Pico Vermelho Geothermal Project, Azores, Portugal

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ABSTRACT

The fourth stage of geothermal power generation on the island of São Miguel was completed at the end of 2006 when the 10 MW (net) Pico Vermelho plant started continuous electricity delivery to the island's grid. It is estimated that geothermal contribution will reach 42% of the production of S. Miguel Island in 2007. The two-phase binary type power plant represents the results of the fruitful cooperation between the Azores geothermic company: SOGEO, GeothermEx and Ormat to provide the optimal plant for the Sao Miguel geothermal resource.

1. Introduction

Electricidade dos Azores, SA (EDA), the local electric company in the Azores Islands, gave the green light for the construction of a new geothermal power plant at the Pico Vermelho site on the São Miguel Island in mid 2004. The new power plant is now in commercial operation and contributes to the efforts of the local authorities to have the base load needs of the Island provided for by dependable, indigenous and clean geothermal power. The new plant optimizes energy utilization by converting geothermal steam and brine from geothermal wells into electric power energy. The new plant uses air-cooled condensers which enable 100% geothermal fluid reinjection. Such reinjection operation serves both to sustain the reservoir and to produce electrical power with virtually no environmental impact. It utilizes the high-performance, high-efficiency organic turbines developed by Ormat for geothermal and industrial recovered-energy applications.

2. Development of the Geothermal Resource

The Sociedade Geotermica dos Açores, S.A. (SOGEO) operates the Ribeira Grande and Pico Vermelho geothermal power plants, both located on the Fogo volcano (Água de Pau) in the central part of the island of São Miguel, Azores, Portugal. The two plants are supplied by separate well fields that exploit different areas within a single extensive geothermal system on the northern slope of the volcano.

Exploration and development of the lower (northern) part of the field, where the Pico Vermelho plant is located, took place during the late 1970's and early 1980's. Five deep wells (RG-1, RG-2, PV-1, PV-2 and SB-1) were drilled during 1978-1981, and the 3 MW Pico Vermelho plant began operation in 1981. Well damage and scaling problems left PV-1 as the only well available for use by the plant, and as a result the plant output has typically not exceeded 0.8 MW.

During the late 1980's, exploration of the southern part of the field (higher elevations on the volcano) was undertaken in an effort to identify a geothermal resource of higher temperature and lower scaling potential. Well CL-1 was drilled in 1988-89 and wells CL-2, CL-3 and CL-4 during 1992-94. The production from these wells was more than sufficient to supply Phase A of the Ribeira Grande 5.08 MW power plant located in the upper part of the field. Constructed in 1993-94, this plant consists of two binary-cycle ORMAT® ENERGY CONVERTERS (OECs). Wells CL-1 and CL-2 were the production wells.

Phase B (9.4 MW) was installed at Ribeira Grande in 1997, bringing the total capacity of the plant to 14 MW (approximately 13 MW net to the grid). Well CL-3 and the excess capacities of wells CL-1 and CL-2 were used to supply this facility. CL-4 has also been used intermittently; however, following the assessment described below, this well has been converted into an injector and a new production well was drilled to replace it. CL-5 which was drilled in 2000 and CL-6, drilled 5 years later, contribute to sustaining the operation of the Ribeira Grande power plant.

3. Description of the Power Plant

3.1 Two-Phase Flow with High Liquid Fraction

The geothermal resource of the Lagoa do Fogo Volcano is characterized by low enthalpy fluid (900 – 1100 kJ/kg) and as a result the separated fluid, consists of a high portion of water (brine) and a low portion of steam. Typical figures are 78% water and 22% steam at a separation pressure of 5 bar a, and a fluid enthalpy of 1100 kJ/kg.

Ormat has developed the two-phase type ORMAT® ENERGY CONVERTER (OEC) to utilize this type of geothermal resource efficiently. The two-phase OEC utilizes the separated steam to vaporize the organic fluid (pentane) in the vaporizer and the mixture of condensed steam and brine is used as the heating source for the preheater. Figure 1 is a schematic flow diagram of the two-phase process. The ratio of heat quantities of steam and condensate/brine mixtures are similar to the heat quantities of the boiling and preheating of the pentane in the OEC. Figure 2 is a TQ (temperature, heat quantity) diagram showing the heat quantities and temperatures of the heating fluid and working fluid in the OEC cycle. The figure shows the good match between the shape and quantities of the working fluid and heating fluid, indicating a high efficiency in utilization of the heating source.

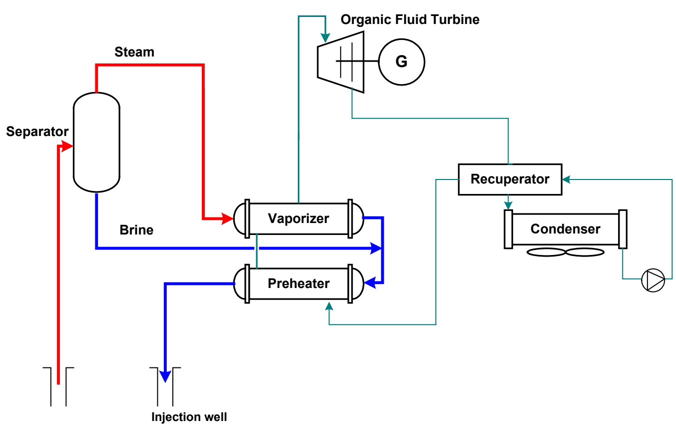

Figure 1. Schematic Flow Diagram of the Two-Phase Process. (G = generator).

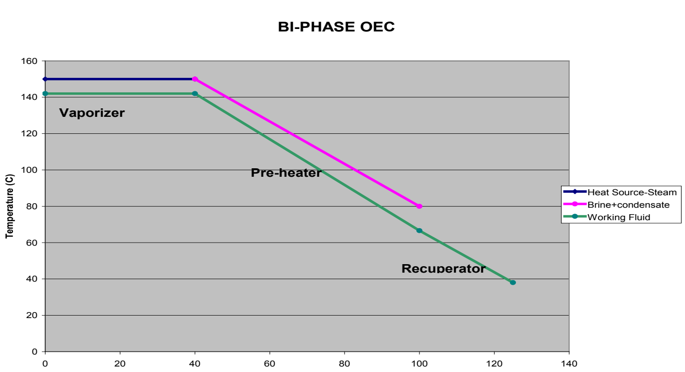

Figure 2. TQ (temperature - heat quantity) Diagram.

The two-phase OEC concept is used in other low-enthalpy geothermal resources in locations such as the Zunil project in Guatemala (24 MW), Ngawha project in New Zealand (12 MW), the Olkaria III early generation project in Kenya (12 MW) and others.

3.2 Stages in the Construction of the São Miguel Geothermal Project

The construction of the Pico Vermelho project is the fourth stage in the development and construction of the geothermal plant on the São Miguel island.

Pico Vermelho Phase A

The first stage was a 3 MW back-pressure steam turbine utilizing the steam of PV-1, but generating only about 800 kW. (1980-2005)

Ribeira Grande Phase A

The first Ormat project in the Azores was the Ribeira Grande Phase A of 5.08 MW gross, utilizing the steam and brine of wells CL-1 and CL-2. The working parameters of the project were as follows in Table 1 (design point):

Table 1.

Steam flow	:	43.7 t/h
Brine flow	:	74.6 t/h
Steam pressure at inlet to plant	:	5.16 bar a
Brine temperature at inlet to plant	:	152°C
NCG in steam	:	7.4% (by weight)
Design ambient temperature	:	13°C
Power generation (gross at generator terminals)	:	5,080 kW
Power generation (net at sub station inlet)	:	5,000 kW

The generation unit consists of two OEC units, each with two turbines connected to a common generator.

Ribeira Grande Phase B

The second phase of the Ribeira Grande project was the construction of two additional OEC units on the same site, using the same plant facilities and utilizing the geothermal fluid from wells CL-1, CL-2 and CL-3, while CL-4 was used as an injection well. Later on CL-5 was added as a production well and then, after further decline in production, CL-6.

Phase B parameters are as follows in Table 2 :

Table 2.

Steam flow	:	71.1 t/h
Brine flow	:	263 t/h
Steam pressure	:	5.11 bar a
Brine temperature	:	153°C
NCG in steam	:	7.6% (by weight)
Design ambient temperature	:	13°
Power generation (gross)	:	9,400 kW
Power generation (net)	:	8,000 kW

The figures given above are at "design point", as given in the project agreement and are based on the best information on well production at the time of the project conceptual phase.

During the acceptance tests of the two phases of the project the well production performance was slightly different from the design point figures. However, at the new conditions the performance of the generating equipment – the OEC units was better than the expected performance when applying the correction curves.

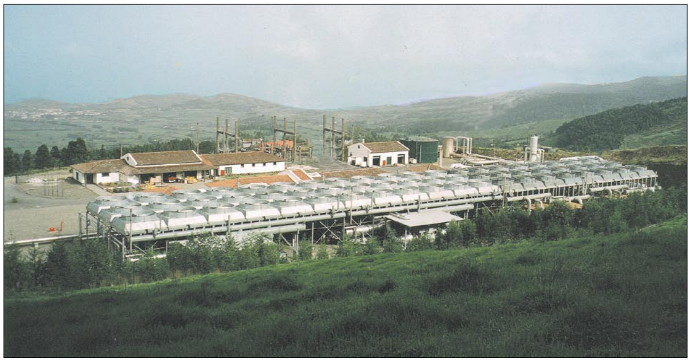

Figure 3. Ribeira Grande Phase B.

Pico Vermelho Phase B

In mid-2004 SOGEO issued a bid for the design, manufacture and construction of a 10 MW (net) geothermal project using the steam and brine from production wells PV-2, PV-3 and additional new wells. The spent fluid would be injected into two injection wells, PV-5 and PV-6.

Based on the experience of the previous phases, a resource analysis was conducted by GeothermEx to determine the design separation pressure which would take into consideration future reservoir depletion and would result in best overall reservoir sustainability and maximum plant energy production. The result was a relatively low design working pressure, as shown in the table below. Wells PV-4, PV-7 and PV-8 have been drilled in parallel to the construction of the power plant and their productivity was higher than the forecast. The Pico Vermelho well field has the potential to supply the fluid to the new Phase B project as well as future generating equipment (see table 3).

Table 3

Steam flow	:	74.86 t/h
Brine flow	:	346.7 t/h
Steam pressure at inlet to plant	:	5 bar a
Brine temperature at inlet to plant	:	161.3°C
NCG in steam	:	1.8% (by weight)
Design ambient temperature	:	22°
Gross power at design point	:	11,450 kW
Gross power at 13°C ambient temperature	:	12,600 kW
Net power at design point	:	10,000 kW

Exergy Analysis for Pico Vermelho Phase B

Applying the exergy equations as in Ronald DiPippo paper* to the recuperated two-phase cycle of the Pico-Vermelho project results in the following:

The operating conditions of the Pico-Vermelho project are as in table 4:

Figure 4. Pico Vermelho Phase B.

Table 4.

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

Exergy	e	=	219 64 kJ/kg
Total mass flow	m	=	117.11 kg/sec
Net power	W_{net}	=	10,500 kW

and the exergetic efficiency is

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

*Second low assessment of binary plants generating power from low-temperature geothermal fluids – Ronald DiPippo April 2003

a very high exergetic efficiency compared to any alternative power conversion cycle for similar heating fluid conditions.

4. Continuous Improvement

The three phases of Ormat equipment in the Azores are a good example of the continuing improvement in energy conversion equipment (OEC unit and the auxiliary component), resulting in higher efficiency and better reliability and lifetime.

The first phase of the Ribeira Grande project included two dual OEC units, each consisting of two 3,000 rpm turbines and two-speed reduction units connected to a 1,500 rpm generator.

The second phase included two improved OEC units with 1,500 rpm turbines directly coupled to the generator without the need for reduction gears and with a much higher expansion efficiency.

The third phase – the Pico Vermelho plant, consists one of the new generation OECs, each with a capacity of up to 10 MW and higher expansion efficiency.

Table 5 presents the improvement in turbine expansion efficiency since Ormat's first geothermal projects in 1984, resulting from an improvement in the nozzle and blade design, and better wheel geometry as a result of the reduction of the

Table 5. Turbine Efficiency.

Year of First Use	Representative Projects	Turbine Efficiency %
1984	Steamboat, USA	72
1985	Ormesa, USA	75
1989	Puna, USA	78
1993	Heber, USA	83
1996	Upper Mahiao/Rotokawa, NZ	84
2000	Olkaria, Kenya	88

turbine speed from 3000/3600 rpm to 1500/1800 rpm (for 50 and 60 Hz grids, respectively).

The reduction in the turbine speed was also one of the main reasons for the significant improvement in the reliability of the mechanical components such as bearings and seals, and of the extremely high availability and lifetime of the plants.

Conclusions

The development of geothermal power generation projects in the Azores started in the late 70's and today includes four power plants with a total capacity close to 23 MW.

The 10 MW Pico Vermelho power plant is the third Ormat plant in the islands and represents the successful cooperation between the Azores electric company, SOGEO and Ormat to develop high reliability, efficient power plants utilizing the available geothermal energy.