Notes from the North: a Report on the Debut Year of the 2 MW Kalina Cycle® Geothermal Power Plant in Húsavík, Iceland

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Abstract

The Orkuveita Húsavíkur Kalina Cycle® plant began generation operations in July 2000. In the performance test conducted after the plant's shakedown year, in November 2001, the plant's net output exceeded the design output as corrected for the actual resource temperature (the resource came in 3ºC [5ºF] below design temperature). Now, after more than two years of operation, the plant reliably produces more than 1,600 kW at a notable level of efficiency, reliability and availability. The Orkuveita Húsavíkur power plant is the first geothermal application of the Kalina Cycle® and the first Kalina plant in Europe.

On the Northern Shore of Iceland, An Innovative Cascaded-Use Geothermal Project

Húsavík has a population of just 2,500 and is located on the north coast of Iceland. The town has set out on a program to become one of the most energy-efficient and energy-diverse towns in the world. In 1998-2000, the City of Húsavík, Iceland, developed an innovative municipal energy system based on the use of hot fluid runs by graviti from the Hveravellir geothermal field to the town. The Orkuveita Húsavíkur installation, in addition to being a showpiece of cascaded direct use, is also a pioneer commercial demonstration of the feasibility of the Kalina Cycle® for generating electrical power from a low-temperature geothermal resource. The heat source for the plant comes from artesian geothermal wells located 20 km [12.4 miles] south of Húsavík. A geothermal flow of 90 kg/s [714,300 pph] at a typical temperature of 121ºC [250ºF] is directed to the Kalina plant to provide 70%-80% of the town's electric demand. In parallel with the power plant, this hot water is now used by local industries for process heat and drying of hardwood, and will soon be used in the production of glucosamine and chitin.

In the course of the Kalina conversion process, the brine is cooled to 80ºC [176ºF]. This hot fluid exiting the plant is used in the city district heating system. Other direct uses include heating of greenhouses and barns, snow melting and heating of the town's swimming pool and spa. Further, the cold mountain water used in the Kalina plant's condenser finds a secondary use. The 5ºC [41ºF] water leaves the condenser at 25ºC [80ºF] and is piped to a trout fish farm. This ambitious energy program allows the city and residents to avoid use of more economically and environmentally punishing energy resources, and provides a reliable source of thermal and electric energy for economic expansion.

The Kalina Cycle® Generation System at Húsavík

Kalina Cycle® System 34 (KCS 34) was selected for the Húsavík project. A flow diagram of KCS 34 is shown in Figure 1. This system was designed by Dr. Alex Kalina, Exergy's founder, specifically for generating electricity with low-to-medium-enthalpy geothermal resources as a "topping" energy conversion prior to district heating. POWER Engineers, Inc. was Exergy's engineering consultant for the design of the power block for the Orkuveita Húsavíkur Kalina plant.

The main components include a vapor turbine-generator, evaporator, separator, condenser, recuperator exchangers and feed pump. The working fluid is an ammonia-water mixture, 82% ammonia by weight. The conspicuous efficiency advantage characteristic of the Kalina cycle is realized from the heat exchange processes of the heat acquisition in the evaporator and the heat rejection in the condenser. Additional efficiency is achieved by the recuperator exchangers. These gains are made possible by the variable boiling and condensing characteristics of the ammonia-water mixture working fluid as it varies in concentration at different points in the cycle.

Through the PFD – Walk This Way Through Figure 1

Starting at the outlet of the water-cooled condenser, the cycle working fluid is an 82% ammonia-water saturated liquid mixture at 5.4 bar-a [78.4 psia] and 12.4ºC [54.3ºF]. This stream is pumped to a high pressure by the feed pump. The feed stream is preheated in the low-temperature (LT) and high-temperature (HT) recuperators to 68ºC [155ºF] before entering the evaporator. In the evaporator, the working fluid is heated to 121ºC [250ºF] against a design brine temperature of 124ºC [255ºF]. The ammonia-water is partially vaporized to a quality of 75 percent (75% vapor, 25% liquid). This mixed-phase fluid is sent to the separator where the vapor component (high in ammonia) is separated from the liquid component (low in ammonia).

The high-pressure rich saturated vapor from the separator drives the turbine as the vapor rapidly expands and cools to a low-temperature, low-pressure exhaust. The lean saturated liquid from the separator is cooled in the HT recuperator where the sensible heat energy in this stream is used to preheat the feed stream to the evaporator. The flow of this fluid is controlled by a level control valve which maintains the liquid level in the separator. This liquid flow is then directed to the inlet of the LT recuperator where it combines with the rich vapor exhaust from the turbine. This liquid stream is sprayed into the exhaust vapor stream, and the two streams unite to reform the basic fluid mixture of 82%. The temperature of the liquid stream from the HT recuperator is 48ºC [119ºF], and vapor stream from the turbine is 60ºC [140ºF].

These two streams, now as a mixed-phase fluid, are cooled in the LT recuperator where the latent and sensible heat energy is used to preheat the feed stream. As this fluid cools, some of the vapor stream from the turbine condenses. The liquid that exits the LT recuperator is collected in a drain tank while the remaining vapor goes directly to the condenser. At this point, the vapor has a high ammonia content, while the liquid in the drain tank has a low ammonia content. The temperature of both the vapor and liquid streams is 38ºC [100ºF].

The liquid in the drain tank is pumped up to the inlet of the condenser to be sprayed into the vapor stream. Spraying this lean liquid into a rich vapor aids the condensation of the vapor by absorption process. The process is repeated in a closed loop arrangement.

A Modest Set of Controls

Operation is surprisingly simple. The Húsavík plant operates unattended for the majority of the time. Except for perhaps the turbine (which every geothermal power plant has), the process is no more complex than that found within an ammonia absorption refrigeration plant. The difference in ammonia concentration in various parts of the plant is not a result of overriding process control. Rather, the concentrations at various points are a result of the pressure and temperature of the working fluid stream. At every point, the constituents of the working fluid seek their own balance. Besides the turbine controls, there are only four control loops: 1) the feed flow control valve, which is controlled in proportion to the geothermal brine flow, 2) the separator level control, 3) the drain tank level control, and 4) the turbine bypass valve which only operates at plant start-up and shut-down.

Equipment

Vapor Turbine: The vapor turbine for this plant is a standard design “steam” turbine model CFR5 G5a manufactured by Kühnle, Kopp & Kausch (KK&K). This is a single-stage radial-flow curtis wheel design with two rows of blades. The blades turn the vapor flow from radially inward to axially out. The turbine wheel operates at 11,226 rpm. The wheel is an overhung (cantilever) design with an integral gear on the shaft. The overhung design eliminates the need to preheat the turbine prior to start-up, allowing rapid starts. This design also requires only one seal, thus reducing losses of the ammonia-water vapor. The turbine has proven to be a very robust design. The gear is used to couple the turbine to a 1,500 rpm TEWAC synchronous generator. The turbine seal is a Burgmann gas-lubricated mechanical seal in a tandem arrangement with integrated intermediate labyrinth. Nitrogen is used as the sealing, or “buffer” gas medium. A nitrogen generator provides a continuous supply of sealing gas.

Heat Exchangers: The evaporator is a shell-and-tube exchanger utilizing low-fin carbon steel tubes. The HT recuperator is a carbon steel shell-and-tube exchanger. The LT recuperator is a welded plate exchanger. The plates are stainless steel surrounded by a carbon steel housing. The condensers are plate-type heat exchangers with welded pairs on the ammonia-water process side to minimize leakage. Plates are stainless steel. There are two 50% capacity condensers arranged in parallel.

Separator: The separator is an impingement-type vane module. The vanes are composed of stainless steel corrugated profile plates assembled with phase separating chambers. The separator module is mounted inside a pressure vessel with an integral liquid reservoir.

Process Pumps: The pumps in the cycle are vertical turbine pumps designed to handle saturated ammonia-water liquids. The pumps are fitted with tandem mechanical seals.

Building: All equipment is housed indoors. The powerhouse footprint is a compact 11.5 x 21 meters [38 x 69 feet]. This area includes laydown and access aisles.

Ammonia Handling

All vents, drains, and safety valve discharges containing ammonia are directed to a water blowdown tank. A perforated header inside this tank sparges the ammonia into 16.1 m^3 [4,250 gallons] of water where the ammonia is absorbed. A breather valve is maintains a slight positive pressure inside the tank to suppress ammonia vapors venting to the atmosphere. The ammonia concentration in the tank is maintained below 10%. The solution is diluted by partially draining the tank and refilling with fresh water.

As an acknowledgment to the environmental friendliness of the ammonia, one use of this “spent” aqueous solution drained from the blowdown tank is as a fertilizer. The aqueous solution is drained into a portable tank and sprayed onto the surrounding turf. Another use is as an industrial-strength cleaning solution. A water flush system is provided for equipment maintenance. For personnel safety reasons, this system ensures all ammonia fluid is purged from a particular section of piping and equipment before the system is opened to atmosphere for maintenance. The ammonia is pushed into the blowdown tank by the water.

There are no intentional releases of ammonia from the plant. The only atmospheric release of ammonia is from minute leakage from valve stems and flanges. During normal plant operation, there has been no noticeable ammonia odor at the facility. This is despite ammonia’s very low odor threshold of 1 to 5 ppmv concentration. All major equipment for the facility is located indoors because of Húsavík’s challenging climatic conditions. The building enclosure has full-time ventilation fans. These fans vent minute fugitive ammonia vapors and maintain the enclosure at a slight negative pressure. The enclosure is equipped with ammonia detection sensors. Any ammonia vapors detected above a concentration of 400 ppm would activate a high-volume ventilation system to direct the vapors outdoors while directing fresh air into the building. Detection of a high level of ammonia vapor would also activate a trip of the plant. The control room is kept at a positive pressure with fresh outside air as a safe haven area to protect personnel. Safety protective gear is also available for plant personnel.

While some may believe the strong odor and irritating properties of ammonia are a nuisance, these are actually beneficial. First, they are self-alarming. Ammonia smell is detected at levels as low as 1 to 5 ppmv, while harmful levels are several orders of magnitude higher. As the odor and irritating properties of ammonia increase, no one will volunteer to stay in an area which has harmful levels of ammonia. Second, these properties will ensure that operators maintain a good tight plant. Minor leaks are readily detected and fixed before they become a hazard. Furthermore, ammonia poses little fire and explosion hazard; ammonia will not support combustion after the ignition source is withdrawn. And finally, ammonia is gaseous at atmospheric pressure. It is much lighter than air and, therefore, easy to vent off.

Because of these operational virtues and comparative environmental friendliness, a strong case can be made for the identification of ammonia as the medium of first choice for binary cycle heat recovery systems. By contrast, the hydrocarbons heretofore dominant in this application are flammable and may represent an explosion hazard. Organic fluids are also identified as contributors to photochemical smogs, depletion of the ozone layer. In the event of an accidental spill, organic fluids can pose a hazard to local ecosystems.

The Plant's Start-up and Initial Operation, July 2000

Pre-operational tasks such as hydro-testing, flushing, instrument calibration and filling of ammonia-water fluid were completed as required for start-up. Hot brine was made available to the Húsavík plant on July 16, 2000. Start-up followed the following basic sequence. All valves were set in the required operating position. The feed pump was started to circulate ammonia-water through the evaporator, separator, recuperators, condenser and back to the feed pump. Hot brine was then admitted, in small increments, to start vaporizing the ammonia-water in order to raise the pressure in the evaporator and separator. When the pressure reached approximately 10 bar-g [145 psig], the turbine bypass valve opened to start circulating vapor through the recuperators and condenser.

As the brine flow was steadily increased, the ammonia-water feed flow was increased proportionally by automatic control. The pressure setpoint for the turbine bypass valve was slowly raised to allow the system to achieve the design operating pressure. After a couple of trips and re-starts, the unit proved to be very predictable and stable. The system operated unattended the very first night at 25% flow on turbine bypass.

The next day was dedicated to adjusting the ammonia-water mixture to the optimum concentration, instrumentation adjustments, rolling the turbine and trip tests. These tasks continued for the next two days. The generator was finally coupled to the turbine and synchronized on July 20, 2000. Instrument adjustments and successive load trip tests were then performed. With less than two days devoted to shakedown and tests, the Kalina plant had to pass its most important test. July 22, 2000 was scheduled as a formal dedication. The president of Iceland, Dr. Ólafur Ragnar Grímsson, pushed the symbolic "Start" button for the plant. The unit started up without problem, with an overflowing crowd of public officials and press personnel as witnesses.

In the following days, the plant output increased as the brine flow and temperature were increased. In October 2000, the unit was pressed into continuous service to comply with the town's supply contract with Iceland's electric utility during the winter peak demand period. After the 2000 winter peak period, the plant's ammonia-water separator was modified to a more conservative design and the plant was pre-operationally cleaned. In November 2001, a performance test was conducted.

The actual temperature of the geothermal brine inlet to the plant is 121ºC [250ºF], or 3ºC [5ºF] lower than the original design temperature of 124ºC [255ºF]. (It should be noted that a peak temperature of 122ºC [252ºF] can be achieved for a short duration of about six hours by special valving procedure at the geothermal wells.) While this degradation of heat source temperature may seem inconsequential, in reality, it is very significant. Thermodynamic law dictates that a lower heat source temperature results in a lower efficiency rate of the heat-to-electricity conversion process. In other words, lower heat source temperatures result in a lowering of not only the amount of energy available to be converted, but the efficiency of the conversion process as well. So while the Kalina Cycle® is the most efficient conversion process available for low-grade heat sources, the further lowering of an already low temperature heat source reduces the plant electrical output.

The Kalina Cycle® offers a significant advantage in situations where the inlet brine temperature is lower than the design value. Since the working fluid is a mixture of ammonia and water, when an important parameter changes, such as the heat source temperature, the concentration of this mixture can be easily re-adjusted to optimize power output for the new temperature. This fluid mix can also be changed on a seasonal basis to optimize the plant output for seasonal temperature changes in the condenser cooling water. This type of plant performance optimization is not possible with other geothermal power plant technologies.

The Tale of the Tape: November 2001

A plant performance test was conducted in November 2001 following operation of the plant for about 15 months. The objective of the performance test was to measure the plant's net efficiency at a maximum electric output condition. To achieve this goal the plant was run for a short period of time at the brine inlet temperature of 122°C (252°F). Both pre-test and post-test uncertainty calculations were performed to evaluate the quality of the test. On November 28, 2001 a two-hour performance test was run at the 122°C (252°F) brine inlet temperature condition. All other plant performance parameters were maintained at the design full-load condition. On November 29, 2001, a maximum output test was run to determine the impact of increased cooling water flow at the plant's normal operating brine inlet temperature of 121°C (250°F). To achieve this test condition, the cooling water flow rate increased approximately 11% above the design full load cooling water flow.

Results of the two test periods are summarized in Table 1 below. During the November 28, 2002 and November 29, 2002 tests, the measured net electrical output was 1,696 kW and 1,719 kW respectively. Consistent with ASME Performance Test Code practice, correction factors were applied to the measured data to correct the plant to design conditions. Correction factors were applied to account for the lower brine inlet temperature, aging and wear of the turbine following 15 months of service, and correcting for auxiliary electrical users to account for deviation from design caused by the low inlet brine temperature. Exergy consulted with the turbine manufacturer to arrive at an appropriate correction factor for the turbine based upon an internal inspection and normal wear experience for this type of machine in similar service. The most significant correction is the low inlet brine temperature.

Orkuveita Húsavíkur Kalina Plant Performance Test Summary

	November 28, 2001	November 29, 2001
Brine Flow, kg. per sec.	90	90
Brine Inlet Temperature, ºC	122	121
Cooling Water Flow, liters per sec.	182	202
Cooling Water Inlet Temperature, ºC	4	4
Gross Electric Power, kW	1,823	1,836
Auxiliary Power, kW	127	127
Net Electric Power, kW	1,696	1,709
Corrected Net Power, kW	1,959	2,060

The plant performance measurements confirm the impressive thermodynamics of the Kalina Cycle® in comparison with conventional binary power generation technologies. A direct comparison of the Kalina plant output with Organic Rankine Cycle (ORC) plants, as characterized by the initial bid offering for Húsavík, is significant. In the Húsavík bid offering, ORC plants competing for the project offered guaranteed net outputs ranging from 1,550 to 1,610 kW at the original higher brine temperature of 124ºC [255ºF]. The test data in the table above show that the Kalina plant's actual net power output is far greater with 121ºC [250ºF] brine than that proposed in the ORC offers, even using the higher 124ºC [255ºF] brine inlet temperature specified as a design condition in the bid request. The measured Kalina Cycle® data confirms a performance advantage of 20% to 25% compared to the ORC offers.

Conclusion

The Húsavík Kalina plant is a conspicuous success from the point of view of its owner and its designers. Its operation over the past two years validates the efficiency, environmental, safety, flexibility and commercial advantages of the Kalina Cycle® over rival binary cycle technologies. The Kalina plant at the hot end of Húsavík's geothermal system has delivered more than 1,600 kW of cost-effective, clean baseload power at an exceptional level of efficiency, reliability and availability. Húsavík has developed a new landmark– an advanced geothermal energy system – in a wild and beautiful place by the Greenland Sea. ✍

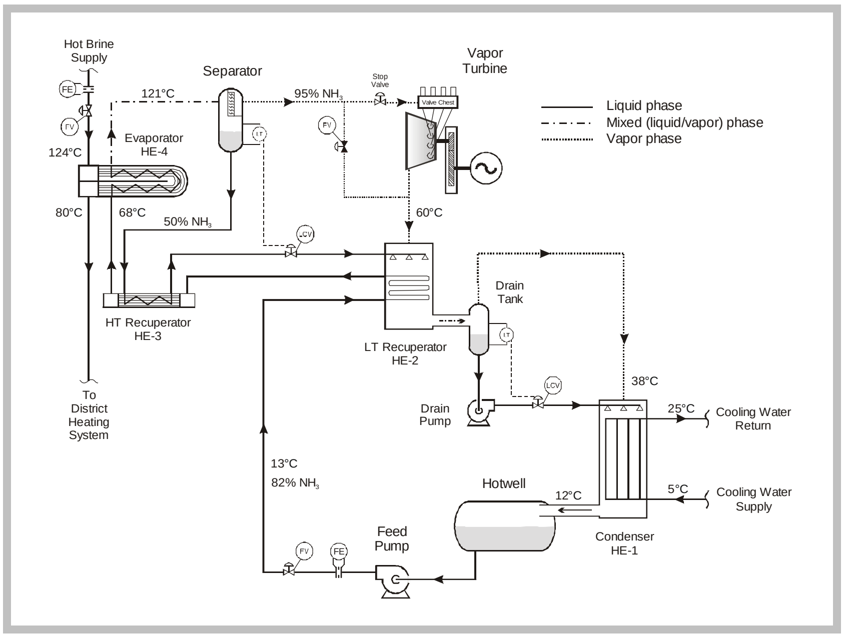

Figure 1: Flow Diagram – Orkuveita Húsavíkur
Geothermal Power Plant

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