Construction and Startup of Low Temperature Geothermal Power Plants

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ABSTRACT

Used in conjunction with the Variable Phase Turbine and the Euler Turbine, the Variable Phase cycle and the Kalina cycle, respectively, can increase the net power production from enhanced geothermal and sensible resources by 30-50% relative to commercially available organic Rankine cycles. These technologies were discussed at the GRC 2010 in the paper "Performance of New Turbines for Geothermal Power Plants." The technology and thermodynamic cycles will be reviewed briefly with primary focus on updates in the start-up of projects using these technologies.

The Variable Phase Turbine consists of discrete nozzles impinging upon an axial impulse rotor and allows for direct drive of the generator with no gearbox. The turbine can operate under any range of two-phase flow conditions and isentropic efficiencies have been measured at over 80%.

The Variable Phase cycle consists of a pump, liquid heat exchanger, Variable Phase Turbine, and condenser. Compared to a typical ORC system, the resultant system has fewer components and allows for a lower discharge temperature of the geothermal brine and, therefore, extraction of more energy from the heat source. The construction of a 1 MW geothermal Variable Phase cycle demonstration project with the DOE at Coso Geothermal is in progress and startup is scheduled in July, 2011.

Another DOE project is currently underway for the development of a 500 kW hermetic Variable Phase Turbine and the design of a scale resistant heat exchanger that allows for lower return temperatures in geothermal bottoming cycles. Experimental testing of different scale inhibition techniques will be performed.

The Euler Turbine is a radial outflow turbine developed for energy recovery in steam systems. This design, coupled with a high strength two-dimensional vane and blade profiles, enables the turbine to be rugged and erosion resistant and allows for expansions into the wet region. Commercial units have been developed and sold, and some are now operating with isentropic efficiencies near 80%.

Euler Turbines have been selected as an ideal prime mover in the Kalina Cycle. A 550 kW gross Kalina cycle geothermal power plant using an Euler Turbine was commissioned in 2009 in Germany. A 50 kW rated system was demonstrated at the Shanghai World Expo in 2010 and was then relocated to Taiwan for a geothermal demonstration. Two more Kalina Cycles will use an Euler Turbine including a 100 kW geothermal plant in Japan using a high speed generator. This approach will both increase efficiency and allow for speed variation to maximize performance over a range of operating conditions. The other turbine will be incorporated into a Kalina cycle test laboratory in China for improvements in the design and production of Kalina cycle systems.

Introduction

Low temperature geothermal resources and enhanced geothermal resources represent a large source of energy. The organic Rankine cycle (ORC) has been a leading candidate to produce power from these geothermal resources. The latent heat transfer of evaporation in the ORC, however, causes a pinch point which limits the total heat input into the 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.[1] Variable Phase cycle, liquid working fluid is pressurized and then heated in the heat exchanger with no vaporization, eliminating the pinch point limitation.

By transferring heat to a multiple component fluid—typically ammonia and water—the Kalina cycle employs variable temperature boiling in the evaporator, reducing the pinch point limitation relative to the ORC. In the Variable Phase cycle, liquid working fluid is pressurized and then heated in the heat exchanger with no vaporization, eliminating the pinch point limitation.

Two turbines, a radial outflow, wet vapor turbine named the Euler Turbine and an axial impulse turbine that allows for efficient two-phase expansion named the Variable Phase Turbine have been designed and developed to enable efficient and reliable operation in Kalina and Variable Phase cycle, respectively. These developments are a step towards the optimization of low temperature geothermal power plant output. A detailed discussion of these technologies and their development as well as a in depth comparison to the ORC has been published in previous Geothermal Resources Council Transactions.[2, 3]

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

Figure 1 shows the design of a compact waste heat recovery system being built at Coso Geothermal under a DOE program for heat recovery from a 235 °F brine stream. Design of the system is nearly completed with construction underway. Commissioning is projected to occur in Q3, 2011. The system includes a boost pump, main pump, heat exchanger, VPT, generator, condenser, and inventory tank. The generator is a standard, double-ended induction generator, with the main pump and the VPT on the shaft. The vertical, canned boost pump will provide the NPSH for the main pump.

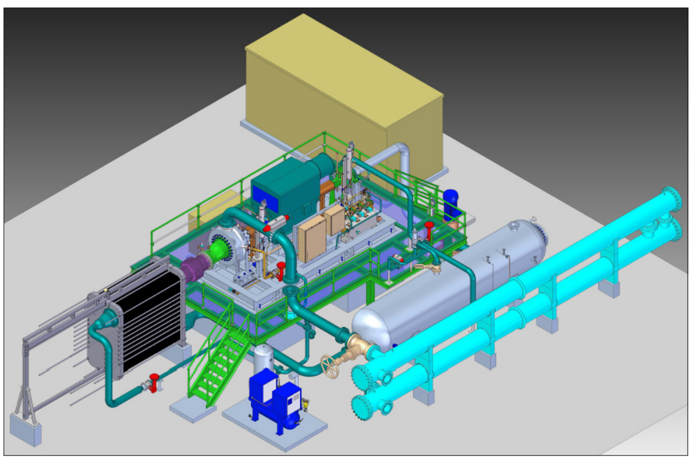

Figure 1. VPC 1 MW bottoming geothermal power plant.

Figure 2. Heat exchanger at Coso Geothermal.

At the time of publication, all of the major equipment was received and the heat exchanger and condenser were already onsite (figure 2).

Figure 3. Condenser at Coso Geothermal site.

Variable Phase Turbine Development: 500 kW Hermetic Design

An advancement to the Variable Phase Turbine design is being developed for a 500 kW Variable Phase cycle geothermal power plant. The cycle will feature a hermetically sealed Variable Phase Turbine. The turbine and generator will be submerged in the process fluid (R134a). This approach completely eliminates the need for a shaft seal and for an oil system as all bearings would be lubricated by the process fluid. A hermetic design retains all of the advantages of the regular Variable Phase Turbine and should be more compact, less expensive and more reliable as well as eliminating another potential leakage area along the shaft.

A DOE award has been given specifically to demonstrate these improvements. The turbine and nozzles would not change at all from the current design. Many large air-conditioning projects already use motors that are submerged in the refrigerant and these motor designs can easily be adapted to create an acceptable induction generator design. Commercial ball bearings that are refrigerant-lubricated are already available. One design challenge is that the refrigerant lubricated ball bearings cannot handle the full radial forces because organic refrigerants are inferior lubricants to oil. To address this issue the design of the turbine-generator has changed from horizontal to vertical with a balance piston at the top of the rotating assembly followed by the generator and then the turbine at the bottom. The design of the balance piston therefore represents the most significant new challenge.

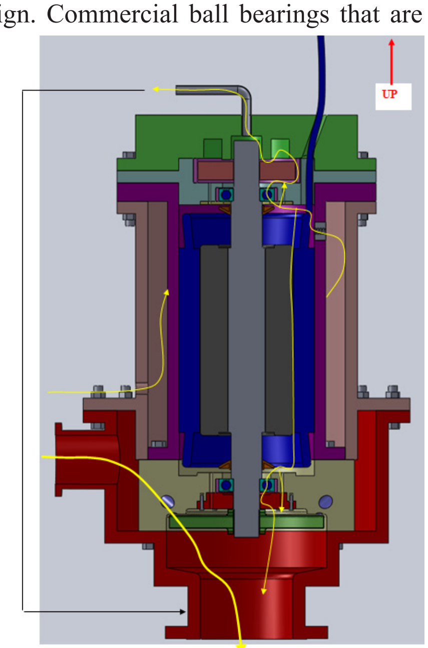

Figure 4. Preliminary hermetic VPT design.

For the DOE project the existing VPC plant at the Coso geothermal fields will be used. The existing turbine-generator will simply be bypassed so that the heat exchangers and balance of plant instead feed the new hermetic VPT design.

Heat Exchanger Scale Testing: 1 MW DOE Geothermal Project

Because of the high silica content in the brine at Coso Geothermal, 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, were tested to determine the preferred geometry for scale reduction. A test skid, figure 5, was built and tested at the geothermal site for one month, disassembled, and then examined for scale formation.

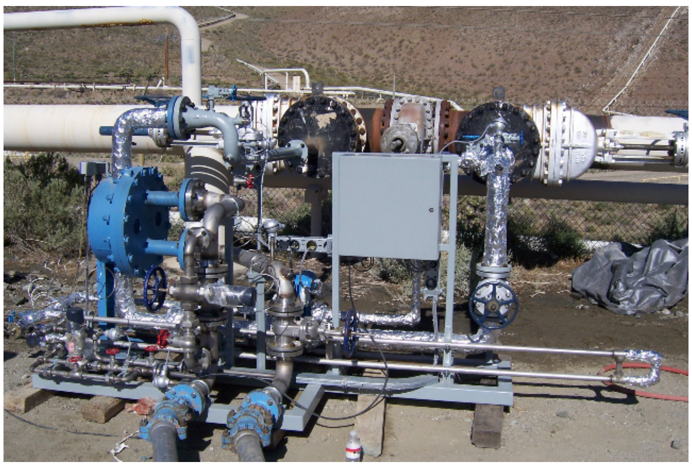

Figure 5. Scale test skid installed at Coso Geothermal.

Table 1 shows the test results from the testing. Note that the pressure drop across the plate-and-shell heat exchanger increased rapidly throughout the testing and the flow conversely decreased. The heat transfer coefficient also declined during the test period. The tube performance was much less affected by the month of operation. Inspection of the equipment at the end of the scale test showed severe scaling on the compact heat exchanger (figure 6), which was partially attributed to the off-the-shelf heat exchanger being oversized for the brine flow rate, reducing turbulence. In contrast, the shell-and-tube heat exchanger showed only small amounts of scaling.

Table 1. Scale Test Results.

	Plate & Shell				
	Flow	**delP**	**LMTD**	**Duty**	**HXfer Coef.**
	GPM	**psid**	**degF**	**MMBTU/hr**	**BTU/hrft^2F**
28-May	117.7	3.7	53.0	3.35	556
13-Jun	100.8	11.0	81.5	3.26	352
16-Jun	103.9	16.4	89.3	3.04	299
18-Jun	99.9	17.7	92.0	2.69	257
21-Jun	78.2	18.9	118.8	1.58	117
	Tube-Tube				
	Flow	**delP**	**LMTD**	**Duty**	**HXfer Coef.**
	GPM	**Psid**	**degF**	**kBTU/hr**	**BTU/hrft^2F**
28-May	2.00	0.26	62.9	53.5	227
16-Jun	1.93	0.15	75.7	57.7	203
18-Jun	1.24	-0.09	65.4	36.8	150
21-Jun	1.96	0.17	73.7	56.4	204

Figure 6. Compact heat exchanger after one month of scale test.

Figure 7. Tubes after one month of scale test.

Upon disassembly it was found that many of the passages in the compact heat exchanger were blocked by what appeared to be sand from hydro-blasting (figure 8). This undoubtedly affected the performance and validity of the test data for the compact heat exchanger. The maintenance crew at Coso attempted to pressure wash the scale off of the plates, but it had little effect. Based on the testing, a shell-and-tube heat exchanger was selected for the 1 MW project.

Scale Resistant Heat Exchanger Project

To fully take advantage of low temperature geothermal resources, scaling in the heat exchanger must be addressed, as many

Figure 8. Hydroblast debris in compact heat exchanger after scale test.

types of scale precipitate as the temperature is lowered. A DOE program is underway to develop a scale resistant heat exchanger that could survive in this harsh service. The test system will be run with the brine and cooling water that are being provided for the 1 MW project discussed above.

Figure 9 shows a preliminary P&ID for the heat exchanger testing. Different chemical additives, along with an electromagnetic device, will be tested in addition to two mechanically cleaned heat exchangers. Because the compact heat exchanger results from the prior test were convoluted by the presence of the hydro-blast sand, another compact heat exchanger test is planned. The brine will be reduced from approximately 235 °F to 120 °F to induce precipitation of the high concentration of silica. Downstream of the outlet of each test setup will be a filter with pores sized to simulate the effect of the scale inhibition technology on the reinjection well.

The results of the scale testing will be used to design a full sized scale resistant heat exchanger for use in conjunction with the Variable Phase Cycle for low temperature geothermal power.

Euler Turbine & Kalina Cycle: Taiwan Geothermal Demonstration

The government of Changhua County, Taiwan wished to take advantage of the Chingshui geothermal fields in their country. Geothermal wells had already been drilled in the past but there were difficulties with the wells that caused them to clog and made a flashing steam turbine impractical. Therefore the local government wanted to determine which binary cycle would best take advantage of the lower temperatures available of around 120 degrees Celsius. They decided that holding a competition would most quickly provide them this information.

Figure 10. Kalina Cycle at Chingshui, Taiwan.

The local government narrowed down the list of entrants to two entities. One elected to use an ORC package and the other chose the Kalina cycle approach. At the heart of the Kalina plant was a radial outflow Euler Turbine identical to a system used to demonstrate the Kalina Cycle at the 2010 Shanghai World Expo. This turbine spun at ~23,000 rpm and was connected to a standard 3000 rpm induction generator by a gearbox. The two cycles ran for the month of January 2011. Over the course of the competition the Kalina cycle was able to generate significantly more energy than its ORC competitor.

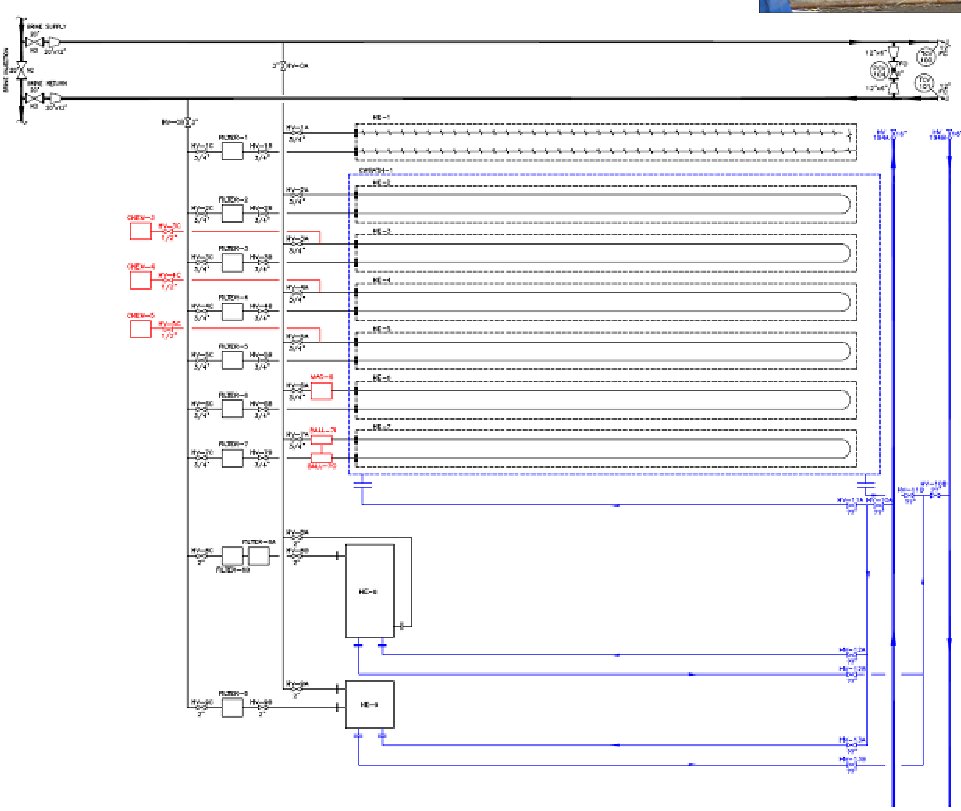

Figure 9. Scale resistant heat exchanger test P&ID.

Figure 11. Final results of competition between ORC and Kalina cycles.

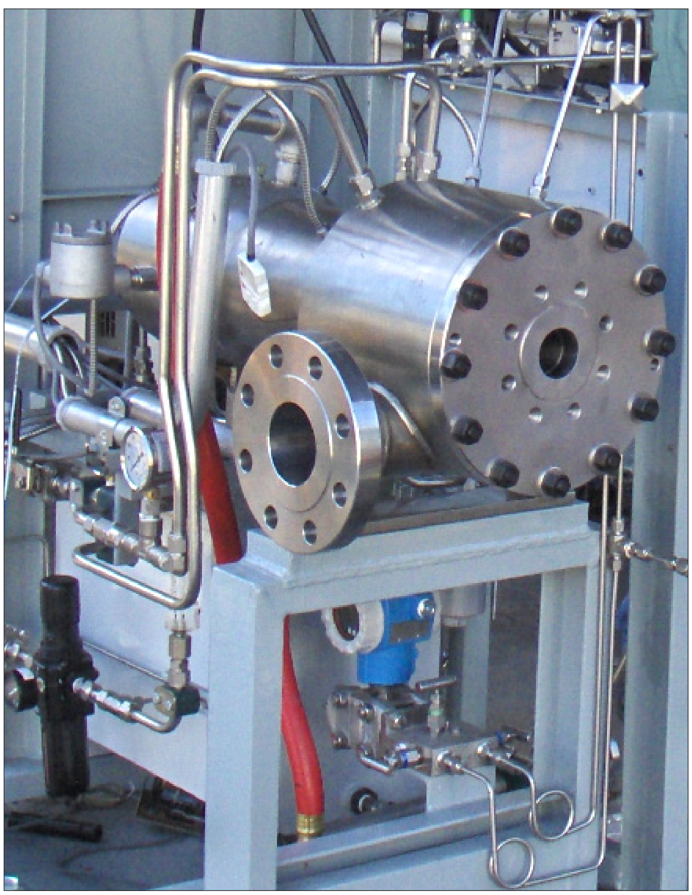

Figure 12. 100kW high-speed Kalina turbine-generator using Euler turbine technology.

Euler Turbine & Kalina Cycle: Small-Scale High-Speed Euler Turbines

A small-scale Euler turbine has been developed to work in conjunction with the Kalina Cycle for low grade heat sources. The turbine spins at 56,000 rpm and is directly coupled to a high-speed permanent magnet generator. The need for a gearbox is completely eliminated which gives several operational benefits from higher efficiency and reduction of maintenance. The 100kW rotating machinery is less than 1 meter in length giving a very high power density. The high-frequency output of the generator is converted to line frequency through a set of power electronics which can be located remotely which is an advantage if space in the machinery room is at a premium. The power electronics also allows flexibility in operational speed for off-design performance. If the resource temperature falls or the ambient temperature rises with an air-cooled condenser, the turbine speed can be reduced to preserve efficiency as much as possible.

Euler Turbine & Kalina Cycle: Kalina Cycle Research Center Unit in Shanghai, China

The first 100 kW turbine-generator was successfully commissioned in Shanghai, China, where a research center has been constructed to further improve on the Kalina cycle. The laboratory is located in an industrial park next to a power plant with a large steam resources and cooling water, providing real world conditions. Of particular interest is testing new heat exchanger designs to learn more about heat transfer, mass transfer, and film formation in heat exchangers, especially for heat exchangers for multi-component fluids. The Euler Turbine is undergoing extensive testing.

Table 2. Efficiency and power measurements from Kalina Cycle Testing in Shanghai, China.

	Speed (rpm)	Turbine Efficiency	Power (kWe)
Data Point 1	30,000	81.4%	24.2
Data Point 2	40,000	76.0%	53.3

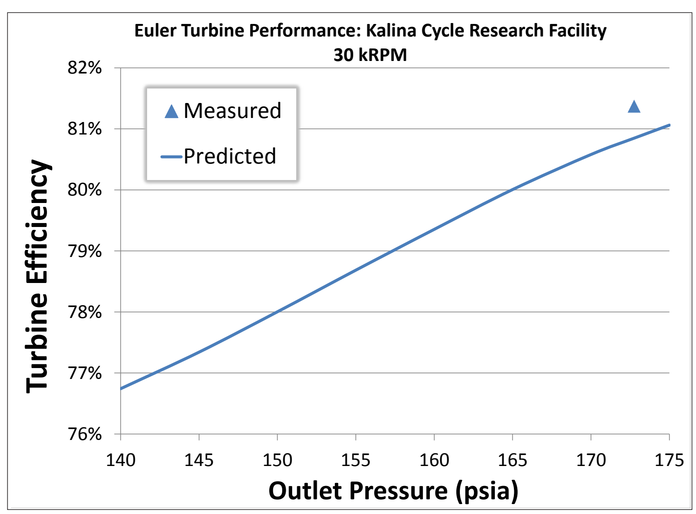

Figure 13. Performance data from operation in a research facility in Shanghai, China.

As depicted in figure 13, the 81.3% measured turbine efficiency at 30,000 rpm was above the predicted performance at the realized conditions. By varying the speed of the turbine via the power electronics, the optimum performance for the test conditions was achieved near 30,000 rpm.

A Discussion on the Economics of High Speed Generators and Power Electronics

Currently the price of the power electronics (at times referred to as a Variable Frequency Drive) is such that it makes the viability of designs using this approach marginal. Electricity is relatively cheap, making the payback of these designs longer than a more conventional approach of an induction or synchronous generator. These designs are ideal in the atypical applications where the unique characteristics can be leveraged. For the 100 kW Kalina cycle, turbine design speed was high enough that a direct connection to the grid with a conventional generator would require a two-stage gearbox. A two-stage gearbox requires a significant amount of design work and brings a number of engineering and reliability challenges to the project. In applications such as these the high-speed generator with power electronics can offer a more reliable design with some additional flexibility.

Another design advantage is the variable speed. If the plant or process does not run under constant conditions or could benefit from off-design operation, then the variable speed of the turbine-generator can be a significant advantage. For a geothermal application, an example of this would be in systems that use an air-cooled condenser. Throughout the day and year the ambient temperature varies significantly and causes the condenser pressure to fluctuate. A turbine with variable speed can continuously operate at its peak efficiency across all conditions in the way that a fixed-speed turbine can not. Additionally, a high speed generator with power electronics can operate across a range of voltages and frequencies with a simple programming change. This allows a manufacturer to create one design for all customers in all countries.

Summary

The Euler Turbine and Variable Phase Turbine are being implemented in the Kalina cycle and Variable Phase cycle to improve resource utilization. Commercial qualification for both the technologies are underway. The start-up of the first Variable Phase cycle will prove to be a validation of the advanced thermodynamic cycle and chance to further improve the working knowledge of the turbine and cycle. Recent and planned Kalina cycle start-ups utilizing the Euler Turbine and creation of a dedicated test facility in Shanghai reflect the international acknowledgement of the cycles benefits and continued growth.

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