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Performance of New Turbines for Geothermal Power Plants

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ABSTRACT

Two high efficiency turbines have enabled the economic use of novel geothermal power cycles, the Variable Phase cycle and the Kalina cycle. Utilizing the Variable Phase Turbine and the Euler Turbine, respectively, the net power production can be increased by 30-50% from enhanced geothermal and sensible resources relative to commercially available organic Rankine cycles. These technologies were introduced at the GRC 2009 in the paper “New Turbines to Enable Efficient Geothermal Power Plants.” An outline of the technology and thermodynamic cycles as well as updates on the design and start-up process of a number of projects will be presented.

The Variable Phase Turbine consists of discrete two-phase nozzles impinging upon an axial impulse rotor. The turbine achieves high isentropic efficiency while also allowing for direct drive of the generator with no gearbox, thus avoiding the efficiency loss while eliminating the need for a lube oil system and reducing capital cost.

The Variable Phase cycle consists of a pump, liquid heat exchanger, Variable Phase Turbine, and condenser. Besides reducing complexity and cost, this cycle can produce between 30 and 50% more power from a given resource than a standard ORC, leveraging the total cost of the geothermal project. The design of a 1 MW geothermal Variable Phase cycle pilot project is currently underway. Details of the design are presented.

The Euler Turbine is a radial outflow turbine with numerous benefits compared to radial inflow turbines. For this reason, Euler Turbines have been selected as an ideal prime mover in the Kalina cycle. A geothermal power plant using the Kalina cycle with a 555 kW (net) Euler Turbine was started-up in November 2009 in Germany. Two more Kalina cycle start-ups utilizing an Euler Turbine are planned. Descriptions of the designs and measured test performances are provided.

Introduction

Low temperature geothermal resources, enhanced geothermal resources, and separated brine from flash plants are huge sources of energy. However, because of their characteristically low temperature, these projects and power systems have a high cost per installed kilowatt of power. To produce power from these resources the energy conversion system must maximize the conversion of available energy to power.

Figure 1. ORC temperature profile.
Organic Rankine cycles absorb heat predominantly in the form of latent heat (evaporation). This creates a pinch point which limits the heat input into the cycle. The ideal thermodynamic cycle would eliminate this boiling pinch point to recover more heat from the geothermal resource while efficiently converting the recovered heat into electricity. The Kalina cycle and Variable Phase cycle are both new thermodynamic cycles designed to approximate the ideal cycle. New turbine technology in the Euler Turbine and Variable Phase Turbine are being utilized in these cycles.

This paper is a continuation of the 2009 GRC paper “New Turbines to Enable Efficient Geothermal Power Plants.” Abridged versions of specific sections will be included for clarity. More detailed descriptions of the turbines and thermodynamic cycles can be found in the 2009 GRC Proceedings.

**Euler Turbine**

The Euler Turbine is a radial outflow reaction turbine consisting of a nozzle row, blade row, and diffuser. Figure 2 shows the flow-path through the turbine. Specifically designed to handle wet expansions, centrifugal forces pull moisture and contaminants away from the nozzle-rotor interface. Other advantages include: rugged two-dimensional vane and blade profiles; reduction of optimum speed to approximately half that of comparable radial inflow machines; and the ability to fit multiple stages on a single rotor.

**Euler Turbine: Application to the Kalina Cycle**

The Kalina cycle was developed as in improvement to the organic Rankine cycle for sensible heat sources. Operating with a multiple component fluid—typically ammonia and water—the Kalina cycle employs a variable temperature boiling in the evaporator. The variable composition during the boiling produces a “glide” effect which reduces the pinch point limitation when compared to an ORC (Figure 3). The turbine inlet is typically saturated vapor, making the Euler Turbine desirable because of its rugged design for wet expansions.

**Euler Turbine & Kalina Cycle: Installation at Bruchsal, Germany**

An Euler Turbine was chosen for a Kalina cycle plant in Bruchsal, Germany. Based on the design point data (Table 1), the shaft power is 610.5 kW and the electrical power is 557.4 kWe for a shaft efficiency of 82.4% and electrical efficiency of 75.3%. These efficiencies include the energy loss in the control valve. The exit vapor quality from the turbine is 96%.

**Table 1. Euler Turbine for Kalina cycle.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia Content</td>
<td>92.7%</td>
</tr>
<tr>
<td>Mass flow</td>
<td>4.83 kg/s</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>115.3°C</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>20.0 bar a</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>7.8 bar a</td>
</tr>
</tbody>
</table>

Figure 4 shows the unit installed at the geothermal plant. The plant was successfully started up in October 2009. The unit has generated up to 585 kWe, more than 25 kW above the guaranteed...
power and the turbine has met efficiency expectations. Initial data of the turbine performance is shown in Figure 5.

**Euler Turbine & Kalina Cycle: Shanghai World Expo**

The world’s first solar-thermal Kalina cycle power plant and China’s first Kalina cycle power plant was started up successfully at the Shanghai World Expo in April 2010. At the heart of the 50 kW plant was a Microsteam Turbine Power System, a 275 kWe system designed for steam PRV replacement operating on an Euler Turbine, modified for use with ammonia. Use of a standard turbine package was necessary due to tight time schedules—the unit was built in only eight weeks, four weeks ahead of the deadline.

The unit was first shipped to an off-site facility in Shanghai (Figure 6), where the entire system was tested using a water heater to simulate the solar source. In a testament to incredible manpower, the entire plant was disassembled and shipped to the site in one day. Once at the World Expo site, the system was reassembled and placed in a new building (Figure 7).

Because of the relatively low power level, the blade height of the turbine had to be greatly reduced. Testing on nitrogen prior to shipping showed that the efficiency predictions were valid for the off-design use of the turbine (Figure 8). Start up with the ammonia-water mixture at the World Expo site confirmed performance of the unit.

Electrical interconnection requirements of the power plant restricted the turbine from operating connected to the grid. The standard design of the Microsteam Turbine Power System utilizes an induction generator, which is unlike a synchronous generator in that it requires connection to a grid for operation. This hurdle was successfully overcome by implementing a technique known as self-excitation.

**Self-Excitation and Induction Generators**

Induction generators are often favored for their lower cost and rugged construction. This translates to a smaller capital investment
and lower maintenance costs. One of the major drawbacks of the induction generator is the difficulty in magnetizing the rotor when not connected to the grid or to another synchronous-type generator. In practical terms, it means that an induction generator cannot produce a voltage on its own. Without voltage, no electrical loads can be powered.

This difficulty can be bypassed by adding a properly sized capacitor bank in parallel with the load. Using this setup it is possible for the induction generator to self-excite and produce voltage. By properly modulating some combination of speed, capacitance, and load, it is possible to regulate the voltage and frequency to within allowable tolerances. This setup has the advantage of retaining the rugged construction of the induction generator, costing less than a synchronous machine and being conceptually simpler to control. Because of these reasons, the self-excited induction generator has been favored for several decades in many of the more remote areas of the world for providing power to small rural villages.

**Euler Turbine & Kalina Cycle: Development Project at Otari, Japan**

A 65 kW Kalina cycle geothermal plant planned for Otari, Japan will use an Euler Turbine with a 56,000 rpm high-speed generator supported by magnetic bearings. This eliminates the need for a gearbox by directly coupling the turbine to the generator and also eliminates the lube oil system and associated equipment. Higher efficiencies should be realized in this design by the reduction of parasitic losses.

Heated nitrogen was successfully used to spin the turbine generator to 38,000 rpm and feed power to a load bank (Figure 9). Much of the functionality of the overall system was tested. Shaft power reached 28 kW and efficiencies as high as 72% were achieved, validating the performance of the turbine (Figure 10). The turbine was well-behaved under a wide range of flow conditions, closely following trends of flow and pressure. The efficiency measurements are conservative due to the heat transfer from the high temperature inlet (upwards of 80 °C in some of the cases) into the low temperature nitrogen outlet (below 0 °C in some cases), decreasing the measured enthalpy drop.

Upon completion of the factory nitrogen tests, the turbine-generator system was integrated into the complete plant (Figure 11). Pressure tests and wiring and control checks were completed.

The high-speed generator experienced higher than expected vibration and was returned to the manufacturer to rebalance the rotor assembly. Once resolved, the entire geothermal plant will be tested at a geothermal test site in the United States that can provide resources that closely resemble that of the actual overseas job site. This approach allows for an almost complete commissioning before even leaving the country. Upon completion, the entire plant will be shipped to the customer and commissioned on-site.
Variable Phase Turbine

The Variable Phase Turbine (VPT) is comprised of a set of individual, fixed nozzles and an axial impulse rotor. The arrangement of the VPT (Figure 12) is similar to a conventional axial impulse turbine. The nozzles are inclined at a tangential angle to the rotor. The two-phase impulse wheel is a blisk—that is, an integrally bladed rotor—which has low stress and incorporates a shroud to control the location of any stray liquid. The inlet to the nozzle can be liquid, two-phase, supercritical, or vapor. The turbine is designed with a special blade contour to optimize performance with two-phase flow. The benefits of the VPT are: efficient operation with two-phase flow; operation at synchronous speeds; limited runaway speed; minimal axial thrust; well below erosion potential. The VPT has been successfully operated in 75 commercial chillers for more than 10 years with no turbine problems.

Variable Phase Cycle

The Variable Phase cycle (VPC), which is based on the triangular or similarly the trilateral cycle, is the ideal thermodynamic cycle for low temperature sensible heat recovery. Liquid working fluid is pressurized and then heated in the heat exchanger with no vaporization. The heated, pressurized liquid leaving the heat exchanger is directly expanded in a Variable Phase Turbine. The low pressure fluid is condensed, closing the cycle. The boiling “pinch point” restriction is eliminated (Figure 13).

Variable Phase Turbine: Application to the Variable Phase Cycle

Designed for two-phase expansions, the Variable Phase Turbine allows for efficient utilization of the VPC. The primary benefit that can be realized by using the VPT is a hermetic, direct-drive shaft assembly that eliminates lube oil skid and shaft seals. A 10 kW Variable Phase cycle pilot plant was built and tested with a VPT, validating the performance predictions. The VPT is also suitable for supercritical versions of the VPC. Figure 14 is a schematic of the Variable Phase cycle applied to geothermal power generation.

Variable Phase Turbine and Variable Phase Cycle: 1 MW DOE Geothermal Project

Figure 15 is an early conceptual drawing of a compact waste heat recovery system being built under a DOE program for recovery of heat from a brine stream at 235 °F.

Design and construction of the power plant is underway, with commissioning projected to occur in early 2011. The system includes a boost pump, main pump, heat exchanger, VPT, generator,
condenser, and inventory tank. The generator will be a standard, double-ended induction generator, with the main pump and the VPT on the shaft. The boost pump is a vertical, canned pump that will provide the NPSHR for the main pump.

Because of the high silica content in the brine, a heat exchanger test was conducted to determine the scaling potential as the brine is dropped to 175 °F. Two types of heat exchanger, shell-and-tube and plate-and-shell, are undergoing testing to determine the preferred geometry for scale reduction. A test skid, Figure 16, was built and tested at the geothermal site for one month, after which it will be disassembled and examined for scale formation.

Results of the scale test will be described in the conference presentation. At the time of publication, the test skid was at the project site undergoing testing. Heat exchanger selection will depend on the results of the scale test.

Summary

The Euler Turbine and Variable Phase Turbine are being implemented in the Kalina cycle and Variable Phase cycle to improve resource utilization. Successful startups of the Euler Turbines have validated the performance and advantages of the radial outflow technology for the Kalina cycle. Design of a 1 MW VPC under a DOE grant is proceeding and will validate the benefits of the VPC utilizing the VPT for improved utilization.

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References