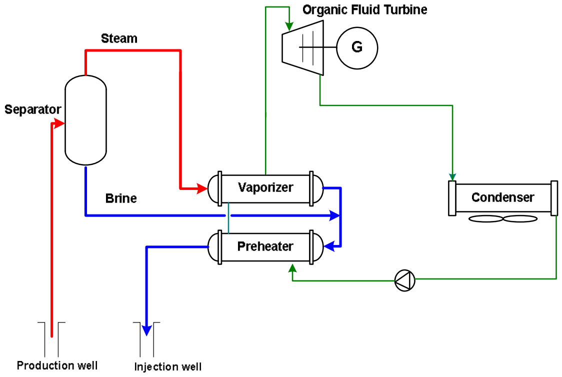

Figure 2

The geothermal condensate is mixed with the separated brine to provide the preheating medium of the organic fluid. In the ideal case, as presented in the Q/T diagram (Figure 3), the steam latent heat would be equal to the heat of vaporization of the organic fluid and the sensible heat of the brine plus condensate would be equal to the heat required to preheat the organic fluid. This "perfect" match of heat transfer between the geothermal fluid and the working fluid represents maximum thermodynamic efficiency with minimum losses.

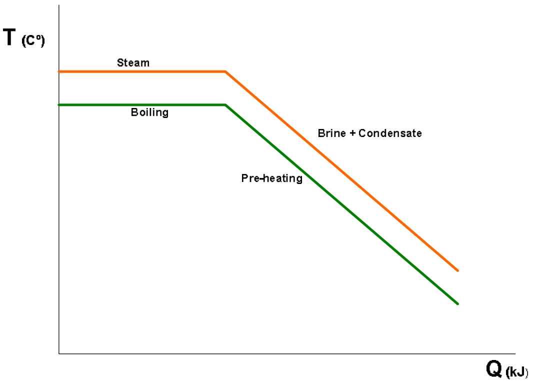

Figure 3

4. RECUPERATED CYCLE [6]

In most of the actual cases, the perfect match as above is not feasible, mainly because of limitation in the cooling temperature of the brine and condensate mixture. The limiting factor in most of the cases is the silica scaling risk, which is increased as the brine temperature drops. A method to partially overcoming the cooling temperature limit is to add a recuperator which provides some of the preheating heat from the vapor exiting the turbine.

The recuperator is applicable when the organic fluid is of the "dry expansion" type, namely a fluid where the expansion in the turbine is done in the dry superheated zone and the expanded vapor contains heat that has to be extracted prior to the condensing stage (Figure 4). The recuperated Organic Rankine cycle is typically 10-15% more efficient than the simple Organic Rankine cycle (Figure 5). This applies also to the two-phase geothermal power plant.

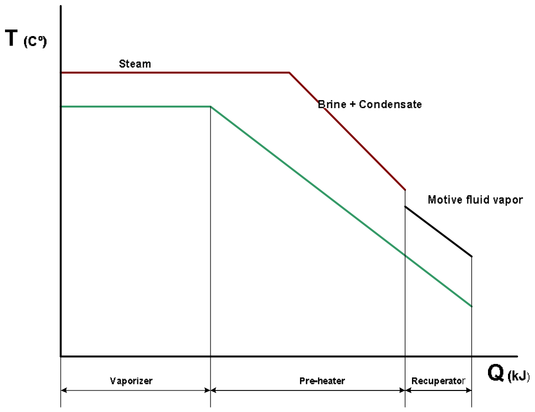

Figure 4

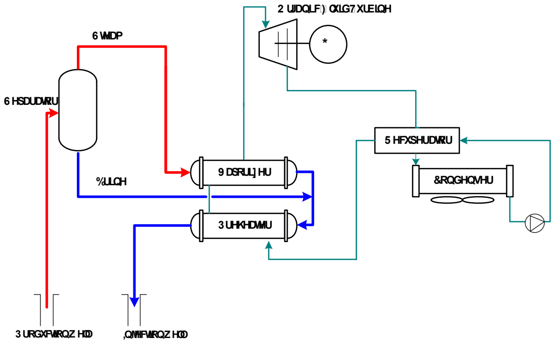

Figure 5

Figure 4 is the process flow diagram of the recuperated two-phase cycle.

The recuperated two-phase process is used by Ormat in many geothermal projects all over the world, such as the 20 MW Zunil project in Guatemala (Figure 6), 14 MW Ribeira Grande I and II in San Miguel in the Azores, 1.8 MW Oserian and 13 MW Olkaria III in Kenya, 6.5 MW Rotokawa Extension and 12 MW Ngawha in New Zealand, and 2.2 MW Hatchobaru in Japan.

Figure 6

In the last quarter of 2006, the 11.5 MW Pico-Vermelho project was commissioned on the island of Sao Miguel in the Azores Islands. This project represents the third stage of development of the geothermal resources of the island, bringing the total installed geothermal power capacity to 24 MW. The project is based on the recuperated two-phase cycle and achieves high utilization efficiency of the heat source.

Figure 7

Operating conditions of the Pico-Vermelho project are as follows:

Steam inlet temperature (°C):	151
Steam flow rate (t/h):	74.86
Brine inlet temperature (°C):	161.3
Brine flow rate (t/h):	346.74
Geothermal fluid outlet temperature (°C):	87
Plant net power (MW):	10,500
Dead state temperature (°C):	22

Applying the exergy equations on the recuperated two-phase cycle of the Pico-Vermelho project results in the following:

e = 219 64 kJ/kg

m = 117.11 kg/sec

W_{net} = 10,500 kW

and the exergetic efficiency is

$$h_{ex} = \frac{10,500\ kW}{117.11\ kg/sec\ \ x\ 219.64\ \ kJ/kg} = 0.408$$

which is very high compared to any alternative power conversion cycle for similar heating fluid conditions.

Table 1 shows a comparison of processes and geothermal power plants prepared by Prof. DiPippo to which the Pico-Vermelho ORC cycle was added in italics.

Kaplan.

Table 1

Geothermal Power Plant Exergetic Efficiencies (in order of increasing efficiency)
by R. DiPippo / Geothermics 33 (2004) 565-586
Science Direct, April 24, 2004

Technology	**Plant Name**	**Specific exergy input (kJ kg)**	**Exergetic efficiency (%)**
Binary	Brady	36.70	16.3
Binary	Brady bottoming	49.86	17.9
Binary: recuperated	Rotokawa	227.96	18.7
Binary	Nigorikawa pilot	92.77	21.6
Binary	Kalina Husavik	81.49	23.1
Double - flash	Beowawe	205.14	26.0
Binary: simple	Rotokawa	646.71	27.8
Single - flash	Blundell	278.67	35.6
Binary two phase	***Pico-Vermelho***	***219.65***	***40.8***
Hybrid flash – binary	Rotokawa	461.45	42.0
Binary: dual – level	Heber SIGC	125.84	43.0
Binary: flash evaporator	Otaka pilot	126.65	53.9

5. HIGHER ENTHALPY TWO-PHASE GEOTHERMAL POWER PLANT

When the resource enthalpy is higher, and as a result the proportion of steam in the total fluid increases, the "perfect match" between the heat source and the working fluid is not maintained. The "gap" between the heating fluid and the working fluid or the irreversibility of the process is relatively high.

One way to increase the efficiency of the cycle and better utilize the available resource is the use of a back pressure steam turbine which generates extra power from excess steam not required for the vaporizer of the ORC. Part of the available steam is directed to a back pressure type steam turbine where it generates some extra power. The lower pressure steam exiting the turbine together with the available brine and condensate preheats the ORC working fluid prior to entering the vaporiser (Figure 8). The process flow diagram of the cycle is shown in Figure 9.

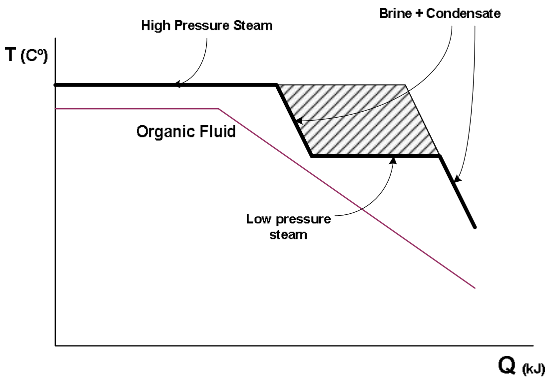

Figure 8

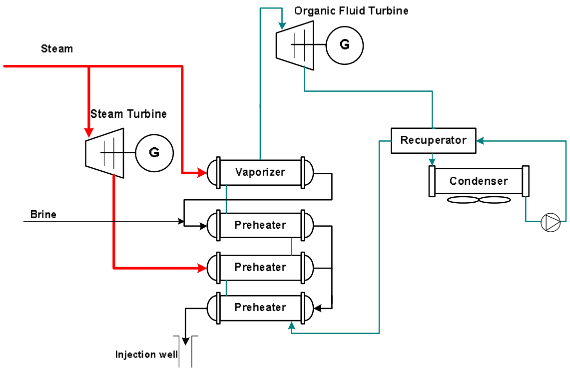

Figure 9

The gap between the steam and the preheating line of the organic fluid could be filled even more efficiently by a multi-stage (two or more) back pressure steam turbine, with extraction of steam between the stages, but the decision on the number of stages is based on the consideration of the trade-off in the process optimization between higher efficiency and the complication (and cost) of the system.

A system based on the above cycle is now operating in the 20 MW Amatitlan geothermal project in Guatemala. (Figure 10).

Figure 10

6. GEOTHERMAL COMBINED CYCLE

For high enthalpy fluids with very high steam content a solution is the geothermal combined cycle configuration where the steam flows through the back pressure turbine to the vaporizer, while the separated brine is used for preheating or in a separate ORC (Figure 11).

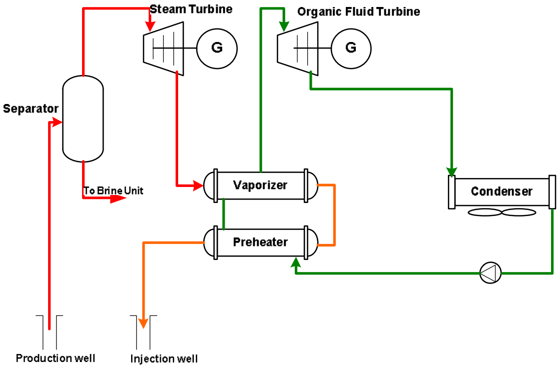

Figure 11

This configuration is used in the 30 MW Puna plant in Hawaii (Figure 12), as well as in the following plants: 125 MW Upper Mahiao in the Philippines (Fugure 13), 100 MW Mokai 1 and II in New Zealand.

Figure 12

Figure 13

7. CONCLUSIONS

Improvement of the efficiency of an energy conversion process can be carried out in many ways, including the selection of a suitable motive fluid or working with a mixture of more than one fluid. In this paper we have described improvement of the conversion efficiency by using advanced thermodynamic cycles, which can be applied to specific conditions of a given heat resource to enable adjustment of process and cycle parameters to different geofluid parameters. Such improved processes and thermodynamic cycles result in high efficiency while maintaining the high reliability, simple construction and operation as well as the high resource sustainability.

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