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Field Performance Evaluation of the Largest Geothermal Organic Rankine Cycle Plant

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ABSTRACT

The first phase of Pamukuren Geothermal Project of Celikler Jeotermal was commissioned in October 2013. Electrical power production capacity of this plant will be in excess of 100 MW when phases two and three are completed.

The Organic Rankine Cycle plant was optimized with normal butane as working fluid. Celikler Jeotermal chose the plant configuration with inflow radial turbine. The first phase consisted of two trains each with nominal capacity of 25 MW electrical power output.

In this paper we present the geothermal resource design conditions, thermodynamic discussion for choice of working fluid and the basic design parameters of the Organic Rankine Cycle and the inflow radial turbine. Field performance of the associated Organic Rankine Cycle and turbine with the actual geothermal resource data will be evaluated, compared and contrasted. Comparison of the expected and actual plant performance will also be presented.

1. INTRODUCTION

Pamukuren Plant is located in the vicinity of town of the Pamukuren in district of Kuyucak in Aydin province in Turkey. Celikler Jeotermal acquired geothermal concession in Pamukuren in 2009.

Celikler Jeotermal awarded an order for phases I and II of the Pamukuren geothermal ORC plant to a consortium consisting of Atlas Copco Gas and Process, Exergy S.p.A. and SPIG A.p.A. both of Italy in 2011. Atlas Copco Gas and Process was the consortium leader.

Pamukuren plant was configured in multiple trains. Each power train is designed with two parallel stages of inflow radial turbines mounted on an integral gearbox driving a single synchronous generator. Nominal electrical power capacity of each train is 25 MW. Electrical output capacity of each train was designed to be 22.5 MW.

Geothermal resource fluid flows to a separator vessel installed at each well head. Steam and None Condensable Gases (NCG) are separated at a predetermined separation pressure. Steam/NCG's and brine flow through separate pipes to the power plant.

Table 1 depicts the original resource fluid conditions for ORC plant design.

Brine Flow	Temperature	Steam Flow	NCG's	NCG's Flow	Design Reinjection Temperature
1,400 t/h	161 ° C	55 t/h	CO^2	22 t/h	80 ° C

Table 1. Geothermal Resource Fluid Data

The working fluid vapor leave evaporator slightly superheated. The superheated vapor enters two parallel turbines mounted on an integral gear box that drives a single synchronous generator. A by-pass line is installed parallel to the turbines. This bypass line has three functions of warming up the plant uniformly at cold start, bypass partial flow until the turboexpander-generator train is synchronized and to bypass full flow in the event of turboexpander-generator shutdown.

A recuperator is installed downstream of the turbines in order to recover the remaining heat of the vapor exiting the turbines and thereby reduce condenser load as well as stabilizing the reinjection temperature. Air cooled condenser are designed to condense the working fluid from the recuperator discharge conditions before it flows to a hot well and is pumped back into the brine heated preheater to complete the cycle.

Normal butane was chosen as the working fluid after optimizing based on the available geothermal resource data and characteristics of an inflow radial turbine. Figure 2 shows an annotated T-s Diagram for n-butane in the range of interest to this project. The source fluids and the cooling air have been added to the T-s Diagram. The entropy values assigned to these fluids in the diagram are fictitious, and are the entropies of the n-butane working fluid at the corresponding location in the heat exchanging process.

The two evaporators (brine and steam/NCG heated) are in parallel on the working fluid side, so there is a single curve for the n-butane fluid in the evaporators, but separate steam/NCG and brine curves for the source fluids.

for n-butane.

Table 2 depicts gas dynamic performance of each expander stage.

The thermodynamic performance advantages of working fluid n-butane could be summarized as follows:

a. The T-s diagram, **Error! Reference source not found.**, shows that majority of the heat from the geothermal brine can be utilized. This ensures a very good ORC efficiency.

b. The thermodynamic properties of n-butane are ideal for an inflow radial expander design.

c. The condensing pressure is higher than atmospheric pressure for all possible ambient temperatures and hence avoiding any risk of atmospheric air leaking into the condenser.

Ambient temperature	Turbine inlet pressure [bar abs]	Turbine inlet temperature [°C]	Turbine outlet pressure [bar abs]	Turbine outlet temperature [°C]	Working fluid mass flow [kg/h]	Gas Power [kW]	Isentopic turbine efficiency [%]	Generator Power [kW]
Winter (5 °C)	25.00	125.00	4.00	57.70	594,000	10,850	87	20,000
Design (18 °C)	25.00	125	2.90	54.70	594,000	12,120	82.5	22,500
Summer (35 °C)	25.00	125	5.10	70.70	594,000	9,080	84	16,500

Table 2. Turbine Stage Performance and Power Train Output

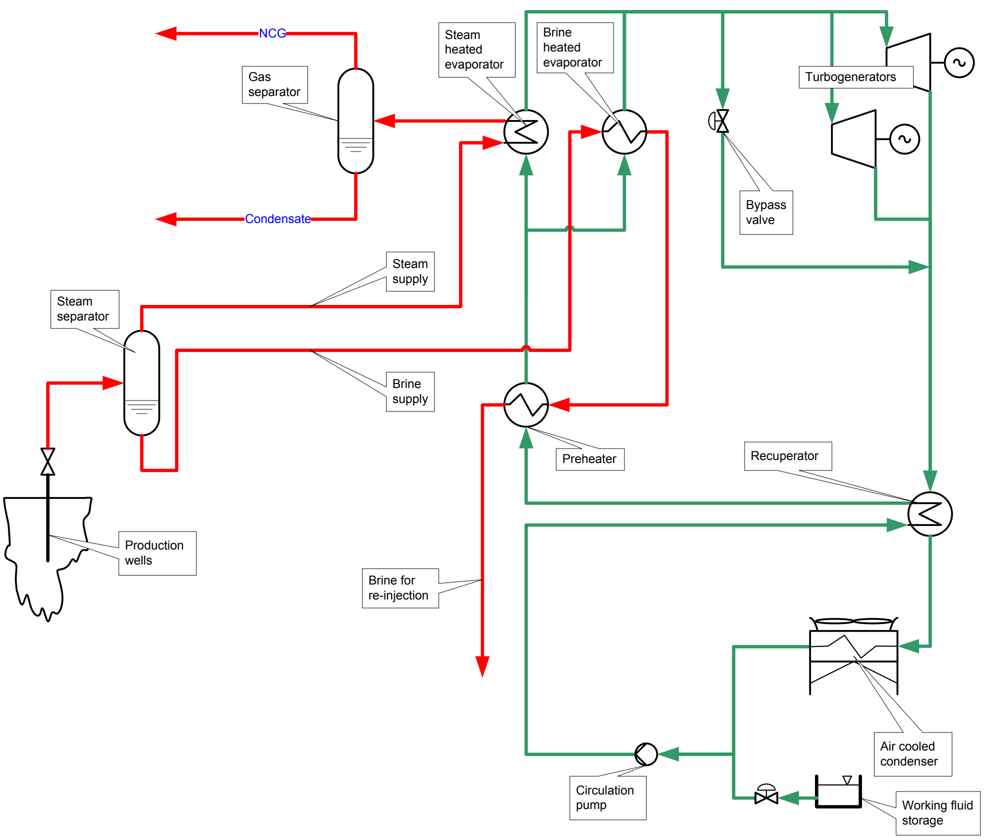

Figure 1. PFD for the ORC Process

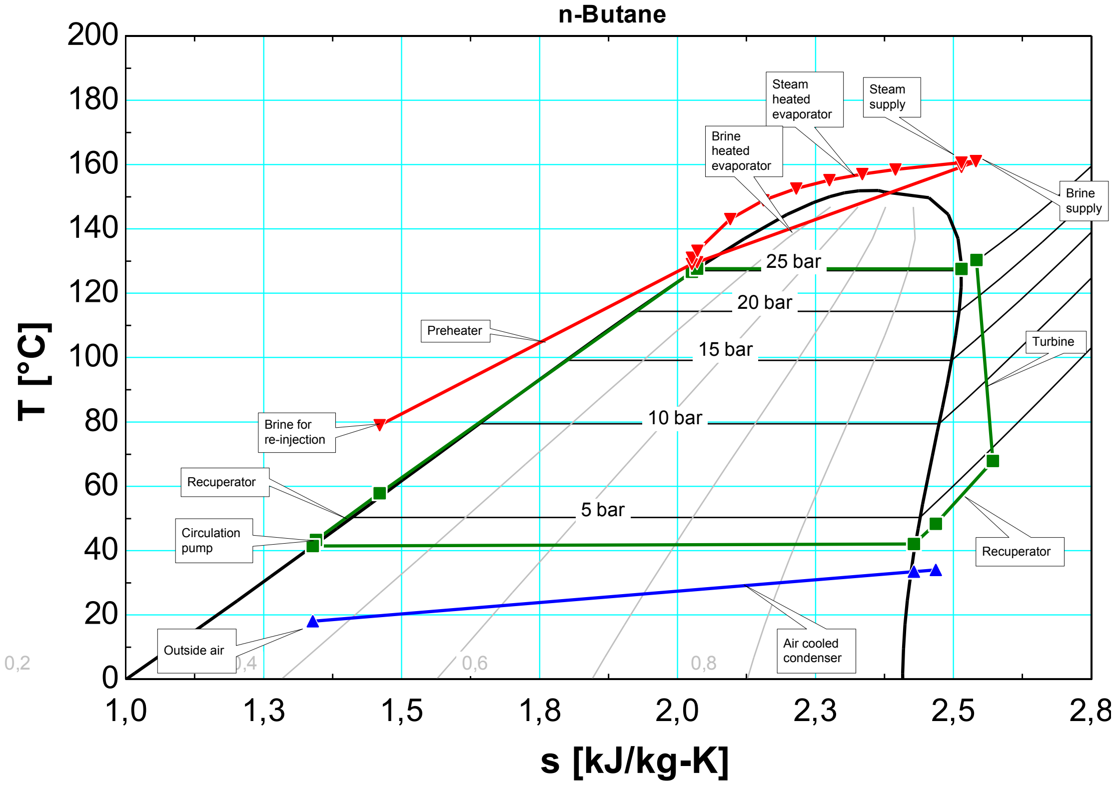

Figure 2. T-s Diagram for the ORC with n-Butane

2. FIELD PERFORMANCE

Renewable power plants in Turkey have to be connected to the electrical transmission grid on or before October 31st of each year in order to benefit from renewable energy incentives (FIT) according to the local regulations. The two trains of Pamukuren plant went on line in the last week of October and first week of November 2013 and the regulatory requirements were satisfactorily fulfilled.

Evaluation of an ORC system may be implemented in two phases. The first phase is to evaluate the turbine performance and the second step is to evaluate the rest of ORC system. If the outcome of the first evaluation is satisfactory and power output is in line with the expectation, the ORC system evaluation is complete and concluded.

The turbine system has to be reviewed in details if the turbine field performance is not as expected. If the turbine performance is as expected but the electrical power output is less than expected then other equipment of the ORC system and their performance are to be scrutinized.

3. TURBINE PERFORMANCE EVALUATION PROCEDURE

Turbine field performance evaluation consists of comparing three efficiency values:

1. Turbine expected efficiency for the operational flow and enthalpy
2. Turbine efficiency based on the operational electrical power output
3. Turbine efficiency based on the operational expander discharge temperature

The turbine system's operation is considered as expected when the above three values are reasonably the same.

Further scrutiny and engineering or maintenance studies of turbine system are required if there are discrepancies and inconsistencies among the above three efficiency values.

On the other hand ORC design and performance of stationary equipment is on the agenda if the outcome of field performance evaluation is acceptable for the turbine system operation but electrical power output is less than expected.

4. TURBINE PERFORMANCE EVALUATION

5. WORKING FLUID

The original design of the ORC system and the gas dynamic design of the turbine system were based on commercial grade n-butane. This assumption is practical and is due to the fact that pure n-butane is difficult to find in local markets and if available will be quite expensive. Table 3 shows the original assumption for commercial grade n-butane composition and the actual composition of the n-butane that was charged into the ORC system.

Commercial Grade n-butane	n-butane	i-butane	Pentane	Propylene	Propane
Design, Mol%	97	0	0	0	3
Actual, Mol%	96	1	2	1	0

Table 3. ORC Working Fluid Composition

6. OPERATIONAL GEOTHERMAL RESOURCE DATA

All design work and specifications for ORC system's equipment were based on the original geothermal resource data depicted in Table 1. Table 4 and Table 5 show geothermal resource data for power trains I and II in the first month of operation

Train	Brine Flow	Temperature	Steam + NCG Flow	NCG's	Reinjection Temperature
I	1,129 t/h	164 ° C	91.00 m^3/h	CO^2	74 °C
II	-	-	-	-	-

Table 4. Operational Geothermal Resource Data

Train	Brine Flow	Temperature	Steam + NCG Flow	NCG's	Reinjection Temperature
I	-	-	-	-	-
II	1,200 t/h	167 ° C	95.00 m^3/h	CO^2	76 °C

Table 5. Operational Geothermal Resource Data

7. TURBINE, POWER TRAIN, EVALUATION

The configuration of each power train consists of two parallel stages of turbine mounted on an integral gear box to drives an electrical generator. Individual turbine performance evaluation based on power is not practical for this configuration. Therefore we have implemented an evaluation based on temperature for each turbine stage but the evaluation based on power has to be combined for both turbine stages or namely for each train.

8. TURBINE EVALUATION BASED ON DISCHARGE TEMPERATURE

This evaluation is based on ratio of two enthalpy drops across the turbine. The theoretical enthalpy is evaluated by considering expander inlet and discharge pressure and an isentropic expansion process. The actual enthalpy is calculated based on inlet and discharge pressure and temperature measurements. The ratio of these enthalpies is defined as efficiency based on enthalpy

9. TURBINE EVALUATION BASED ON ELECTRICAL POWER

In this evaluation the theoretical and actual electrical power are compared. The theoretical power is calculated based on the given process data, i.e. working fluid flow, density, average theoretical enthalpy of the turbine stages, generator efficiency at the given ambient temperature and given gear box power loss for the given operating load. The actual power is available from generator output power meter

Table 6 and Table 7 show gas dynamics performance for individual turbines and electrical power production of train I for measurement

Train/Exp/ Ambient 3.0 °C	Turbine inlet pressure [bar abs]	Turbine inlet temperature [°C]	Turbine outlet pressure [bar abs]	Turbine outlet temperature [°C]	Working fluid mass flow [kg/h]	Gas Power [kW]	Isentopic turbine efficiency based on turbine exhaust temperature [%]	Isentopic turbine efficiency based on power [%]	Expected isentropic efficiency [%]
II / 1	25.30	133.60	3.20	59.70	499,200	-	91	-	
II / 2	25.80	136.90	3.20	64.20	499,200	-	92	-	
II	-	-	-	-	998,400	19,030	-	78	84

Table 6. Turbo Expander Stage Performance

Train/Exp/ Ambient 10.0 °C	Turbine inlet pressure [bar abs]	Turbine inlet temperature [°C]	Turbine outlet pressure [bar abs]	Turbine outlet temperature [°C]	Working fluid mass flow [kg/h]	Gas Power [kW]	Isentopic turbine efficiency based on turbine exhaust temperature [%]	Isentopic turbine efficiency based on power [%]	Expected isentropic efficiency [%]
I / 1	25.00	128.90	3.70	63.80	570,750	-	81.4	-	
I / 2	24.70	132.40	4.30	60.00	570,750	-	>100	-	
I	-	-	-	-	1,141,500	9,080	-	87	87

Table 7. Turbine Stage Gas Dynamics Performance

Table 6 shows that there are discrepancies between calculated expanders 1 and 2 efficiencies based on temperature. Furthermore it depicts that the train power output is less than expected.

The former discrepancies implies that expander discharge measuring instruments need calibration and the latter implies that the condensers in train II need to be vented from none condensable gas, i.e. nitrogen.

10. CONCLUSIONS

A geothermal energy company selected inflow radial turbine technology for their ORC plant in Turkey. The plant was designed with air cooled condenser. The turbine with variable inlet guide vanes (IGV) is a preferred solution considering variation in ambient temperature. Preliminary start up and commissioning was completed in October 2013. Turbine performance was evaluated in the first month of commercial operation to tune and fine tune the ORC system. The evaluation was to compare the turbine's thermal efficiency by process temperature measurements and by generator output. The preliminary evaluation showed that several temperature transmitters are in need of calibration and non-compressible gases should be vented from condenser more frequently.

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